Rapid Manufacturing of Vacuum Forming Components Utilising Reconfigurable Screw-Pin Tooling

by

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ABSTRACT

Current market trends are moving from large quantity production towards small batch production and mass customization. This has led to the high demand for the flexibility and adaptability of manufacturing technology and systems. Several reconfigurable pin type tooling systems have been proposed and developed to satisfy such demands. However, these reconfigurable tooling systems still suffer from several drawbacks, including difficulties associated with positioning and locking the pins and problems of uneven “staircase” surface effects from relying on discrete finite size pins.

The main focus of this research is on building a hybrid vacuum-forming machine system (**HAVES**) based on reconfigurable screw-pin tooling (**SPT**) as a test bed for understanding the processes involved in developing this technology and to examine the feasibility of implementing such technology in an industrial system. The SPT used is composed of identical screw pins, which are engaged with each other in an array pattern. By adjusting vertical displacement of the screw pins, a wide variety of component geometry can be formed. The adjustment methodology of the SPT is formulated mathematically in order to help construction of the SPT be parametrical thus enabling automatic CNC G-code generation. The HAVES test bed development involves full machine design and hardware and software integration. The hardware integration task included a CNC controller, drive motors, encoders, milling and screw adjustment heads, SPT, vacuum forming system. The software integration task involved the processing of three-dimensional CAD geometry to automatically generate post processed G codes in order to adjust the screw-pin to the required component geometry and subsequent surface machining for driving the final die geometry and minimize operator intervention. The completed HAVES test bed has been tested for accuracy, repeatability and functionalities with quality good results. An economic analysis has been also conducted to verify the economic feasibility of the HAVES test bed by comparing the cost of making vacuum forming components using a dedicated mould versus using the HAVES test bed.

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ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AHP	Analytic Hierarchy Process
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CMM	Coordinate Measurement Machine
CNC	Computer Numerical Control
FEA	Finite Element Analysis
HAVES	Hybrid Vacuum-forming Machine System
HA	Hydraulically Actuated pin tooling
HIPS	High impact polystyrene
MPF	Multi-point forming
NC	Numerical Control
PC	Polycarbonate
PE	Polyethelene
PETG	Co-Polyester
PMMA	Acrylic
PP	Polypropylene
PVC	Polyvinylchloride
SCAG	Screw pin tooling construction, adjustment and G code generation
SPT	Screw-Pin Tooling
SPT-Demo	Screw pin tooling display and verification
SSU	Sequential Set-Up pin tooling
SDL	Shaft-Driven Leadscrew pin tooling

NOMENCLATURE

θ	Squareness error
$\omega_{a,b}$	Weights of 3D control points
B axis	Router spindle for milling 3D forms from screw-pin tooling
$B_{a,p}$	Normalized B-splines of degree p in the u directions;
$B_{b,q}$	Normalized B-splines of degree q in the v directions;
c	The numbers of columns
C axis	Rotary axis attached to Z axis saddle
cmx	The complexity of the pin
C_{1-pin}	Price for a single pin
C_{app}	The application cost of the screw pin tooling
C_{bed}	Cost of the machine bed
C_{cnc}	Cost of the Numerical Control Device package
$C_{control}$	Control system cost of the manufacturing cost model
C_{dir}	Direct costs of the screw pin tooling application
C_{encs}	Cost of the encodes
C_{fa}	Frame assembly cost
C_{fmanu}	Frame manufacturing cost
C_{fm}	Frame material cost
C_{fmanu}	Frame manufacturing cost
C_{frame}	Frames cost of the manufacturing cost model
$C_{h-parts}$	Cost of the other related parts for hardware
$C_{hardware}$	Hardware cost of the manufacturing cost model
C_{indir}	Indirect costs of the screw pin tooling application
C_{lsa}	Cost of the leadscrew actuators
C_{motors}	Cost of the drive motors
C_{others}	Other cost of the manufacturing cost model

C_{pc}	Cost of personal computer
C_{pins}	Pins cost of the manufacturing cost model
C_{sf}	Cost of safety equipments
C_t	The total cost of the manufacturing cost model
C_{ws}	Service cost for wiring the machine for CNC control
$Cost\,(M_c)$	The material costs
$Cost(T_{tech})$.	Technician cost
COLpin	Columns of screw pin tooling
CXmax	The maximum X coordinate value on the component
CXmin	The minimum X coordinate value on the component
CYmax	The maximum Y coordinate value on the component
CYmin	The minimum Y coordinate value on the component
Dev	Dial gage deviation
Dpin	Screw pin diameter
em	The engagement method
f	The pin number calculation function
$f1$	Mapping function from screw pin domain to tooling working surface domain
$f2$	Mapping function from component surface models to screw pin tooling working surface
$f3$	Mapping function from S_c to S_n
F_{adj}	Screw-pin adjustment feed rate
$F_{dis-eng}$	Disengagement feed rate
F_{eng}	Engagement feed rate
F_x	Feed rate in X axis
F_y	Feed rate in Y axis.
g	Price compute function for single pin
$\Delta h(i, j)$	Pin height change matrix
$h_{current}(i, j)$	Current die shape

$h_{new}(i, j)$	New die shape
i	Represent the number of row and of the screw-pin tooling
.inp	Analysis input file
j	Represent the number of volume of the screw-pin tooling
k	Numbers of control points in the v directions
l	Numbers of control points in the u directions
Lpin	Screw pin length
$L_{dis-eng}$	Disengagement distance
L_{eng}	Engagement distance
L_x	move length for X axis
L_y	Move length for Y axis;
$m \times n$	Number of array pattern
mat	The pin material
M_c	Material consumption
M_{pin}	Machined screw pins material
M_{pps}	Product plastic sheet
M_s	Sacrificial plastic sheet material
M_{wf}	Wood filler material
N	All the nodes that build the surface model
N_S	The sample size
N^{ij}	Nodes in the ith row and jth column surface area
N_e^{ij}	A node in the ith row and jth column surface area
P1	Current screw pin Z coordinate
P2	Length to be adjusted
P3	Tool tip position for changing feed rate
P4	Tool tip position for starting adjustment
P5	Degrees to be adjusted
P6	Retract plane height

ΔP_{ij}	Adjustment distance of P_{ij}
$P_{a,b}$	3D control points
P_{ij}	Screw pin at the i^{th} row and j^{th} column in the array pattern
P_{ij}^{c}	Pin position for current design model
P_{ij}^{n}	Pin position for new design model
Pc (x,y,z)	A point of component
Pnt (i,j)	Point position on the top of the screw-pin central axis position on the i^{th} row and j^{th} column of the screw-pin array pattern
Pnt(i,j).X	X coordinate value of the screw-pin **Pnt**(i,j)
Pnt(i,j).Y	Y coordinate value of the screw-pin **Pnt**(i,j)
Pnt(i,j).Z0	Z coordinate of the screw-pin **Pnt**(i,j) before adjustment
Pnt(i,j).Z1	Z coordinate of the screw-pin **Pnt**(i,j) after adjustment
Ppin	Screw pin pitch
P_{sp}	The pitch of screw-pins
Pt^{k}(x,y,z)	k_{th} point within the area of the Pnt(i,j)
r	The numbers of rows
$R_{a,b}(u,v)$	Rational basis functions
ROWpin	Rows of screw pin tooling
S	Geometry model surface
S_{dev}	Sample standard deviation
S^{ij}	A surface patch of geometry model
SL	Sliding length
S_a	Average absolute deviation of the surface
S_c	Current component geometry
S_n	New component geometry;
S_T	Working surface of the tooling
ΔS_T	The difference between S_T^n and S_T^c
S_T^{ij}	Z-coordinates of a screw pin sampling points

S_T^c	Screw pin tooling working surface used to produce S_c
S_T^n	Screw pin tooling working surface used to produce S_n
S_v	Largest valley depth within the definition area
t	Total number of nodes in the N^{ij} point set
t_{eng}	Time needed to engage and disengage the adjustment tool with the screw pins
t_{pins},	Pins positioning time
t_{xy}	X and Y axis motion time
T_c .	Total time per mould
T_{mf} .	Wood filler surface machining time
T_{mp}	Screw-pin machining time
T_{ms}	Sacrificial machining time
T_{p-cnc}	CNC programming time
T_{setup}	Screw-pin tooling shape set up time
T_v	Vacuum forming time
T_{wf}	Wood filler set up time
T_{tech}	Time spent by technician
W axis	Vertical axis with router spindle, move up/down
$\bar{x}$	Arithmetic mean of the samples x_i
X axis	Axis for machine tool moves left/right
Xpin	Distance between two screw central axes in the x direction
Y axis	Axis for machine tool moves forward/backward
Ypin	Distance between two screw central axes in the y direction
Z axis	Vertical axis with screw-pin adjustment, move up/down

CHAPTER 1

INTRODUCTION

1.1 Background to reconfigurable pin tooling

Tooling equipments, such as dies and moulds, play a paramount role in the modern manufacturing industry. A large number of manufacturing technologies such as injection moulding, casting, stamping, vacuum forming and forging rely heavily on design and fabrication of dies and moulds. In today’s highly competitive manufacturing environment, companies are constantly seeking to reduce the cost and lead time of tooling development for product fabrication.

Current mould making techniques are primarily designed for mass production, not short runs, and cannot easily be reused. This makes the production of tools for limited volume applications very expensive (Halford, 2008). This is especially true for complex tooling, where both development time and manufacturing costs make it extremely expensive. These conventional methods are adequate for mass production because the cost of dies can be shared by a large number of parts. However, such tooling is not suitable for rapid customization.

The current market trend is moving from mass production towards small batch and large variation production runs. The need for rapid, low-cost tooling fabrication and modification methods is greater than ever in the modern manufacturing industry. This has led to a high demand for an increased flexibility and adaptability of the manufacturing technologies and systems.

Manufacturers have long desired universal tools that could make many different shapes (Papazian, 2002). Several rapid prototyping (RP) technologies such as selective laser sintering, 3D printing, layered manufacturing (LM) and similar technologies have been developed with great speed over the last decade, and have shown the capability to produce small lots, and complex geometries. However, those processes are limited by the choice of materials and may not be feasible for final production or mass-production. While RP technologies can directly produce small to medium size component parts, large functional plastic, metallic, and composite components (such as car bodywork) still have to be made using mould tools (Halford, 2006).

1.2 Research motivation

Among the various techniques used for small lot sizes, the idea of the “discrete-die” reconfigurable tooling approach has gained increased attention over the past few decades. In the reconfigurable tooling approach, the surface of the tool is made up of the ends of individual elements, usually pins, arranged in a matrix with the pins able to move up or down to change the tool shape (Papazian *et al.*, 2004).

The obvious advantage of reconfigurable tooling is that the same tool can be used to form many different shapes when moulding, fixturing or in tool trials. Additionally, the same tool can be used for multiple purposes including as a die, a mould or a fixture. The leadtime and costs for developing and manufacturing a product using reconfigurable tooling are considerably lower when compared to tools fabricated by conventional methods. Moreover, it is an environmentally benign technology since it does not involve any waste product (Owodunni et al., 2004 and 2005).

However, this promising manufacturing technology is not yet widely used in industry. One reason for this is that pin adjusting and locking mechanisms are still complicated and their construction cost remains high. While some researchers and engineers have explored various methods such as mechanical, pneumatic and hydraulic approaches, a simple, cheap and industry scale reconfigurable tooling has not yet been developed.

An essential ingredient for the viability of any reconfigurable tooling system is its incorporation into a complete factory system for the production of parts. A stand-alone reconfigurable tool would have little impact on the production stream (Papazian et al., 2004). The prior art process of mould reconfiguring and moulding of reconfigurable tooling have been separated due to a lack of integration and automation. The development of a robust, streamlined and commercially available reconfigurable tooling system has not yet occurred in plastic vacuum forming.

Due to the natural characteristics of the discrete pin, current reconfigurable tooling is often suitable for the moulding of components with simple geometry, and is not suitable for components with complicated and intricate geometry.

The reconfiguration of the mould is normally realised by a software package, which is used to generate the control information from a CAD model.

1.3 Aim and objectives

In view of the above, the aim of this research is to build a hybrid vacuum-forming machine system (**HAVES**) based on reconfigurable screw-pin tooling (**SPT**) as the test bed to understand the processes involved before examining the feasibility of implementing this machine in an industrial system and then providing suggestions for designing better systems in the future. In order to achieve this, the specific research objectives are:

- To design and build a machine test bed that integrates the reconfigurable SPT with the CNC and vacuum forming machines.
- To develop a tooling shape control methodology for the SPT to adjust the screw pins from one position to another by using digital CAD as input.
- To test and validate the developed hardware and support software of the HAVES test bed.
- To investigate the economic feasibility of the developed HAVES in producing plastic parts.

1.4 Thesis contributions

The research work in this thesis provides an integrated prototype system for applying the SPT in vacuum forming. The contributions made by the thesis are concluded as follows:

1. The design and construction of an economic HAVES prototype composed of five modules: screw-pin tooling module, CNC control module, dual tooling head module, vacuum forming module and surface measurement module.
2. The development of a software package aimed at generating the CNC program for screw pin adjustment from a 3D surface CAD model.
3. The development of a program for simulation of screw pin adjustment based on Unigraphics /GRIP.
4. The identification of necessary methods for surface quality improvement of the SPT.
5. Economic model analysis of the developed HAVES prototype.
6. A contribution to the academic community by publishing one patent, five conference papers and one journal paper.

1.5 Thesis outline

The research presented in this thesis is contained within seven chapters. The thesis outline is illustrated in Figure 1-1. In particular,

Chapter 1 introduces the background of reconfigurable tooling and objectives of this research work.

Chapter 2 reviews the state of the art research in the field of reconfigurable tooling. This literature review is categorized into four groups: a summary of the main types of applications of the technology; a realization of tooling reconfigurability; relevant simulation and algorithm for application; the occurring problems and respective solutions.

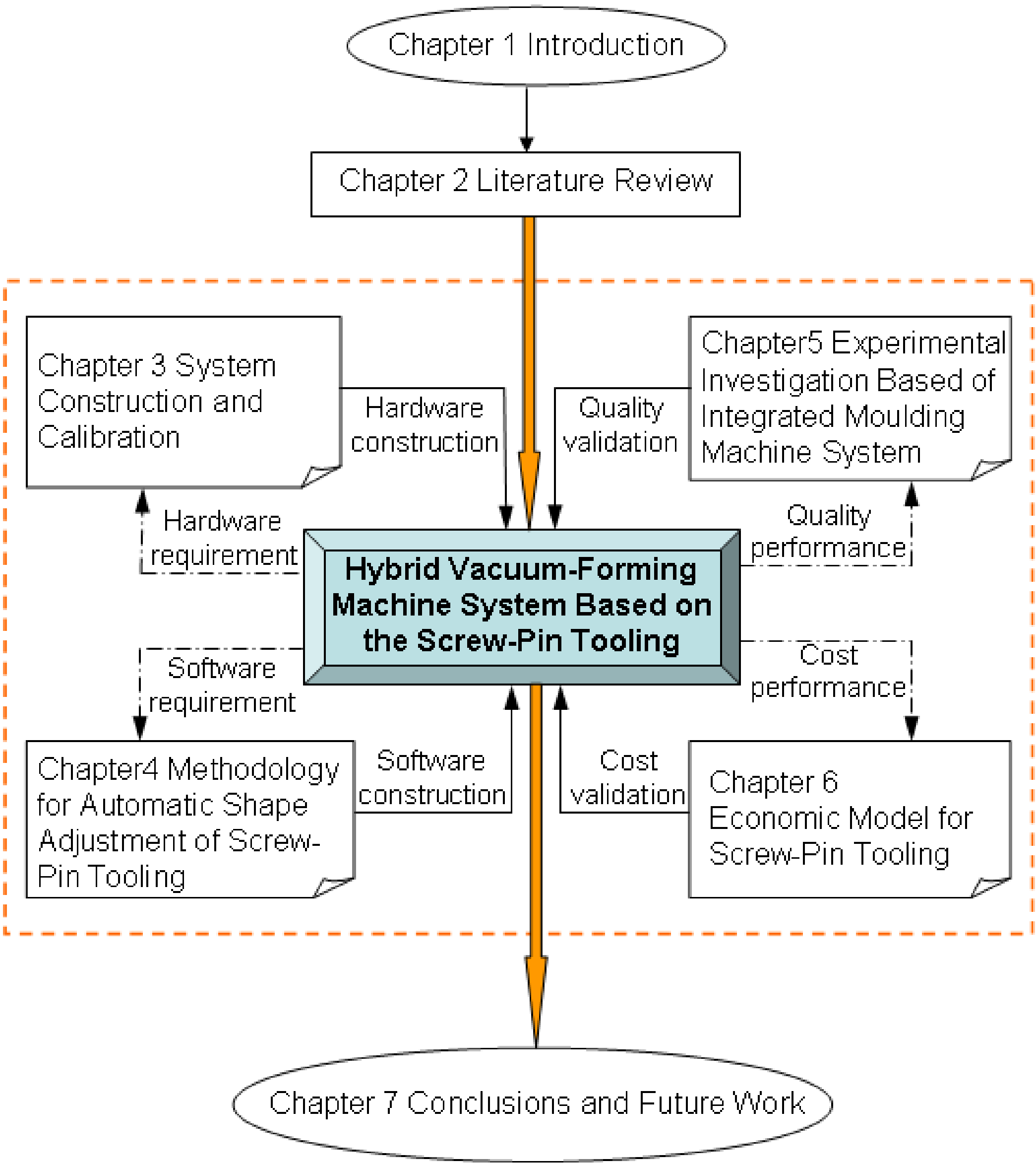


Figure 1-1 An overview of the thesis outline

Chapter 3, on the outset, describes the basic concept of the screw-pin tooling and then an overall architecture is proposed for integrating the SPT into the HAVES test bed development. This chapter also illustrates the main features of the hardware construction of the integrated machine system which includes the SPT module, the CNC control module, the dual tooling head module, the vacuum forming module and the component inspection module. Several important components such as drive motors, heaters, vacuum pumps, etc. are selected and integrated within the system. The machine system calibration for accuracy, repeatability, circularity and squareness are also outlined.

Chapter 4 illustrates the mathematical representation of the mapping process between the component surface model and screw-pin array pattern. Software development for the integrated machine system is also illustrated in detail. The software integrates information from CAD/CAM software, finite element analysis software, reverse engineering, Visual basic etc., and has four functions: component discretisation, parametric expression of screw pin array pattern; mapping between components to screw pin array pattern; and automatic generation of CNC and simulation program.

Chapter 5 presents several experimental investigations to test the performance of the developed HAVES test bed. The experiments are conducted to evaluate the repeatability and accuracy of the screw-pin adjustment. Surface quality of the vacuum formed plastic components based on different tooling in the tests will be measured, recorded, compared and analysed.

Chapter 6 develops a construction cost model and an application cost model for the reconfigurable pin tooling. The construction cost of the HAVES test bed is analyzed and compared with that of sequential set-up reconfigurable pin tooling, hydraulically actuated pin tooling and shaft-driven leadscrew pin tooling. The component manufacturing cost is also compared with similarities and differences between using the HAVES test bed and traditional solid tooling are stated. Break-even analysis is also performed for the HAVES test bed by setting several selling prices for different components.

Chapter 7 summarises the main contributions and conclusions of this research work and some suggestions and recommendations are put forward for further future research work on the HAVES test bed.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The manufacturing industry is moving toward rapid customization**;** this has an important effect on the nature of the tooling, namely fixtures, dies and moulds that are used to clamp or produce components. The research and application of reconfigurable pin tooling will become a necessity. Development of a reconfigurable pin tooling system is a complex procedure, as it involves many aspects of the system to be integrated: design, process planning, manufacturing, assembly etc. A thorough investigation of previous research into reconfigurable pin tooling is made in this chapter. The literature review is comprised of four parts as shown in Figure 2-1: pin design, adjustment methods, tooling surface treatments and applications.

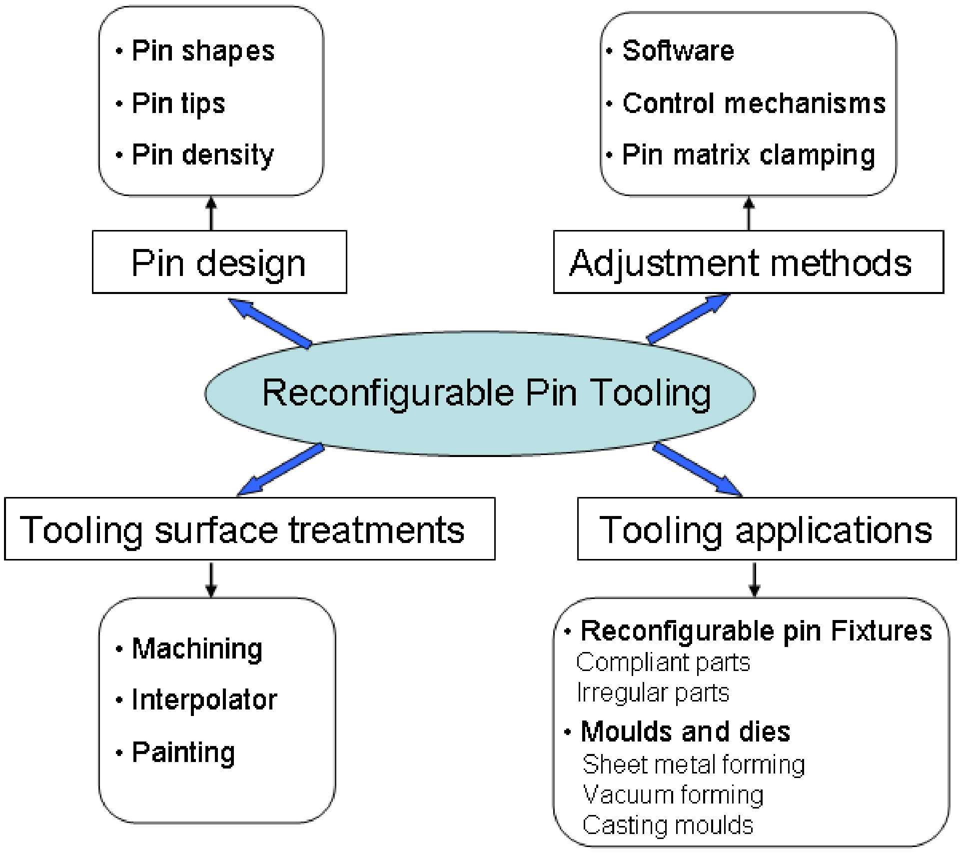


Figure 2-1 Outline of the literature review

2.2 Pin design

Pins play very important roles in reconfigurable pin tooling. To easily fabricate and assemble them into a densely packed matrix and then set them to the desired shape, the pin design should pay attention to the following items (Walczyk and Hardt, 1998):

1) The pins should have a uniform cross-sectional shape, size, and length to minimize the cost and lead time of fabrication;

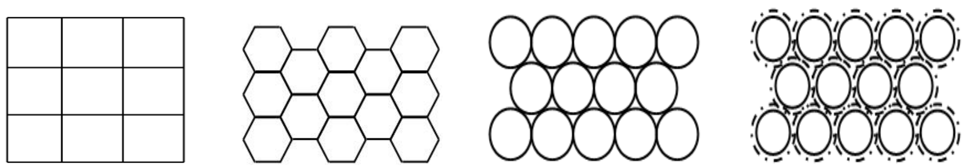
2) The pins must be strong enough to withstand the buckling and bending forces produced during application;

3) A matrix of identical pins should be easily clamped into a rigid tool;

4) The cross section of the pins should be as small as possible to allow for adequate tooling shape fidelity.

2.2.1 Pin cross-sectional shape

One of the most important geometrical concerns for the pins is cross-sectional shape. There are four types of cross-sectional shapes that have been most commonly used by previous researchers: square (Papazian, 2002; Liu *et al.*, 2008; Walczyk and Hardt, 1998), hexagonal (Peterson, 1956; Hoffman and Florissant, 1998), round (Moore and Gindy, 2006; Meintrup and Schwock, 1999) and threaded pin (Gindy, 2006) as shown in Figure 2-2. The square and hexagon shaped pins can be densely packed into a consistent matrix without gaps between adjacent pins. There are some small gaps among the closed pack round pins and threaded pins. Each round pin in reconfigurable tooling is normally made into a hydraulic or pneumatic cylinder allowing them to be individually actuated. Neighbouring pins in the closed pack threaded pin tooling are naturally engaged and can provide a much higher work load than other pin cross-sectional shapes.



(a) Square (b) Hexagonal (c) Round (d) Threaded

Figure 2-2 Pin shapes

2.2.2 Pin tips

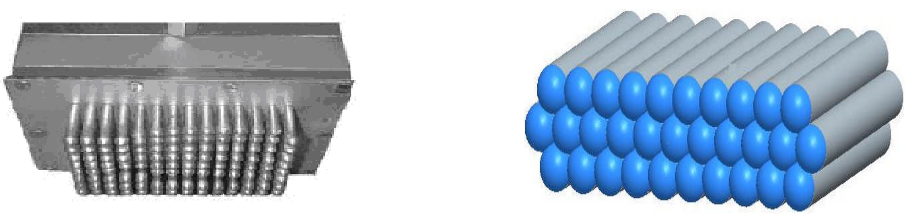
The pin tips used in reconfigurable pin tooling define the actual forming or molding surface and must not have any sharp edges that could pierce through the interpolator and into the sheet during forming. One of the easiest solutions to avoid this problem is to use spherical pin tips. The pin's spherical tip will always be contacting the sheet material at a tangency point and not at a sharp point. The diameter of the spherical end should be equal to the maximum distance across the pin's cross section (Walczyk and Hardt, 1998). There are also many unique pin tip concepts which have been developed by inventors to allow for special capabilities (e.g. replacement and reconfiguration). The first known patent to use reconfigurable rubber tipped pins was granted to Trudell (1942). The discrete pin points were attached by a continuous rubber sheet to allow for natural interpolation of the tool surface. This concept is also described in later patents such as Walters (1943), Hoffman and Florissant (1998) and Sherrill and Young (2001). Some secondary registering and holding inserts such as registration points, stops and clamps are incorporated into the primary tool pins in the U.S. Patent No. 5,738,345 by Schroeder and Stevenson (1996). The inserts are threaded into the tips of hollowed out pins and can be placed in key positions as required. Extra flexibility is achieved by cutting slits in rubber swivel pin tips as done by Hoffman and Florissant (1998). In order to deliver hot/cold air or gasses to a honeycomb panel being formed, the hollowed out pins and pin tips with holes drilled into them can be employed as was discovered by Haas *et al.* (2000). Alternatively, the square pins in a matrix are chamfered along the length-wise edges to create channels for hot and cold gases. Instead of using a dedicated interpolating layer, Papazian *et al.* (2001) develop many different pin tip configurations to prevent damage caused by the pin tips and to increase forming efficiency. Those pin tips are made mainly of rubber and have a protective thrust pad attached to the working surface that can be formed by different materials. There are concave and convex shaped tips that are either solid or have an air cavity. In some cases the cavity is filled with pressurized gas from a tube running through a hollow pin or compression springs. Several pin tip concepts as shown in Figure 2-3 are introduced to support thin-walled components to reduce machining deformation and vibration (Wang *et al.,* 2008). Its swivel ball support can be used when the supporting direction is not the normal direction of the component surface.

(a) (b) (c) (d) (e)

Figure 2-3 Various pin tip concepts (Wang *et al*., 2008)

2.2.3 Pin density

There are two types of reconfigurable pin tooling constructions that have been developed: uniformly spaced matrix of pins, as shown in Figure 2-4(a) or closed-packed matrix of pins, as shown in Figure 2-4(b). In both configurations, the reconfigurable pins are adjusted to the desired shape and then locked into rigid tooling.



(a) Uniformly spaced pin tooling (Al-Habaibeh and Gindy, 2003)

(b) Close-packed pin tooling (Gindy, 2006)

Figure 2-4 Pin density

In the close-packed pin tooling, there is no or less space (for round pin tooling or threaded pin tooling) between the pins so that adjacent pins can support each other to withstand high forming loads. However, when pins are densely packed together in a matrix, individual actuation of each pin becomes difficult.

Compared with close-packed pin tooling, the uniformly spaced pin tooling is easily automated because the distance between pins allows room for their individual drive mechanisms. Although pin actuation is much easier when pins are uniformly spaced, the lack of direct structural support from adjacent pins severely limits the forming loads that reconfigurable tooling can withstand and the surface formability that a component can achieve.

2.3 Adjustment methods

2.3.1 Support software

Support software has been developed to receive, analyze and filter data information from CAD/CAM or reverse engineering systems in order to derive the position of the reconfigurable pins, to generate control instructions automatically for the actuator device or the CNC machine used for adjusting reconfigurable pins.

Walczyk, Lakshmikanthan and Kirk (1998) developed a pin position control system which consists of a set of PC-controlled relays, one for each hydraulic solenoid valve. The Graphical User Interface (GUI) of the control system is programmed using Visual Basic. The surface model can be input by either specifying the heights of each individual pin or by specifying parameters of standard shapes like a cylindrical shape or saddle shape. The GUI sets the pin positions by selectively stopping the motion of each pin.

Researchers at the University of Manchester have carried out some investigations on the application of reconfigurable pin tooling. A low-cost rapid tooling system that is easily reconfigurable by a single computer-controlled actuator or conventional CNC machine has been developed (Owodunni, Diaz-Rozo and Hinduja, 2004). Its software system has been developed and implemented in C++ as part of the UMIST CAD/CAM test bed using Spatial Technology's ACIS 3D geometry modeling Kernel. The input to the software is a surface model that can be approached in the axial direction of the pins. With the determination of every pin height, software can be employed to generate the toolpath and the corresponding NC code for driving the CNC machine. Optimisation of the toolpath is necessary because the CNC tool has many pins to adjust. Five strategies were considered and evaluated to determine the most efficient tool path.

Surface Generation's software for the Near-net-shape Pin Tooling™ application is demonstrated in Figure 2-5 (Surface Generation, 2006). The software uses an interactive real time Virtual Reality model. The application allows the user to import and manipulate STL files, select different bed configurations and then calculates pin positions and resulting volumetric data.

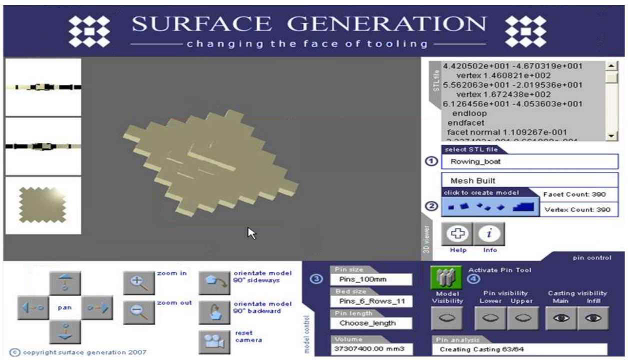


Figure 2-5 Software for Near-net-shape Pin Tooling

A multi-point forming (MPF) technology is developed for flexible sheet metal forming (Li *et al.*, 1999 and 2002, Liu, Li and Fu, 2008). The software for the MPF system is mainly composed of two modules: CAD integrated software subsystem (CADS) and computer control subsystem (CCS). The front end of the MPF software is a GUI developed using VISUAL C++6.0 under the WINDOWS platform. The CADS are designed to receive CAD data files, construct 3D shapes, select the MPF forming method, calculate the height matrixes and simulate the forming process. The calculated height matrixes would be transferred to the CCS. The CCS is developed as a multi-axes numerical control system to create numerical code automatically based on the received data and command digital AC servo motors to adjust the pin elements. The detail tasks that can be performed in the CCS include data exchange with CADS, process parameters set up, communication with slave control units that are distributed in apparatus via an industrial field bus, the element group shape contour adjustment, data save, equipment test and protection, etc.

2.3.2 Pin actuation methods

The key to reconfigurable tooling is to move a matrix of pins upward or downward to positions determined by component geometry. Therefore, the actuation of the pin movement is critical for the reconfigurable tooling using discrete pins. Several pin actuation methods including manual, mechanical (e.g. leadscrew-driven), hydraulic or pneumatic, and numerical control have been developed by researchers to set the shape of the pin matrix prior to it being clamped into a rigid tool.

The manual pin actuation method is widely used in adjusting different types of reconfigurable pin tooling. Williams (1923) developed a 2-dimensional forming device for automobile leaf springs consisting of two opposed rows of uniformly-spaced, manually-adjustable pins. Walters (1943) took this same idea and expanded it to 3 dimensions by adding multiple rows for the purpose of shaping sheet metal in an opposed press arrangement.

The first attempt to create automatically reconfigurable pin tooling was made by Nakajima (1969). In this research, a positioning stylus was mounted to the headstock of a CNC milling machine to position the matrix of small diameter pins. Two ways were used to form surface contours: (1) numerical point-point control using a push rod and (2) incrementally changing the die shape using a triangular-shaped pusher that swept back and forth across the backside of the tool surface (shown in Figure 2-6). The shortcoming of this design was the difficulty to move one pin without dragging the adjacent pins.

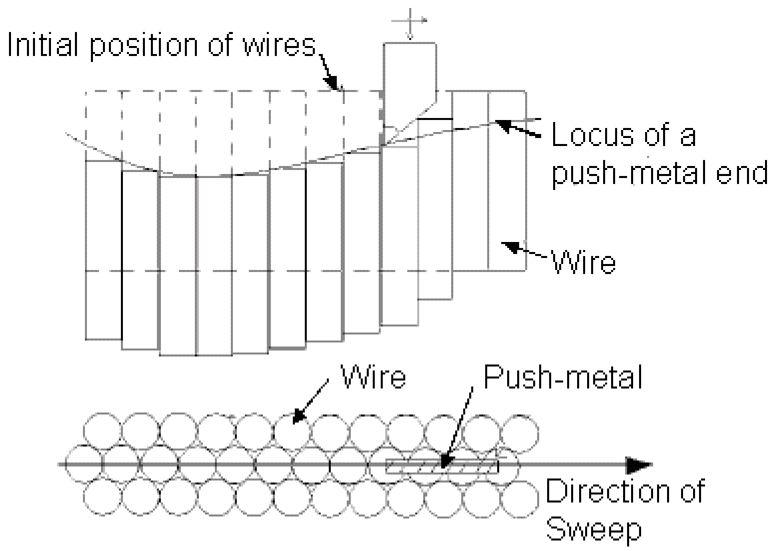


Figure 2-6 A reconfigurable pin-type tool (Nakajima, 1969)

Pinson (1980) patented the first self-contained automatically controlled 3D reconfigurable pin tooling that has the capability of being set automatically by computer-controlled servo-actuators connected to each pin. Finckenstein and Kleiner (1991) constructed a four-axis servomechanism machine to individually adjust a matrix of threaded rods, which would be used to impart the desired die shape onto a close-packed discrete die consisting of square elements. Walczyk and Hardt (1998) solved Nakajima's problem by separating each row of pins using a sheet metal spacer, rigidly attached to the die frame in their developed reconfigurable pin tooling.

A leadscrew is an effective mechanical way to adjust reconfigurable pin tooling. The element of the leadscrew pin actuation method is designed as Figure 2-7 including a hollow pin with internal thread support on a self locking leadscrew, a hemispherical end and supporting plate. The element group can be set to serial adjusting mode (one pin or column at a time) or parallel adjusting mode (all at the same time) via a servo motor device. By driving the leadscrew towards the top of the hollow pin, its height can be adjusted easily. When all elements are set to the desired heights according to the CAD data, they will function as solid dies. A shaft-driven leadscrew was employed to actuate a 42x64 pin matrix based on the design of Haas *et al.* (1996, 2002) at Northrop Grumman, and a 48x72 pin matrix based on the design by Boas (1997) at Massachusetts Institute of Technology, which sequentially actuates 16 pins at a time. A group of motor-driven leadscrews were used to adjust all pin elements simultaneously in Multi-Point Forming technology developed by Liu, Li and Fu (2008) at Jilin University, China.

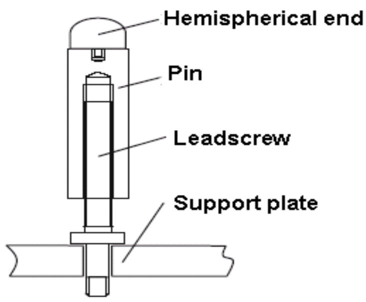


Figure 2-7 Leadscrew pin actuation (Liu *et al.,* 2008)

A hydraulically actuated pin tooling concept has been developed as shown in Figure 2-8 (Walczyk and Hardt, 1998; Walczyk and Im, 2000) at Rensselaer Polytechnic Institute. Each pin is essentially hydraulic cylinders controlled by an in-line hydraulic servo valve. The piston is stationary, hollow, and uses hydraulic fluid to move the pin body upward. Hydraulic power from a single source is provided to each pin by a series of plenums. The concept for setting the entire tool in a parallel fashion is to upwardly move each pin in the matrix against a slowly moving platen. The position of an individual pin is set by closing its in-line servo valve at the prescribed platen height. All other pins that have not reached their specified height continue to move upward with the setting platen. The entire pin-setting process is controlled and monitored by a computer. After the shape is set, the entire matrix is clamped from the side into a rigid tool. Retraction of the pins to their lowest position for resetting of the die shape is accomplished by unclamping the pin matrix, opening up all the servo valves, and evacuating the hydraulic fluid using the pump.

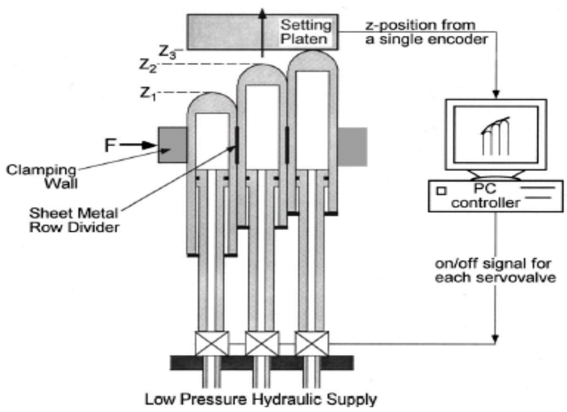
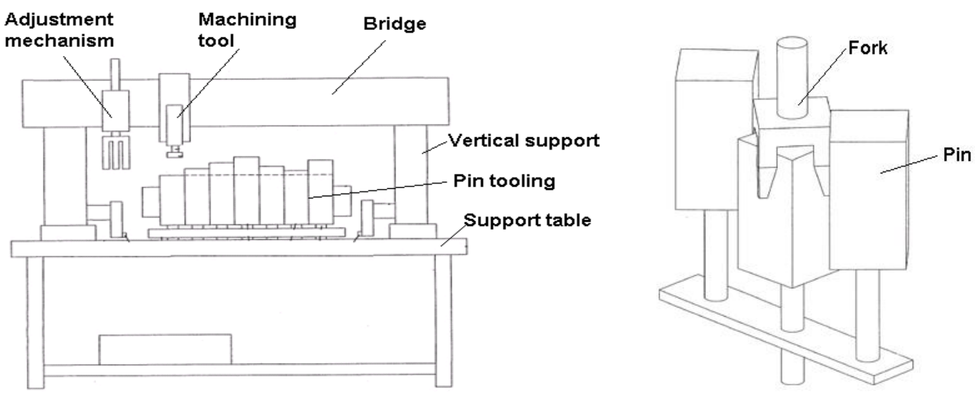


Figure 2-8 Hydraulic pin actuation (Walczyk and Im, 2000)

Reconfigurable pin tooling technology was developed by Surface Generation Ltd. using patented pin technology (Halford, 2005, 2006) called the Subtractive Pin Tooling (SPT). The pin tooling system has a matrix of square shaped pins made of a consumable tool material. When adjusting a pin, the pin rows next to the pin to be adjusted can be separated automatically to allow individual pins, which are mounted on screws, to be adjusted vertically by rotating them around their central axis. After adjustment, all the square pins are oriented 45 degrees to allow efficient packing with adjacent rows. Finally the rough upper surface of adjusted pin ends is CNC machined to the final tool shape without the need for excessive material waste. In this device pin tooling can be integrated with NC machining (as shown in Figure 2-9), which was considered a breakthrough compared to other prior art. Machining operation was conducted on the pins to achieve good surface finish of the moulded components. Owodunni *et al.* (2004) developed another reconfigurable pin tooling whose height was also adjusted by a conventional CNC machine. The use of such an approach reduced the complexity and cost of the tool and uses equipment that is readily available and affordable to those likely to need the tooling. However, since pin actuation involves the moving the row of pins that are adjacent to the pin to be adjusted and the rotation of individual pins, it is still a very time consuming process.



(a) Machine layout (b) Fork and pin

Figure 2-9 Numerical control pin actuation (Halford, 2005, 2006)

Three pin actuation schemes including Sequential Set-up (SSU) devices with leadscrew-driven pins, Hydraulically Actuated (HA) pins and Shaft-driven Leadscrews (SDL) were compared to each other in terms of performance criteria by Im *et al.* (2000). The compared performance criteria included pin positioning accuracy, repeatability, setting speed, suitability for a production environment, fabrication costs, manufacturability and maintainability and maximum forming load. All of the schemes could meet or exceeded the major performance criteria. Take repeatability and accuracy as examples, the SSU design has the best pin positioning accuracy at 0.005mm and all three of the design prototypes fulfill the target accuracy requirement of 0.1mm. However, the SDL scheme was found to be twice as expensive and more complicated to implement than the other two designs.

2.3.3 Pin position determination

The positions of the tip of the reconfigurable pins are used as an input to the program which generates instructions for the actuator device or CNC machine. The determination of the pin position is classified into two conditions: from the surface model and from the physical component.

To determine the height of a reconfigurable pin from a surface model, a line which represents the centre line of the reconfigurable pin is applied to intersect with the surface model of the die, and then the intersection point can be used to gain the pin position (Walczyk and Im, 2000, Owodunni, Hinduja and Mekid, 2005).

To determine the position of a reconfigurable pin from a physical component, Cai and Li (2003, 2006) developed a finite element method to make the calculation. The physical component is digitized with reverse engineering devices first, and then the measured data is reconstructed by using 18 degree-of-freedoms triangular finite-element. The interpolating function over the finite-element is expressed as follows:

$$f^{(e)}(x,y)=\sum_{k=0}^{5}\sum_{l=0}^{k}D_{k(k+1)/2+l+1}x^{k-l}y^{l} = XD_e^T \tag{2-1}$$

Where, $D_e=[D_1\ D_2\ ...D_{21}]$, D_e is the coefficient vector of interpolating function; $\mathrm{X}=[1\,x\,y\,x^2\ xy\,y^2\ x^3\ x^2y\,xy^2\ y^3\ x^4\ x^3y\,x^2y^2\ xy^3\ y^4\ x^5\ x^4y\,x^3y^2\ x^2y^3\ xy^4\ y^5]$.

The contact point $T(x_T,y_T,z_T)$ of the pin element with the component surface (as shown in Figure 2-10) is calculated by the following equation:

$$\mathrm{X}_{,x}D_e^T+\frac{x-x_p^k}{\sqrt{R_p^2-(x-x_p^k)^2-(y-y_p^k)^2}}=0$$

$$\mathrm{X}_{,y}D_e^T+\frac{y-y_p^k}{\sqrt{R_p^2-(x-x_p^k)^2-(y-y_p^k)^2}}=0 \tag{2-2}$$

$$\mathrm{X}D_e^T-z=0$$

$$e\in\varepsilon_k,\ \ e=1,\ 2,\ ...,\ n_k,\ \ k=1,\ 2,\ ...,\ m$$

Where, m is the total number of pins in the pin matrix; n_k is the number of finite elements which will perhaps contact with a $k-$element; ε_k denotes the set of the n_k element; x_p^k and y_p^k are the coordinates of the centerline of the k^{th} punch; R_p is the radii of the sphere on the end of the k- element; X contains the x and y terms of the quintic polynomial and is expressed as:

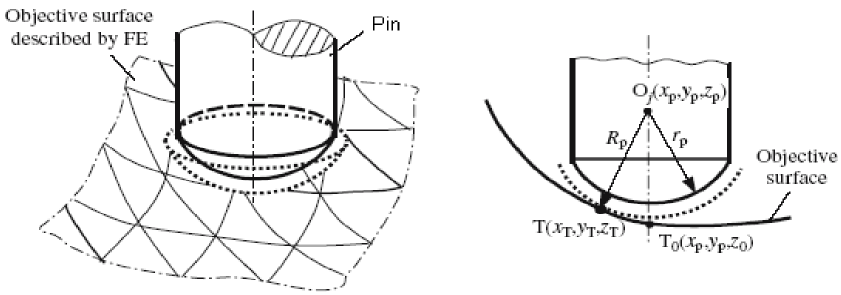
$$\mathrm{X}_{,x}=[0\,1\,0\ 2x\ y\ 0\ 3x^2\ 2xy\ y^2\ 0\ 4x^3\ 3x^2y\ 2xy^2\ y^3\ 0\ 5x^4\ 4x^3y\ 3x^2y^2\ 2xy^3\ y^4\ 0];$$

$$\mathrm{X}_{,y}=[0\ 0\,1\,0\ x\ 2y\ 0\ x^2\ 2xy\ 3y^2\ 0\ x^3\ 2x^2y\ 3xy^2\ 4y^3\ 0\ x^4\ 2x^3y\ 3x^2y^2\ 4xy^3\ 5y^4];$$

The equation (2-2) can be solved by the Newton-Raphson procedure:

$$x_{k+1} = x_k - \nabla^{-1} G(x_k) G(x_k) \qquad (2\text{-}3)$$

Where $G = [G_1 G_2 G_3]^T, x = [x\ y\ z]^T$. The initial value of the iterative scheme of Equation (2-3) is set as the coordinates of point T_0 of Figure 2-10(b). If contact point T is inside the element e, then the z-coordinate of the centre of spherical end of the pin is $z = z_T + d_p$. Otherwise, the search should be continued over the adjacent elements.



(a) A pin contact with objective surface (b) Contact point

Figure 2-10 Pin position (Cai and Li, 2006)

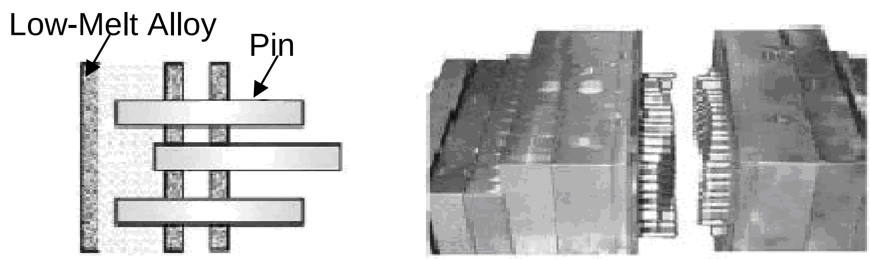
2.3.4 Pin matrix clamping

Once the pins are locked into position, they must be capable of withstanding the high forming loads encountered. Pin slippage during forming (due to insufficient locking force) is completely unacceptable because the intended die shape is immediately lost. Three types of methods for temporarily locking pin positions of a reconfigurable pin tooling are summarized as follows:

1. Each pin was locked individually by using leadscrew or hydraulic methods. These methods require large pins to be used. A reconfigurable tooling for flexible fabrication system has been developed by using the shaft-driven lead screw (SDL) to streamline the manufacturing process for small lot aircraft

skins (Anagnostou and Papazian, 2004). In the SDL concept, individual pins are supported on self locking leadscrews that are connected to an input shaft via a worm gear and clutch. In multi-point die forming technology developed by Jilin University, each pin was also supported by a leadscrew (Liu, Li and Fu, 2008).

2. Backfill the nonforming side of the pin matrix with some moldable backing material. The moldable backing material has the ability to change from a fluid to a solid and back to a fluid again. When material is in a liquid phase, the reconfigurable pin is immersed to the required depth. Then the material's solid phase is introduced, providing rigid support and work-holding force for each pin. For example, a low-melt alloy (bismuth-lead-tin-cadmium) is applied as the holding mechanism in a pin-type clamping system to hold complex-shaped aerospace components during machining processes as shown in Figure (2-11) (Al-Habaibeh and Gindy, 2003). The low-melt temperature allows the use of hot water or induction heating as the power source of phase change.



(a) Concept (b) Pair of platforms

Figure 2-11 Backfill clamping (Al-Habaibeh and Gindy, 2003)

3. The entire pin matrix was clamped by using a side wall with a high enough force to prevent individual pins from slipping during forming. The total z-direction (into the die) forming loads on the side-clamped pin matrix must not

exceed the maximum frictional load the pin/pin interfaces can withstand. There are many methods that can be applied to create high forces for clamping the pin matrix of reconfigurable tooling. Walczyk (1996) introduced a simply hydraulic actuator, a toggle mechanism and mechanical wedge method and further proposed two unconventional methods: stack of piezoelectric laminations and thermally-induced contraction of a discrete die frame (as shown in Figure 2-12). Their clamping forces F_{clamp} are calculated by using Equations (2-4) to (2-8) respectively:

1) Simple hydraulic actuator:

$$F_{clamp} = P_o \bullet A_{cs} \bullet (1 - K_f) \tag{2-4}$$

Where P_o is hydraulic pressure; A_{cs} is cross-sectional area of the cylinder and K_f is force loss coefficient of the cylinder.

2) Toggle mechanism

$$F_{clamp} = \frac{F_{lm}}{2 \cdot \tan\theta} \tag{2-5}$$

Where F_{lm} is a force that is applied perpendicularly to the wall travel at joint C and θ is the angle that the links make with the x-axis.

3) Mechanical wedge or screw

$$F_{clamp} = \frac{F_w \cdot (\cos\phi - \mu_A \sin\phi)}{\left[(\mu_A + \mu_B) \cdot \cos\phi + (1 - \mu_A \mu_B) \cdot \sin\phi\right]} \tag{2-6}$$

Where F_w is the input force; ϕ is a incline angle of the wedge; μ_A is the static frictional coefficient between part A and part B, and μ_B is the static frictional coefficient between part B and the horizontal wall.

4) Stack of piezoelectric laminations

$$F_{clamp} = \frac{V \cdot L_p \cdot W_p}{t_p \cdot g_{33}} \tag{2-7}$$

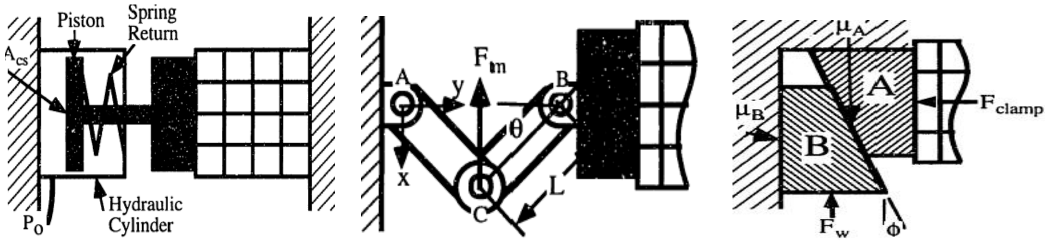
Where V is voltage; L_p is length of lamination; W_p is width of lamination; t_p is thickness of lamination and g_{33} is piezoelectric voltage coefficient.

5) Thermally-induced contraction of a discrete die frame

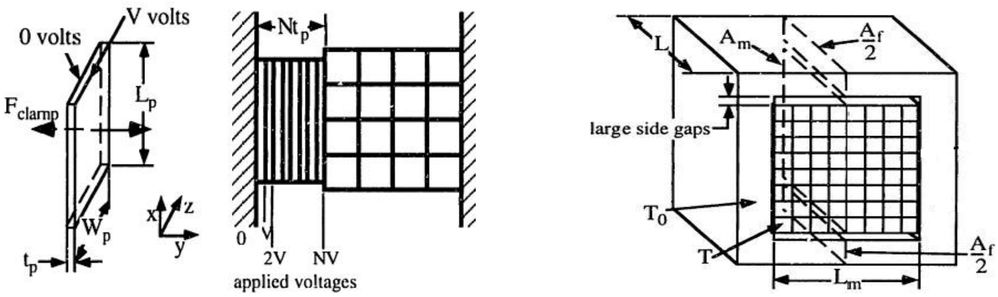
$$F_{clamp} = \frac{\alpha_f \cdot (T - T_o)}{\left[\frac{1}{A_m E_m} - \frac{1}{A_f E_f}\right]} \qquad (2\text{-}8)$$

Where α_f is the thermal coefficient of linear expansion of the frame material; E_f is the elastic modulus of the frame material; A_f is the total cross-sectional area of the element matrix in a plane normal to the loading direction; A_m is the cross-sectional area of the element matrix in a plane normal to the loading direction; E_m is the elastic modulus of the discrete elements; T is the temperature that the frame is cooled and T_o is it's initial temperature of the entire discrete die.

Each clamping force method is then compared with the other methods in a case study. It was concluded that the choice of a particular method for achieving a high clamping force in reconfigurable tooling would depend on the type and magnitude of the forming forces encountered, the size of the die, space constraints and the manufacturing environment in general. Walczyk and Hardt (1998) also recommended a single compression wall clamping method in design of reconfigurable discrete dies for sheet metal forming. Owodunni *et al.* (2004) employed a square cage to support and lock the pin matrix. In order to produce the clamping force required, one of the four walls used in the cage is movable, thus pushing the matrix from one side with a clamping screw which passes through a support plate.



(a) Hydraulic actuator (b) Toggle mechanism (c) Mechanical wedge



(d) Stack of piezoelectric laminations (e)Thermally-induced contraction frame

Figure 2-12 High clamping force creation (Walczyk, 1996)

Among the above three methods, the first method usually requires that the elements are individually actuated, this makes the reconfigurable pin tooling system very expensive and complex; Of the second and third methods, side clamping the pin matrix is considerably easier and quicker to implement than using a backing material.

2.4 Tooling surface treatment and part shape control

2.4.1 Tooling surface treatment

The discrete surface of reconfigurable pin tooling limits its applicability, and a smooth method is required to suppress dimpling and wringling in the component surfaces caused by the discrete pin tips. Measures have to be taken to create a smooth tooling surface over the inherently dimpled surface of pin-type tooling before it can be applied for component forming. Several smoothing methods including a deformable interpolating layer (both attached and detached from pin tips), deformable pin tips, and machining (milling pin top ends or hardenable surface formed by filler) have been discussed by researchers.

Most previous research work with reconfigurable pin tooling has involved the application of hemispherical pin ends and an interpolating layer, typically an elastomer, to smooth the discrete pin surface as shown in Figure 2-13 (Walczyk *et al.,* 2003). High durometer neoprene or urethane was usually used as interpolating material. It was discovered by Eigen (1992) that using a moldable elastomeric material can further improve formability for sheet metal forming, although it is not able to be recycled. Chen, Liu, *et al.* (2005) used a rubber or polyurethane pad between the pins and sheet to eliminate dimples in the sheet metal forming. Liu *et al.* (2008) sandwiched the steel sheet between the two elastic pads and then put them between the upper and lower pin matrixes for press forming. This method avoided dimpling and wrinkling during forming via distributing the centralized load to the whole sheet. Due to the outstanding abrasion resistance and toughness of the polyurethanes, it can be applied several times.

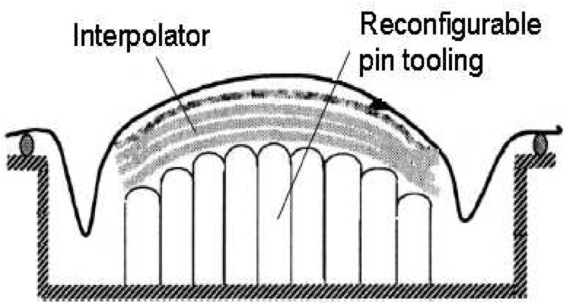


Figure 2-13 Schematic of the interpolator application (Walczyk *et al*., 2003)

The research work by Hardt, Boyce, *et al.* (1991, 1992), Walczyk *et al.* (1998, 1999 and 2000), and Northrop Grumman as part of the RTFF program has suggested that surface defect is suppressed in sheet metal forming when the interpolator thickness is about the same as the pin size. The experiments performed by Walczyk *et al.* (2003), Prabhakara (2002), and Munro *et al.* (2004) also showed that thinner material is required to suppress dimpling for composites forming than for sheet metal forming. For example, 12.7 mm thick dense polyethylene foam was adequate for suppressing dimples in double diaphragm forming using 28.6 mm square pins. It can be concluded that a smooth forming surface is possible for pins of any size as long as an interpolator with adequate stiffness and thickness is selected for the particular sheet forming process.

The deformable pin tips method for surface treatment is employed in an apparatus for forming sheet metal in the Boeing Company (Pinson, 1980). The apparatus includes two opposed sets of rams placed in matrix arrays with corresponding rams of opposite sets in alignment. Pivotally mounted heads with rounded surfaces are provided on the rams to improve the surface finish of the workpiece. Another apparatus for constructing a composite structure is disclosed as shown in Figure 2-14 (Sherrill and Young, 2001, 2004). The method comprises of a matrix of threaded pins with pivoting ends attached to a flexible layer. The position of the flexible layer can be adjusted according to a configuration suitable for constructing the composite structure. More specifically, the flexible layer may have internal reinforcing elements for added strength and durability.

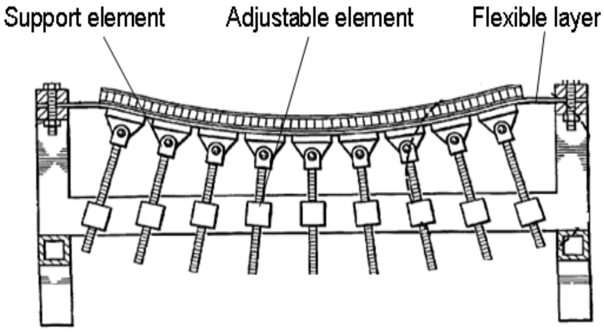
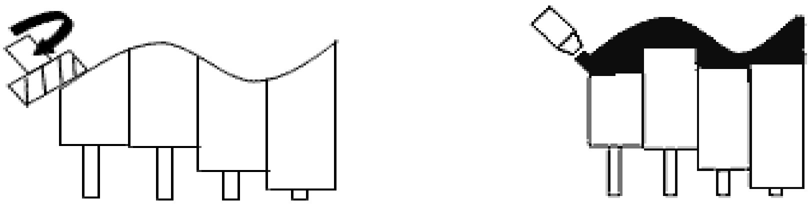


Figure 2-14 Flexible layer method (Sherrill and Yong, 2004)

The machining surface treatment method is applied in Subtractive pin tooling technology Near-net-shape Pin Tooling™ technology (NPT™) (Surface Generation, 2006). Subtractive pin tooling and NPT™ using beds of adjustable square pins to create near shape surfaces automatically. For the Subtractive pin tooling, the top ends of the pins are machined (as shown in Figure 2-15 (a)) according to a predetermined pattern after adjustment. For the NPT™, filler is applied on top of the pins when it is in liquid status and is left to cool to solid status (As shown in Figure 2-15(b)). Milling operation is carried out on the filler rather than on the pins to take off extra materials from the filler so that the machined filler will have shape of the geometry of the component.



(a) Subtractive pin tooling (b) Near-net-shape pin tooling

Figure 2-15 Milling of tooling surface (Surface Generation, 2006)

2.4.2 Part shape control

The reconfigurable pin tooling's adjustment needs to compensate for elastic springback, changes in material properties or other production variables (Papazian, 2002). Solutions for shape control of parts produced by reconfigurable pin tooling have been addressed by several researches and two approaches have been proposed.

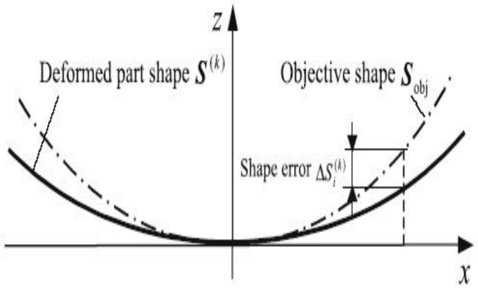
One approach is to use an iterative process to compare the actual part shape obtained in each forming with the desired shape, and the difference between them is then used as an error signal to reconfigure the tool. A mathematic procedure called the "deformation transfer function" is used to predict the tool new configuration. Based on the new tool position, a next part can be formed. This approach was devised by Hardt, Boyce and Walczyk (1993), Valjavec (1999) and Norfleet (2001). Cai, Li and Chen (2006) and Li, Cai et al. (2007, 2008) applied this approach to make die shape correction for spring back in their Digitized Die Forming technology.

The process can be expressed in general as:

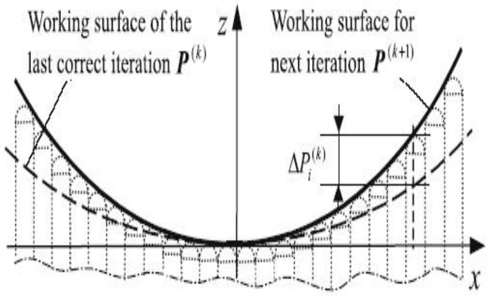
$$P^{(k+1)} = P^{(k)} + \nabla^{-1} F^{(k)} \Delta S^{(k)} \tag{2-9}$$

Where k is the number of correcting iteration; As shown in Figure 2-16, $P^{(k)}$ and $\Delta S^{(k)}$ are the shape of the reconfigurable tooling surface and shape error of the deformed part after k times correcting iteration respectively; $P^{(k+1)}$ is the working surface for the next iteration and $\nabla^{-1} F^{(k)}$ is a $(m \times n) \times (m \times n)$ correcting matrix. The total shape error $E_S^{(k)}$ of a deformed part is evaluated by:

$$E_S^{(k)} = \frac{1}{mn} \sum_{i=1}^{mxn} \left| \Delta S_i^{(k)} \right| \tag{2-10}$$



(a)



(b)

Figure 2-16 Springback correcting of the working surface of digitized die (Cai, Li and Chen, 2006)

The second approach is to use finite element modeling to predict the correct tool shape beforehand. This approach can get rid of the requirements for any forming tests or iterations (Papazian, Nardiello *et al.*, 2002). Anagnostou and Papazian (2002, 2004) developed a software system based on this approach to predict a die shape that is compensated for elastic springback and for distortion of the polymeric interpolator automatically. The proposed tooling design algorithm for rigid die shape is written as follows:

$$\mu_L = h(\mu_L, \alpha_n I_L) \tag{2-11}$$

Where α_n is spring-forward factor; I_L is internal force vector; μ_L represents the mapping of the flat sheet into the desired part shape. For the case of stretch forming over a smooth compliant die shape and the compliant die shape is $d_{(k+1)c}$, it can be expressed:

$$\mu_{k+2} = g(d_{(k+1)c}(t)) \tag{2-12}$$

Where d_k is the springback compensated die shape; d_{kc} is the compliant die shape. If $t = 0$, $d_{(k+1)c}(0) = d_k + U_c$; if at fully loaded time T ,. $d_{(k+1)c}(T) = d_k$.

Therefore, the unloaded configuration of the pins can be written as:

$$\mu_{k+2} \approx g(d_k) \approx \mu_L \tag{2-13}$$

2.5 Pin tooling applications

2.5.1 Reconfigurable pin fixtures

Fixtures are required in nearly every process of manufacturing. A common problem is the requirement for product specific fixtures for each component, leading to high tooling costs and long lead times. These problems can be overcome through the use of the reconfigurable pin fixture. Reconfigurable pin tooling is widely used to clamp or support large compliant components or irregularly shaped components and has been documented in several patents over the past 30 years. The application of the reconfigurable pin fixtures reported in the literature can be broadly classified into two groups i.e. large compliant components versus irregularly shaped components.

1. Fixturing of compliant parts

The first known patented system that can be used to clamp flexibility and compliant parts for machining was created by Frosch *et al.* (1978). The invention discloses a variable contour securing system comprising of a plurality of adjustable spindles mounted on a housing. There is a supporting cup at the top end of each spindle, and a vacuum source is coupled to the cups for seating the part adjacent to the cups. The spindles are raised and contour the workpiece using springs, and then are secured in position using locking plugs driven by a pressurized air source. Douglas and Ozer (1987) patented a universal holding device similar in design to that of Frosch except that each pin is automatically set with individual computer-controlled servo actuators and a motor-driven leadscrew, respectively. By individually adjusting the height of these pins, the locus of the ends of the pins form a contoured surface adapted to the particular workpiece to be held. The contour of the pins can be carried out in a parallel fashion.

A patent by Martinez (1992) discloses a machine tool system for holding and machining components (as shown in Figure 2-17). This patent has been included as an example of large scale pin array fixturing within the aerospace industry. The patent details an integrated pin array fixture and gantry machine for large skin panel trim and drilling. Each support pin incorporates its own motor to drive the vertical movements to achieve the exact positioning of the parts and has a vacuum cup at its tip to engage positively with the work piece. The longitudinal and transverse movements of the pins are controlled by a computer programme in the gantry machine.

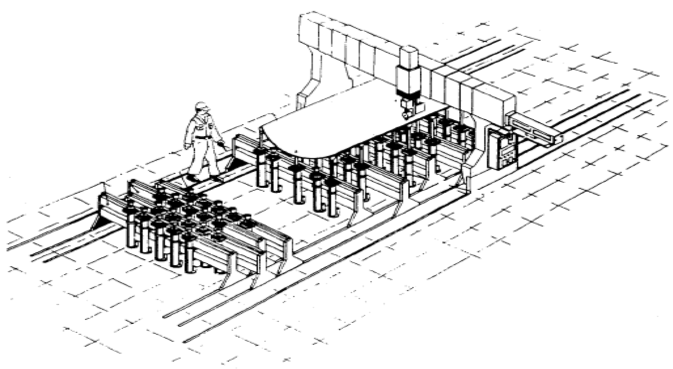


Figure 2-17 Machine tool for compliant workpieces (Martinez, 1992)

A patent by Ross and Gannon (1994) is similar in design to that of Douglas except for the design of the end of each pin. An end effector made of a pliable impervious material such as polyurethane is attached. These end effectors are formed in a soft, vertically compressible bellows configuration which allows the end effectors to adapt angularly and linearly to the workpiece being held. A work-supporting deck patented by Blaimschein (1994 and1995) is also very similar in design to Douglas except that the vertical adjustment method of the vacuum cups. Each vacuum cup comprises of a lifting ram, which is operatively connected to an actuator and is vertically slidable fitted in a bushing, which is contained in a vacuum chamber. The lifting ram can be adjusted in a simple manner by the associated actuator, which preferably consists of a piston-cylinder unit, and by its displacement does not only impart to the vacuum cup the desired position but also connects the vacuum cup to the vacuum chamber, to which a vacuum is constantly applied.

A patent was awarded to Soderberg *et al.* (1998) for flexible tooling apparatus. The invention comprises of a support table which has the plurality of supporting holes. Each supporting hole is used to receive a self-contained actuator and provides a vacuum and air supply line as well as a bush. Every actuator has corresponding connectors for receiving the vacuum and air supply as well as for interfacing with the bush, and then each actuator can be addressed on the bush for it to be commanded to raise, lower and lock in position. Hoffman’s patent U.S. Pat. No. 5851563 (1998) describes a reconfigurable modular tooling for workpiece support. An array of hexagonal pins is positioned in hexagonal apertures of modular tooling units which are generally blocks of hard rubber. A base drive unit, which is disposed to provide motions along x, y, z directions, is applied to adjust all the pins. A linear actuator of the drive unit powered by a stepper motor is used to vertically adjust the pin to any desired height. The locking function is accomplished by rotating the base drive unit 30 degrees to distort the aperture and force the pins into a naturally locking position.

Another universal fixture was patented by Abrahamson *et al.* (1999) for holding printed circuit board (PCB) assemblies. A plurality of pins with a foot supported by springs is movably attached to a base. The height of the pins is adjusted by pressing a PCB assembly against the support pins till they conform to the topography of the side of the PCB assembly. A lock-plate driven by cam-lever is then used to hold the support pins at a desired height.

The DEK Company was granted four patents, i.e. Beale (1992), Bennett *et al.* (2004, 2005) and Hertz *et al.* (2004) for 3-dimensional devices. Beale patented a useful workpiece support and clamping means for circuit board printing. The invention is an apparatus that provides a means of support by using electro-magnets to act upon the specified pins for predetermined positions and a means of holding by selectively supplying electric current to the electro-magnets. Beale's apparatus can secure a workpiece to a fixture using thin clamping foils which will not damage or interfere with the screen printing process. The patent by Hertz is a workpiece support system for a holding printed circuit assembly. The illustrated embodiment of the invention is quite similar in structure to that of Abrahamson, except that the supporting pins are temporarily held in position by the frictional forces induced by a resistance plate and the support pins return to a home position driven by a reset plate. The two patents by Bennett *et al.* are the most recent patents for compliant components, and illustrate a tooling fixture for supporting flexible substrates such as a printed circuit board in a screen printing machine. According to the invention, a workpiece is fixed at a position spaced above the upper surface of support pins. Under the control of a controller and fluid valves, compressed air is driven to flow into an accumulator and push the support pins upwards in the respective cylinder. After each of the support pins contacts the workpiece and the pressure comes to a predetermined value, the workpiece is in a fully supported position, and can be used for the next process.

2. Fixturing of irregular shaped components

The first known patent based on a pin array fixture was awarded to Pressman (1946). The patent details a hydraulically actuated pin array fixture, of which each pin is a hydraulic piston and is actuated from a singular source. The system is hydraulically balanced by applying force to both sides by splitting the same supply. The patent also describes a C-clamp that includes a semicircular member extending through an arcuate slot formed in a tool block holder. The C-clamp's jaws contain a plurality of parallel screw pins, which can be adjusted until their tips contact the surface of the object, and can be moved toward and away from the object by actuating the hand wheel. The C-clamp, once set, can be rapidly employed in handling objects having a similar contour.

A patent by Barowsky (1953) discloses an adjustable vice assembly for holding irregularly-shaped objects. The vice utilizes a pair of opposing jaws, each having a series of individual jaw segments that are extendable at different lengths from the face of the jaw. A reservoir of small steel balls positioned behind the segments distributes the load to adjacent segments and a back housing wall. Various cams and levers are used to press against the jaw segments in order to lock them in place or move them to new positions. A variety of parts may be repetitively inserted into the jaws of this vice assembly because the jaws retain a given configuration.

A work-holding device having a clamping jaw with a multitude of clamping pins was developed by Peterson (1956). The clamping pins are hexagonal in cross section as shown in Figure 2-18. They are packed up in the frame so that they fill up the frame completely, aside from the border region of the packing. Here also, the clamping pins are constrained by its immediate neighbours and with regard to the frame by means of a movable wall of the frame, to which the fixing force is applied by a fixing screw. At their backsides, the clamping pins are connected with retaining bars, which pass through a through-drilled retaining plate and which are provided with a retaining collar behind the retaining plate. Helical compression springs are arranged on the retaining bars, which push the clamping pins away from the retaining plate forward to the workpiece. The clamping mechanism here also comprises a stationary but pivoted spindle passing through a tapped hole in the clamping jaw. A patent by Meintrup and Schwock (1999) describes a pin array fixture for holding parts on CMM machines. This patent is very similar to that of Gault, except that the invention uses round pins instead of hexagonal ones.

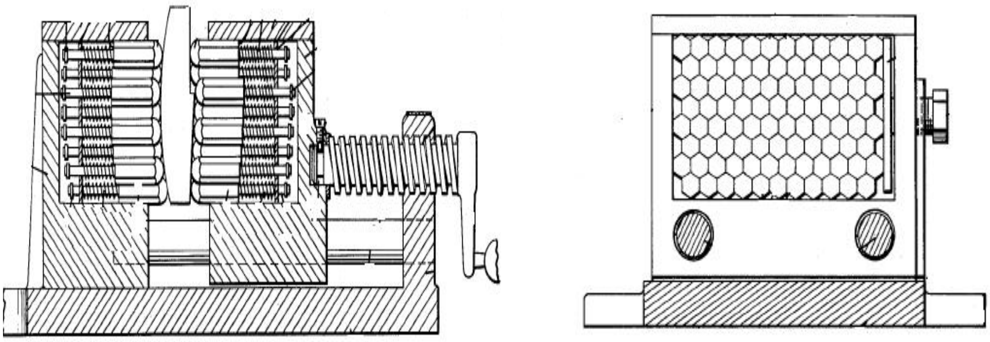


Figure 2-18 Vice for irregularly shaped objects (Peterson, 1956)

Blazek (1959) patented a work holding device that had plungers actuated by hydraulic fluid composed of a fusible alloy. The patent details a vice which has pin array fixtures in the jaws. The pins are hydraulically driven by a low melt point alloy heated to its liquid state. The hydraulic system drives the pins forward to conform to the work piece. The low melt point alloy is then allowed to cool to its solid state. Thus, each of the hydraulically actuated pins is fixed in position. A patent by Rossman (1965) descries a similar vice to that of Blazek but uses hydraulic fluid instead of low melt point alloy to drive the pins and a stop valve to lock the pins. The vice uses pin arrays on one side of the jaw only.

A work-holding device patented by Gault (1971) comprises of an enclosure open at one end packed with a multiplicity of pins, which enable it to grip a workpiece pushed into the mass of pins, by a wedging action provided by a taper in the enclosure itself or by small balls within a space between a closed end of the enclosure and the inner ends of the elements and also extending round the sides of the mass of elements. Two such devices are capable of being incorporated into the jaws of a vice with the pins in the two jaws extending towards each other. The mechanism of the vice attachment patent by Nagy (1988) is very similar to that of Gault (1971), except that the invention uses a plurality of specially designed blade-pins to conform to the shape of an object and does not require any type of hand actuation or hydraulic pressure to reset. Each blade pin comprises of a plate member having smooth planar surfaces and a concave curved back edge and stop on both the upper and lower edges for setting a limit for extension of the blade from the housing. An internal spring pushes a pressure plate forward which causes balls to exert a forward driving force on the blade-pins and extends them out of the housing until they encounter the stops.

Denney (1972) patented a fastener actuator for removing and tightening fasteners. The fastener actuator includes housing which has a support plate connected to it. A plurality of fastener engaging pins is supported in the housing and each pin includes an engaging portion and a sliding portion. The engaging portion has a basically rectangularly shaped cross-section and the sliding portion has a circularly shaped cross-section and is sized to slide and extend through one of the apertures in the support plate. The housing bottom contains permanent magnetic material or springs to support the end surfaces of the sliding portion.

A patent by Peterson (1973) illustrates a special fixture for holding precisely shaped parts. The fixture employs a series of opposing pins to press against opposite sides of a curved or irregularly-shaped object and hold it in place. One or more set screws and bolts are then pressed laterally against the sides of the pins to fix them in position against the object. The individual slidable pins are manually manipulated by an operator and locked into position by means of a plate.

Pasbrig (1975) patented a concept of a clamping tool with a housing in which a chamber is open at one side of the housing. A pack of pins is disposed through sliding in the housing, with a spring in the form of a compression spring pad urging the pins towards the outside of the chamber. The pins are prevented from sliding completely out of the chamber by the interengagement of projections and recesses at the inward ends of the pins. To clamp a component, the outward ends of the pins are pressed against the component; those pins which lie within the cross-sectional region of the component are displaced towards the inside of the housing, and the component is held positively.

A patent by Thyberg *et al.* (1977) discloses a clamping device that uses a clamping jaw having a plurality of movable plungers extending from one face of the housing. The plungers, driven by springs, interact with the exterior surfaces of an irregularly shaped object to position themselves at various projected lengths from the face of the clamping device. Hydraulic pressure is then used to press a medium, generally comprising of spherical balls, into a series of annular depressions on the sides of the plungers to lock them in place.

Godding (1980) patented a work holder for locating an irregularly shaped workpiece during treatment. As shown in Figure 2-19, the work holder comprises of a flat horizontal table and a two-dimensional array of vertically disposed spaced-apart pins mounted vertically and movable in relation to the table as they protrude upwards through the table. The table has upper and lower surfaces through which the pins protrude upwards. The pins in the array are pushed upwards by helical springs and locked by means of an inflatable tube that runs between the rows of pins. When this tube is pressurized, it expands pushing the pins to engage frictionally with the side wall.

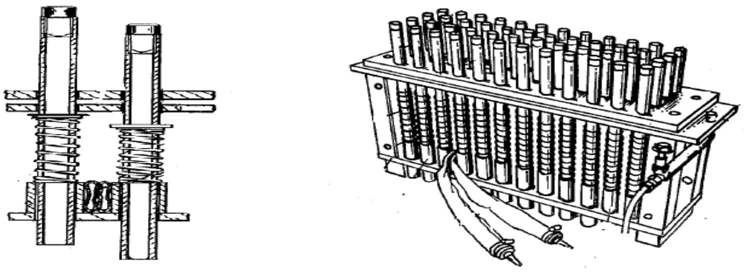


Figure 2-19 Holder for Irregularly Shaped Articles (Godding, 1980)

Cipolla (1986) patented an adaptive gripping device whose opposing jaws have a matrix of axially movable pins each of which is mechanically locked in any axial position. Any jaw operating mechanism that allows opposing linear relative motion can be used. Two stationary locking plates and a movable stripper plate are applied to lock and unlock the pins which are returned by springs to a fixed coplanar position. The raising and lowering of the stripper plate is performed by four coplanar pneumatic cylinders, to each of which is attached an operating cam. A patent by Zehnpfennig *et al.* (1995) details a pin array fixturing system as an end effector for pick and place robots. The device drives and locks the pins pneumatically as well. The pins are driven by a pneumatic wire mesh diaphragm at their base. The pins are locked in a similar manner to the Matrix fixture but use a pneumatically driven lever to enhance the locking force. Puettmer and Abraham (1996) also patented a clamping jaw concept which uses a hydraulic method of driving and locking the pins. Unfortunately, Römheld have ceased production of this item finding it unprofitable.

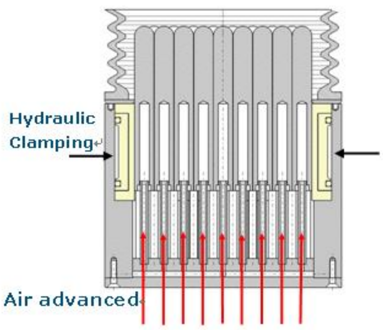
A patent by Puttmer *et al.* (1997) depicts a holding device for peripherally holding workpieces of any desired outline. The invention comprises of two shape-adjustable jaws arranged opposite one another on a base body. The jaws contain a plurality of plunger-pins which are able to move independently driven by hydraulic fluid power and contact with a workpiece. The base body possesses a connection member for the hydraulic fluid power to drive plunger-pins. Hydraulically actuated shut off valves are used for locking the position of the plunger-pins in the clamping state.

A patent was granted to Arov (1998) for precision machine tool vice with self-adjusting clamp. The vice has a movable jaw and a normal fixed jaw. The movable jaw includes housing with clamp pins and two rows of load transfer elements. A first row of elements is built behind the clamp pins and a second row of elements is built behind the first row. There are the same numbers of elements in the first row as there are clamp pins and one less element in the second row. Each load transfer element is disc-shaped and can be arranged to move relative to each other and interlock with each other to promote flexibility and clamp stability.

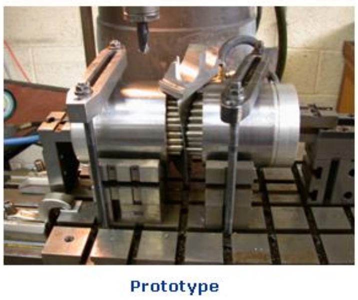
3. Research at UoN

The purpose of this section is to introduce the various reconfigurable pin device and technology available at The University of Nottingham (**NoU**). With the development of complex geometry components comes the need for more advanced manufacturing techniques. The basic difficulty in advanced manufacturing technology and machining is the art of accurately locating and fixturing the workpiece. Most manufacturing companies face the difficulty of having dedicated fixtures. Researchers in the Responsive Manufacturing Research Group of the University of Nottingham study the feasibility of using reconfigurable pin tooling for fixturing complex geometry components used in the aerospace industry, and several fixturing system prototypes and patents have been achieved.

Al-Habaibeh and Gindy (2003) developed a pin-type clamping system that uses a low-melt alloy (bismuth-lead-tin-cadmium) as the holding mechanism for holding complex-shaped aerospace components during machining processes. Moore and Gindy (2006) patented a pin-array fixture system utilising a modular device which has a reconfigurable and lockable clamping face that can encapsulate the blade surface topology without imparting deforming forces. The invention, as shown in Figure 2-20, includes an array of engagement elements for engaging a work piece, and a pneumatic actuator is used to move the engagement elements. A deformable clamping member driven by hydraulic actuator is used to clamp the engagement elements.



(a) Section view



(b) Prototype

Figure 2-20 Work piece holding arrangement (Moore and Gindy, 2005)

Gindy (2006) patented a fixture system utilising screw threaded pins that can be individually manipulated to form around complex geometry components during machining. The screw-pins of the fixture meshed with each other can mechanically self-lock. The moving means of the screw-pins can be manual, automatic or any combination of manual and automatic. Two developed prototypes based on this patent are cheap and rigid and suit DIY applications. According to the patent, the application of the screw-pin principle can also be extended to stretch-forming, vacuum-forming, etc.

Garry, Wang et al. (2008) patented a modular fixture system for supporting the thin-walled components (e.g. casings) for machining (U.S. Patent no. US2008185488). In the constructed fixture, a row of work supports are evenly bolted onto a central ring. There are a few such central rings with work supports, and “C” shape spacers are put between the rings which are recessed to prevent the spacers slipping out from the rings. The central rings and components are put on a base. A top lid is placed on the top of the component. A through screw is used to connect all the base, rings, spacers and top lid. In order to prevent the work support and central ring moving in a radial direction, the central rings together with spacer are bolted on the base by threaded nut. The work supports are driven by pneumatics or hydraulics or combination of both and are connected to each other by pipes or hoses so that the pressure can be applied from one pump. The number of central rings and work support on each of the central rings as well as the height of the spacers are variable according to the relative dimensions of the component family and can be reconfigured quickly to support different sizes of components.

Based on the above described modular fixture patent, an intelligent support fixture patent embodiment shown in Figure 2-21 was further developed by

Wang, Shi *et al.* (2007) with the purpose of on-line measurements of machining deformation, machining force and vibration (UK patent no. GB0722831.5). Meanwhile, evaluations and detections are conducted in-process to prevent fixture related failure. A force sensor (Kistler 9602) is mounted on the work support. A non-contact displacement sensor (Philtec RC25) is held between two work supports with an additional seat to hold the sensor. An accelerometer (Kistler 8702B500) is mounted on the components. The signals from the sensors are collected and processed by the computer and displaced online. The online measured displacement information is evaluated against tolerance. The force sensors measure the reaction forces on the work support which are evaluated against the holding forces applied by the hydraulic pressure on the piston of work support. The accelerometer is used for measurement of vibration and evaluated against chattering. A pressure switch is connected with hydraulic pressure, and in the case that the hydraulic pressure is low if leakage occurs, the pressure switch will close the current circuit and trigger the alarm.

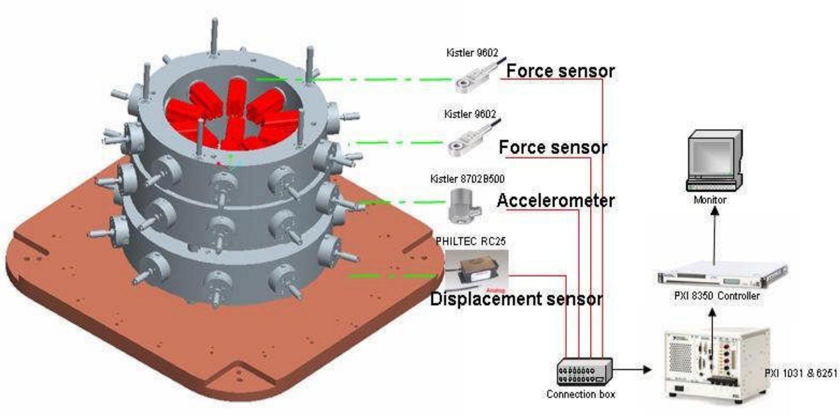


Figure2-21 Intelligent fixture (Wang and Shi *et al.*, 2007)

There are another two patents being examined currently at The University of Nottingham. One pending patent by Wang and Gindy *et al.* (2009) called “A configurable fixture” relates to a universal work holding arrangement using an array of engagement elements and a multitude of solid balls or small particles that have smooth shapes. The balls or the small particles are pushed to move the engagement elements to conform to the shape of the part. The solid balls or the small particles act like a fluid medium for advancing the pins towards the part and are solidly locked together once in contact with the part. Means are provided to stop the pins and balls/small particles falling out of the housing. The implementation of solid balls in the machining fixtures, CMM fixtures etc. make the system much cheaper and capable of resisting large machining forces.

The other pending patent called “Engagement arrangement” is also by Gindy *et al.* (2009), The invention relates to a reconfigurable modular fixture using magnetorheological (MR) fluids for holding regular or irregular shaped components using the Rabinow concept, by increasing viscosity or solidification MR fluid for assembly or machining operations. The apparatus comprise of two clamp blocks and a fixture base. Each of the clamp blocks comprises of a set of middle blocks, which are further comprised of pushpins and clamp pins disposed into sleeves from either direction, with MR fluid filling the space in-between. The clamp pins are enabled to move to the desired location by independently pushing each of the corresponding pushpins. By using magnets, the viscosity of the MR fluid flowing in the orifice connecting push pin and force is increased there by restricting the movement of the clamp pins.

2.5.2 Reconfigurable pin tooling for dies and moulds

1. Leaf springs forming

One of the most important applications for early reconfigurable pin tooling is to produce vehicle leaf springs for supporting carriages and automobiles. The first known patent based on this application was awarded to Ansted (1892). The patent describes a device (as shown in Figure 2-22) composed of a sliding frame and a former-frame; each of them has a coiled spring-loaded pin row applied to form springs. Any desired adjustment of the pins is obtained by means of a series of adjustable collars of varying lengths and the movement of the sliding frame is driven by a hand-lever. A 1920 patent by Elkins is quite similar to that of Ansted except that screws are used to precisely adjust the individual pins. A patent by Williams and Skinner (1923) discloses a spring-forming device. The device contains a plurality of uniformly spaced screw pins with pivoting heads, and two threaded shafts driven by the sprocket chain which are used to adjust two carrier bars of the device.

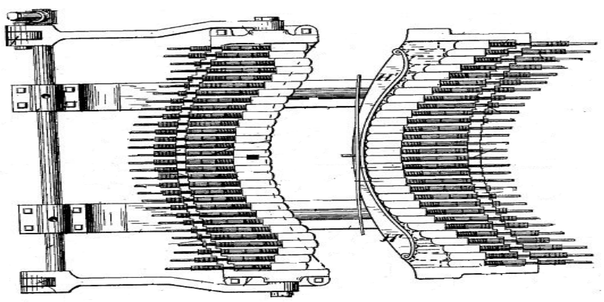


Figure 2-22 Machine for bending and forming springs (Ansted, 1892)

A patent by O’Kelley (1945) describes a reconfigurable pin device for restoring the original shape of hood and fender of automobiles. The device consists of two opposed rows of uniformly spaced pins with soft tips, whereby pin positions are manually adjusted by using screws and rams. The device can also be applied to forming automobile leaf springs. A spring forming die patented by Tegarden (1957) comprises of a punch including a plurality of contacting pins that can be hydraulically actuated to the desired shape and then clamped from the side into a rigid tool. There is a flexible work bed at opposite ends of the punch to support spring forming. An oil-filled tank is provided by the machine to enable rapid quenching of the formed springs.

The most recent patented reconfigurable device used for leaf spring forming is leaf spring cambering apparatus (Morita, 1993). The device consists of a pair of moulds with a plurality of pins wherein the lower mould is fixed on a base and the upper mould fixed upon the press head driven by a hydraulic cylinder. Each of the pins is connected to the corresponding motors and operated under the control command from the computer.

2. Reconfigurable tooling for forming sheet metal

A number of patents describe reconfigurable tools applied for sheet metal forming. Walters (1943) patented a hydraulically actuated press with two opposed reconfigurable pin matrixes to form heated metal plates. Each pin matrix contains a number of uniformly spaced threaded pins with pivoting ends attached to a flexible, insulated forming surface. The forming surfaces of the pin matrixes are manually adjusted. One of the most relevant patents to this reconfigurable tooling is awarded to Pinson (1980). The patented tool is very similar to that of Walters (1943) in construction, except that the each pin is actuated by motor-driven leadscrew with the instruction from computer numerically controlled (CNC). This is the first patent for the application of CNC in reconfigurable tooling.

The idea of forming sheet metal foot orthotics using a reconfigurable tool was patented by Hess (1931). The tool contains two oppositely arranged pin matrixes with spring-loaded square pins. The forming surface of the lower pin matrix is produced by feet impressions of patients and the forming surface of the upper pin matrix is formed by dropping down its loose pins over the feet. And then both of the pin matrixes are locked from side. Hoffman and Florissant (1992) patented a reconfigurable tooling that quite similar to that of Hess (1931), expect that each pin has a reduced cross-sectional in the middle and a plate with a matrix of apertures (similar to PinArt toy by Fleming in 1987) corresponding to the pin matrix is applied to prevent pins from dropped off. A patented reconfigurable tooling by Umetsu and Toshihiko (1993) is identical to that of Hoffman and Florissant (1992), which is used for pressing or stamping sheet materials. A three-axis, computer-controlled positioning device is employed to adjust pins in the two matched reconfigurable dies. The device pushes each pin in the upper die and the corresponding pin in the lower die into position simultaneously. The set position of each pin is maintained by friction rings until both pin matrices are side-clamped.

Between 1980 and 1999, Hardt and his research group at MIT developed a long term project to study the feasibility of using a flexible die system (FDS) for sheet metal forming (Walczyk and Hardt, 1999). The pin matrix die created in the FDS project was composed of a group of square pins (Hardt *et al.*, 1981 and 1982). The pin positioning concept was unique because it allowed pin columns to be set automatically using a column of leadscrew driven push rods without interfering with neighbouring pin columns by separating them with metal dividers. Pins in a column were made to conform to the array of push rods pushing from behind by side clamping the pin matrix during positioning, so that side friction between the pin and divider sheets became greater than friction between pins in a column. Hardt and Webb *et al.* (1985) also discussed closed loop control of sheet metal forming utilizing a spatial frequency description of the part shape and transfer function algorithm to minimize part shape error from springback, material property variation, etc. A coordinate measuring machine (CMM) was built to accurately measure the final part shape between trials. It is concluded by Hardt *et al.* (1991 and 1992) that the prototype FDS was capable of continuously varying the forming surface based on a computer model and can be used to form high quality three dimensional parts using a neoprene interpolator.

From 1996 to 2002, one of the most important projects in the field called reconfigurable tooling for flexible fabrication (RTFF) was jointly developed between MIT, Northrop Grumman Corporation and Cyril Bath Company. This long term project was sponsored by the Defense Advanced Research Projects Agency (DARPA) Flexible Fabrication Program, and its aim was to develop a large-scale, computer-controlled reconfigurable tool with close-packed pin matrix for stretch forming of sheet metal body panels for use in aircraft (Munro and Walczyk, 2007). There were several issued patents related to this project. Haas *et al*. (1996) patented a shaft pin actuation system for a reconfigurable tool consisting of a matrix of identical length pins with hemispherical tips. Sullivan *et al.* (2000) patented a new CNC pin actuation system for the Haas (1996) reconfigurable tool and Nardiello *et al.* (2000) patented a manually adjusted reconfigurable tool similar to that of Haas *et al*. (1996).

As a result of the RTFF project, the Cyril Bath Company designed and constructed a commercially reconfigurable pin tooling for stretch forming of an aluminum sheet, as shown in Figure 2-23. This production tool has a working volume of 1.06×1.83×0.30 m^3 and contains 2688 adjustable pins (Sillery, 2002). Each pin is 1.125×1.125×21 inches and is controlled by a DC motor attached to a leadscrew. Each DC motor includes an integral 84:1 in-line planetary gear reducer and a position encoder (Papazian, 2002). There are eight modules in total and each module has a microprocessor and a driver for its motor. The modules are daisy-chained together and communicate with the host computer via RS-232 lines. An interpolator is applied to suppress the dimples caused by the discrete pins during the period of the tooling application. This device has been used for both opposed-die and rubber-pad sheet metal forming processes (Sullivan *et al.,* 2000).

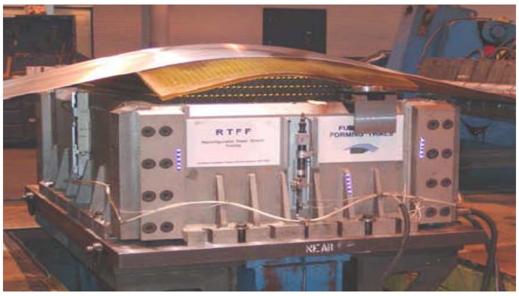


Figure 2-23 RTFF reconfigurable pin-type tool (Papazian et al., 2004)

Walczyk *et al.* (1996 and 2000) designed a reconfigurable tooling system for use in stretch and matched-die forming of sheet metal aircraft skins at Rensselaer Polytechnic Institute (RPI). The reconfigurable tooling was equipped with a hydraulic pin actuation scheme and an in-line, solenoid-actuated hydraulic valve was used in open and closed-loop control of an individual prototype pin. Smooth and relatively accurate open and closed-loop control of the pins was demonstrated, although the accuracy of leadscrew-driven pins was never matched due to the effect of pressure gradients in the hydraulic system. These methods are limited to create a single surface geometry and can be used only for formed parts with limited geometric complexity because of the nature of the forming process.

Papazian, Nardiello *et al.* (2002) and Papazian, Anagnostou *et al.* (2004) developed a reconfigurable tooling concept for stretch forming of sheet metal in aerospace applications. The research contributed to the pin-setting control system and suggested techniques to compensate for spring back and other size variations such as the effects of the compliant interpolator and release of residual stresses. This method specifically addresses the forming of large surfaces for aerospace applications. The die, consisting of 1120 pins, is reconfigured using servo-actuators at each pin. However, the die developed at the cost of over a million pounds is not a low price tool, and would not be affordable to most small and medium enterprises.

Cai and Li (2001, 2003) and Chen *et al.* (2006) have developed a multi-point forming (MPF) technique for sheet metal forming. In MPF, by controlling the position of each punch, a pair of matrices of punches is transformed to multipoint dies (MPD) to replace the conventional stamping dies. With MPD, the forming process of sheet metal parts of various three-dimensional shapes can be finished. During die shape adjusting, each punch is controlled by a computerized numerical control unit, which including a microprocessor board, a mini motor, and a set of driving gears. The board consists of a microprocessor, motor controller chips, and associated circuitry. Computer-controlled motors move the punches along their axes individually and all punches are adjusted simultaneously. With finer punches and smaller space between punches, a better surface approximation is realized. As the working surface of a die can be constructed in real-time, a sheet part can be manufactured along a specific forming path in MPF.

Owodunni, Hinduja *et al.* (2004 and 2005) have also carried out preliminary investigations on the use of reconfigurable tooling. The bed-of-pins concepts were enhanced with a novel approach of positioning and clamping the pins in a simple, low-cost and time-saving way. Tool path strategies, from the simplest to the most complex, for positioning the pins by a single actuator or CNC machine, were proposed and evaluated to obtain an optimal strategy.

3. Reconfigurable tools for vacuum forming

Vacuum forming is another important application area for the reconfigurable pin tooling. There is a great deal of interest in developing reconfigurable pin tooling for forming thermoplastic and composite parts with compound curvatures (Walczy, Hosford *et al.*, 2003).

Fuchs *et al.* (1982) received a patent for a reconfigurable tool with a single forming surface for producing curved sails. The tool design is very identical to Walters (1943), except that pins need not be vertically oriented. Kommineni *et al.* (1988) patented a single surface tool for forming double curvature composite antenna panels. The pin actuation system is identical to that of Pinson (1980), except that each pin contains manually adjusted threaded rods connected in a series arrangement. A close-packed reconfigurable tooling concept was patented by Bernardon and Foley (1992) for resin transfer moulding of composite parts. Lateral and longitudinal plates are applied to separate Individual pins from neighbouring pins and pin actuation is performed using an array of CNC linear actuators.

Klesspies and Crawford (1998) presented a method for producing large compound curved surfaces using a variable configuration vacuum forming mould. The mould is composed of a number of uniformly spaced round discrete pins, which are covered by a rubber interpolation sheet. A thermoplastic sheet is placed over the reconfigurable mould, heated using radiant heaters, and drawn into the mould surface using a drawing vacuum. A multi-parameter design study, using theoretical, numerical, and experimental results, showed that there is a tradeoff between final part waviness and severity of the parts' compound curvature.

A patent by Haas *et al.* (2000) describes a modularized reconfigurable pin tool for the forming of composite honeycomb panels. The pin actuation scheme for the two pin matrixes is similar to that of Sullivan *et al.* (2000). The composite is heated or cooled by force air or inert gas through the modified hollow pins. An interpolating cloth is applied to evenly distribute the forced air over the composite surface and to suppress pin dimpling. Another patent was issued to Haas *et al.* (2003), which is similar to Haas *et al.* (2000), except that an upper reconfigurable tool forms a honeycomb material in a deformable material that provides sufficient backing pressure. Meilunas *et al.* (2002) patented a reconfigurable tooling concept for forming laminated composite structures. The part shape and the desired ply stack are represented by CAD format in system design; the pre-impregnated composite materials are cut into plies automatically and a ply feeder and stacker are used to stack the plies subsequently. The laminate is then transferred to the designed reconfigurable tool that equipped with double-diaphragm forming capabilities. Halford (2002, 2005 and 2006) received several patents for the SPT technology described in section 2.3.2. After pins' adjustment and packing, the rough upper surface of the SPT can be CNC-machined to an exact contour and used for vacuum forming.

Walczyk *et al.* (2003) developed a computer-controlled, reconfigurable mould with square pins to sequentially form a compound curvature part shape from a flat composite lay-up, thereby facilitate composite shaping process automation (as shown in Figure 2-24). The reconfigurable mould is similar in structure to that of Klesspies and Crawford (1998) except that the pins are square and close-packed. The hemispherical forming ends of the die elements are covered by an elastomeric interpolator to prevent dimpling of the composite lay-up. A vacuum pressure is applied to pull the top diaphragm, composite, and interpolator into contact with the mould surface in the process.

It was successfully demonstrated by Walczyk *et al.* (2003) that the range of carbon/epoxy composite parts that could be formed with double diaphragm forming (DDF) increased when a reconfigurable forming tool is employed to control the forming rate and intermediate shapes.

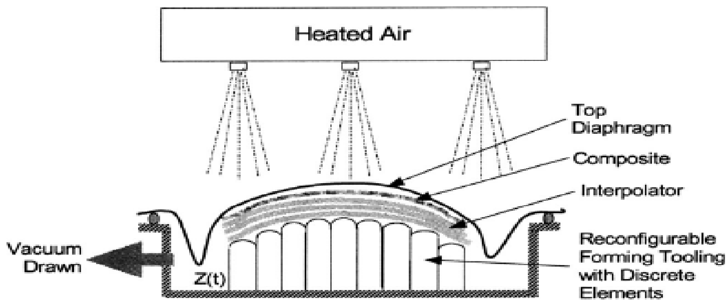


Figure 2-24 Composite forming over a reconfigurable forming tool (Walczyk *et al.*, 2003)

Although a number of patents for reconfigurable tool have been applied and small-scale reconfigurable tool prototypes have been built for vacuum forming application, only two designs have actually been commercialized to date. One is by North Sails North America (2005) to manufacture custom-designed composite racing sails and the other is by Surface Generation, Ltd (2006) to make composites and thermoforming moulds. They demonstrate how a computer-based reconfigurable tool can be used successfully in production.

4. Reconfigurable tooling used as casting moulds

1) Permanent casting moulds

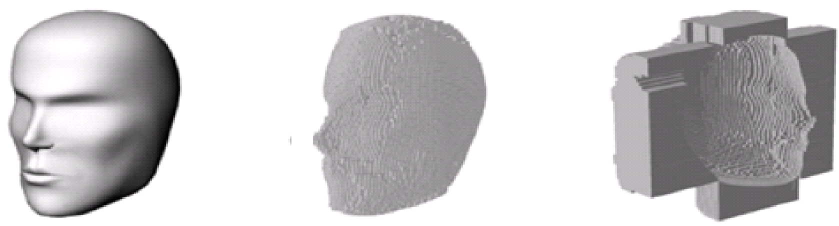
There are several patents that use matrix pins to construct permanent moulds. Wakefield (1943) received the first patent for a method of producing a die by brazing together a number of metallic pins, the bottom ends of the pins in a plane and the top ends of the pins at different levels to form an approximate contour. Hicks (1961) patented a die similar in construction to that of Wakefield (1943), except that the pins are not bonded together, but clamped by a steel frame. Whitacre (1971) patented a method of producing permanent dies from a hexagonal pin matrix that is machined to design contour using numerical control (NC). However, the development of CNC machine tools has largely superseded the application of patents by Wakefield (1943), Hicks (1961) and Whitacre (1971).

2) Reconfigurable casting moulds

Several patents are introduced to produce mould for casting components out of hardenable liquids or molten materials. Todoroki *et al.* (1993) patented an idea for stacking a number of identical pins horizontally in a clamping device by a computer-controlled robot. Each pin positions are determined by a pre-defined mould shape. Molten metal or plastic is filled in the formed mould cavity to produce castings, and then CNC machine is selected to achieve the final shape of the mould. Hong (1994) patented a method for creating gypsum moulds using pin matrixes. Several pin matrixes are pressed against an object in certain directions and then clamped into rigid mould to be used for gypsum casting.

Laskowski and Pintz (1998) patented an idea for using a reconfigurable tool with uniformly spaced pins to make wax or foam core. The CAD model of the wax or foam core is input directly into the tool's control system, and then the pins are adjusted and locked to create a mould in a method very identical to that of Hoffman and Florissant (1998). The mould surface is lined by a compliant diaphragm or a liquid rubber material and then can be used to cast a wax or foam core.

A patent by Kelkar, Nagi and Koc (2005) described a reconfigurable tooling system for fabrication of freeform components (as shown in Figure 2-25). The proposed tool contains a mould block, with n faces, each of which is formed by a set of discrete pins. The component surfaces from different part geometry are approximate produced by rapid moving these pins in and out from the suitable mould block faces.



(a) NURBS model of human head model

(b) Model obtained from mould cavity

(c) Mould generated for human head model

Figure 2-25 A reconfigurable tooling system for freeform objects (Kelkar *et al.*, 2005)

2.6 Research gap

From the literature view of reconfigurable tooling, it can be concluded that:

1) Most research attention has been on the application of reconfigurable tooling on sheet metal forming and complex components clamping; thermoplastic and composite sheet forming has been given less attention by the research community;

2) No mathematical expressions are given for the description of the general mapping process from component surface model to the pin array pattern;

3) The discrete elements in a reconfigurable forming tool can either be densely or sparsely arranged. The tool with sparsely arranged pins limits part

shape fidelity and die geometry, whilst the tool with densely arranged pins constrains the maximum forming loads;

4) Little research has addressed techniques that can be widely used to find each pin position in different types of reconfigurable tooling and there is a lack of systematic knowledge for supporting software development of tooling shape control;

5) An interpolating layer is used to smooth the discontinuous surface of reconfigurable tooling, but it can cause waviness on the formed surface. An iterative procedure of trail is needed to find ways of avoiding such waviness;

6) Different methods of positioning and clamping of discrete elements are discussed; these methods usually need to build complex and expensive control systems. A simple and cheap control system is required;

7) There is no shape fidelity control methodology for thermoplastic or composite sheet components formed by vacuum forming over reconfigurable tooling;

8) No manufacturing cost model and application cost model for the reconfigurable pin tooling are built and breakeven analysis for the constructed reconfigurable pin tooling is also absent.

CHAPTER 3

SYSTEM CONSTRUCTION AND CALIBRATION

3.1 Introduction

This chapter focuses on the hardware aspects of the tooling system: machine construction. Firstly, the basic concept of the SPT is introduced; system basic requirements are analysed and then an overall architecture is proposed for integrating the SPT into the HAVES test bed development. Secondly, the system specifications are listed, based on which, the concept design of the machine system is presented. Thirdly, a previous machine is retrofitted according to the system specification and with contents including CNC control, machine bridge, SPT, dual tool head and vacuum forming etc. Fourthly, key components of the system including driving motors, frame, heater and vacuum forming machine are selected, purchased and assembled. Finally, the constructed machine system is then calibrated.

3.2 Screw-pin tooling

3.2.1 Concept

The literature review shows that pin adjusting and locking mechanisms of reconfigurable tooling using square pins, round pins or hexagonal pins are still complicated and expensive to construct. To overcome these problems, reconfigurable tooling using the screw-pins is proposed for producing customization and small batch components in this research. The screw-pin tooling (SPT), as shown in Figure 3-1, is defined as a device that is composed of a group of identical screw pins and a container which is formed by four engaged blocks. To gain a reference for screw pin position, a small precise square block used as a datum is also assembled on top of the container blocks. The SPT can be repeatedly configured by the user in order to shape mechanical parts in a manufacturing setting. The screw pins are engaged with each other within an array pattern. By adjusting vertical displacement of the screw pins, a wide variety of geometry is formed.

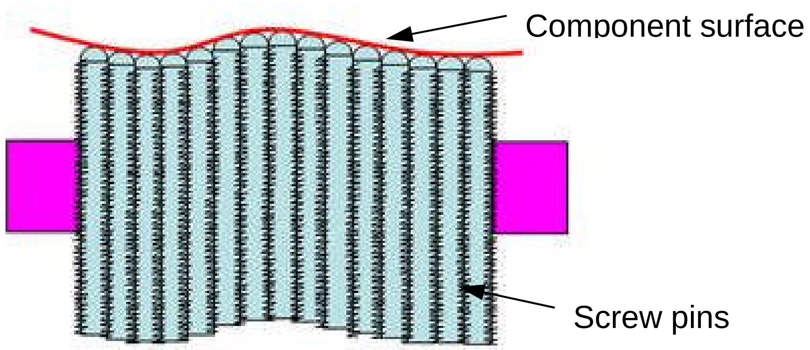


Figure 3-1 Reconfigurable screw-pin tooling

Compared with the pin tooling technology reviewed in prior art in Chapter 2, the SPT is very simple and cheap, and it can be used for forming, moulding or in the casting of complex curvature parts from different materials such as plastic, metal, composites etc. As stated in the literature review, research into the application of pin tooling in vacuum forming has not been paid much attention to but has great potential. This piece of research will explore an application methodology of the SPT in vacuum forming. Design specification of the SPT is illustrated in Section 4.6.2.

3.2.2 Pin actuation method

The pin actuation method of the SPT is one of the most important issues needs to be solved. There are a few pin actuation methods such as the leadscrew-driven, pneumatic, hydraulic and robotic manipulator approaches developed by researchers as shown in the literature review. These methods are often dedicated and expensive and are not widely accepted by industry. Since the CNC machine is widely used in industry and its cost is acceptable to companies, it will be applied to actuate the screw pins in the SPT as well as for manufacturing the surface if required in this research.

3.3 HAVES test bed architecture

3.3.1 HAVES test bed requirements

To realize the aforementioned objectives, the proposed HAVES test bed should possess the following four basic functions at the minimum: screw-pin adjustment, surface machining, vacuum forming and component evaluation.

1. Screw-pin adjustment

As the shape of the SPT needs to be changed in response to different component geometry, the screw-pins can be adjusted in the axial direction. Rather than having a motor to simultaneously drive each individual pin to a pre-specified position, the screw-pin is rotated around its central axis to the required position one by one, and therefore only one tool is needed. To this end, a tool that is actuated by a servo motor to rotate screw-pins, thus moving them vertically is needed. The degree of freedom of the tool would be four axes: X, Y, Z and Z rotation (designated as C).

2. Screw-pin tooling machining

After adjustment of the screw-pins, CNC machining can be prepared in order to eliminate most of the stairs that have been produced by discrete screw-pins and gain a relatively smooth mould surface. The machined screw-pin tooling surface may need further treatment before forming a vacuum because of the small gaps among the screw-pins. A milling cutter is needed for milling operations and the degree of freedom should be the four axes: X, Y, Z (designated as W in order to differentiate from the Z motion of screw-pin adjustment) and Z rotation (designated as B to differentiate from C).

The axes and spindle requirement of the HAVES can be summarized as in table 3-1.

Table 3-1 Axes and spindle of the HAVES

Axis/ Spindle	**Description**
X axis	Axis for machine tool moves left/right
Y axis	Axis for machine tool moves forward/backward
W axis	Vertical axis with router spindle, moves up/down
Z axis	Vertical axis with screw-pin adjustment, moves up/down
C axis	Rotary axis attached to Z axis saddle
B axis	Router spindle for milling 3D forms from Screw-pin tooling

3. Vacuum forming

The vacuum forming process is applied to produce plastic components over the developed SPT. This vacuum forming module includes a heater, a vacuum pump and a suit of parts for plastic sheet clamping and movement. The selection of the vacuum pump, the heater and its associated control system will be dependent on the size of the component to be produced.

4. Component evaluation

A digital model scanned from the vacuum formed component is compared with its CAD design model to the quality control of the finished product. The difference between the produced plastic component and the design model is to be used in further screw-pin tooling adjustment. A GOM ATOS II-400 digitizing system will be employed to evaluate the components while the system communicates with the HAVES test bed via the internet.

3.3.2 HAVES test bed architecture

Based on the system research objectives and system functional requirement analysis, a hybrid vacuum-forming machine system (**HAVES**) that integrated with the SPT was developed to facilitate plastic component manufacture. Figure 3-2 shows the development architecture of the HAVES test bed.

The HAVES integrates CAD/CAM, reconfigurable tooling, CNC, vacuum forming and optical measurement device together to satisfy functional requirements. The reconfigurable SPT plays an important role in the architecture. In operation, the candidate part is imported into CAD/CAM/CAE environments, where the appropriate screw-pin height positions are calculated and transferred to the CNC; an adjustment tool and a milling tool driven by the CNC are used to reconfigure and mill the SPT separately. The finished SPT is applied to the vacuum forming system to produce thermoplastic parts before the thermoplastic part is scanned and compared

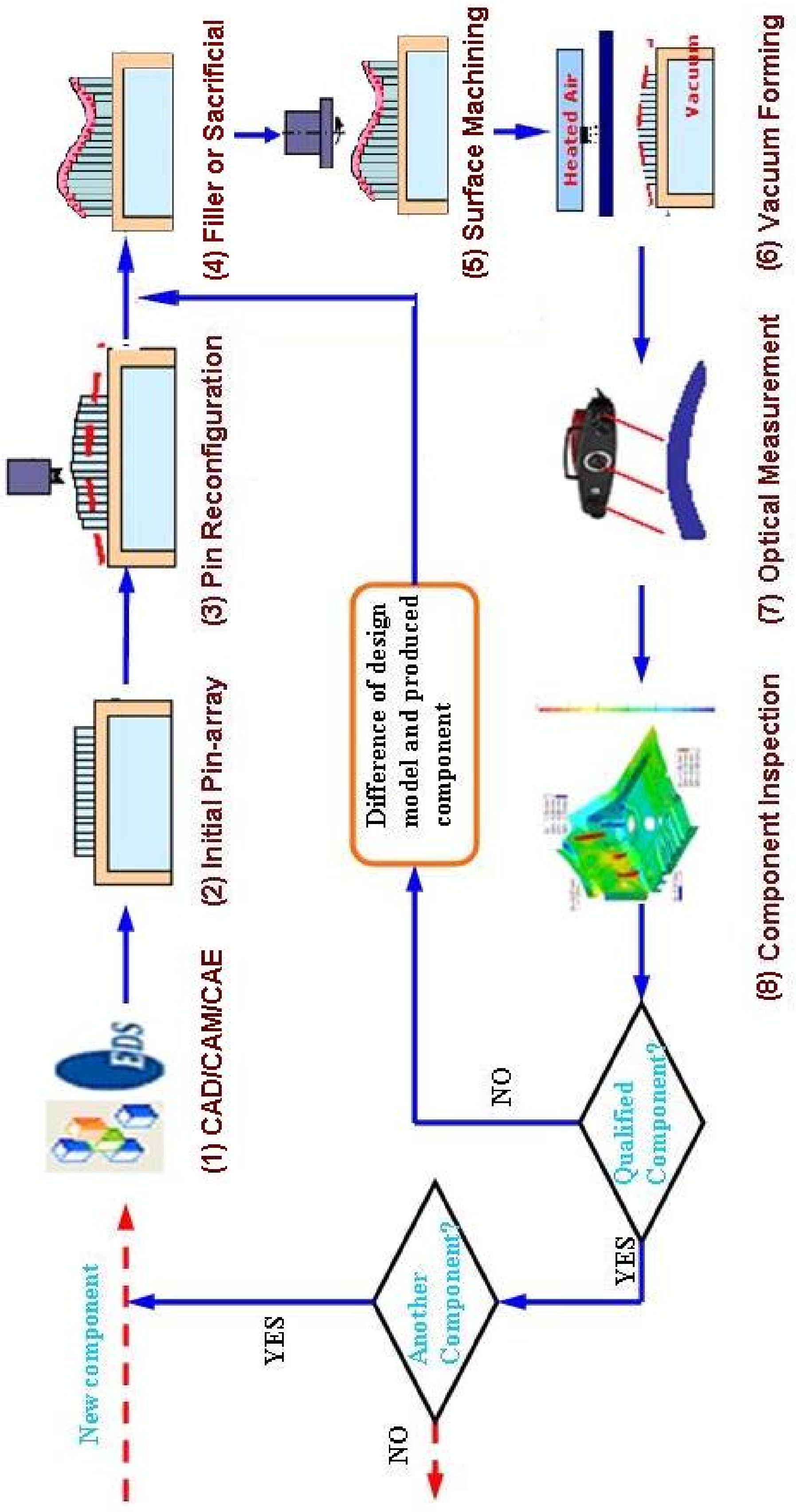


Figure 3-2 Development architecture of the HAVES test bed

with the design model for further quality improvement. The overall development procedure of the HAVES test bed includes hardware development (Chapter 3), software development (Chapter 4), experiments (Chapter 5) and economic analysis (Chapter 6). The following sections will give a brief introduction to hardware development.

3.4 Background to machine construction

3.4.1 Introduction to the CNC machine

Machine construction is a complicated job, needing specialised expertise. Instead of explaining how to construct a machine, this section attempts to provide some background information that appears later in this chapter. **Numerical control** (**NC**) refers to the automation of machine tools that are operated by abstractly programmed commands encoded on a storage medium, as opposed to manually controlled via hand wheels or levers or mechanically automated via cams alone. The first NC machines were built in the 1940s and 50s and were based on existing tools that were modified with motors that moved the controls to follow points fed into the system on paper tape (Thyer, 1991). These early servomechanisms were rapidly augmented with analog and digital computers, creating the modern **computer numerical controlled** (**CNC**) machine tools that have revolutionized the design process.

All CNC machine types share this commonality: They all have two or more programmable directions of motion called *axes*. An axis of motion can be linear (along a straight line) or rotary (along a circular path). One of the first specifications that implies a CNC machine's level of complexity is the number of axes it has. Generally speaking, the more axes, the more complex the machine (Seames, 1990).

The axes of any CNC machine are required for the purpose of causing the motions needed for the manufacturing process. In the drilling example, these three axes would position the tool over the hole to be machined (in two axes) and machine the hole (with the third axis). Axes are named with letters. Common linear axis names are X, Y, and Z. Common rotary axis names are A, B, and C.

3.4.2 Construction of CNC machine

As shown in Figure 3-3, in order to create relative movement between component and machine tools, there are several essential components:

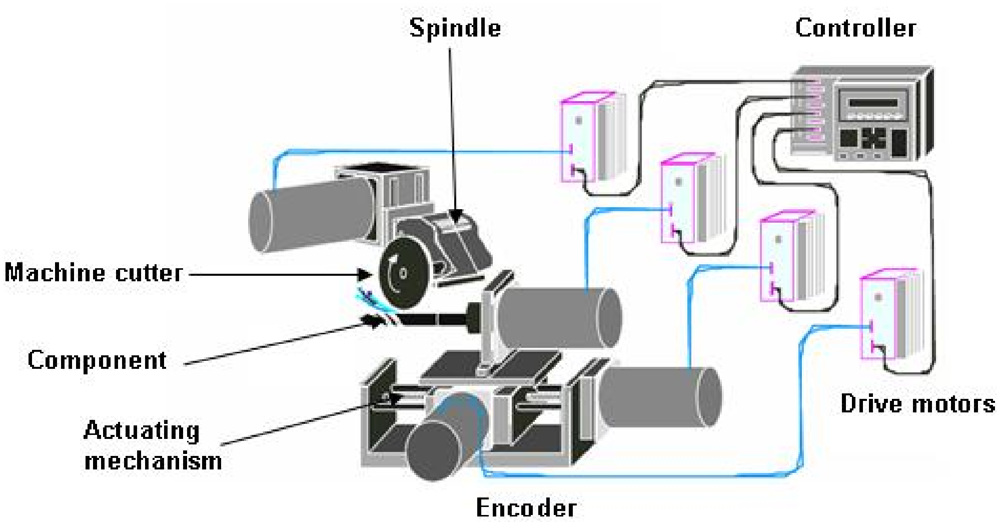


Figure 3-3 CNC machine architecture (Thyer, 1991)

(1) Drive motors

Drive motors, also called power units, are required to drive the main spindle for machining (milling for our machine), for driving the saddle or carriages (feed); or providing power for ancillary service (screw-pin adjustment). The motor for cutting, generally an electric motor, must be capable of providing power and high speeds at the main spindle. Drive motors that provide the feed movement do not have to be as powerful as these used for driving the main spindle. In addition, the feed rates are much slower than cutting speeds. These rates of feed can easily be obtained with a screw and nut driving system. Though feed for moving the saddle is slower than the main spindle speed, it is essential that the movement provided by feed motors can be controlled very precisely and quickly; and it must be reversible. To obtain position control, there are two systems:

(a) An open loop system. In the open loop servo driver control system, the power supply level is set to a position for which the desired speed is indicated by the input. The motor continues to turn until the absence of power indicates that the programmed location has been attained and the driving mechanism is disengaged. There is no monitoring of the position and if any movement takes place at this time, its magnitude would normally be unknown. Nevertheless, the open loop control system is reliable, considerably less expensive than the closed loop system and its maintenance if far less complicated.

(b) A closed loop system. The closed loop system used in CNC is characterised by the presence of feedback. The term “feedback” is used to describe the various methods of transmitting positional information on the machine slide motion back to the information command section of the CNC. The information is continuously compared with the programmed slide motion data. Compared to the open loop system, the closed loop system is more accurate, however, its implementation costs are much higher.

(2) Monitoring system (encoder):

In order to control speed in the closed loop servo motor, it needs to be measured first. Encoders are measuring devices to sense the position, angle and speed and velocity of a machine’s moving parts. Without the position transducer, a closed loop system for numerical control could not have been developed.

(3) Actuating mechanisms:

Of all the constructional features that make up numerically controlled machine tools, the efficiency and responsiveness of the actuating mechanisms have the greatest influence on the accuracy of the work produced. Lead screw and nut is one of the actuating mechanisms for the carriage of tools or work found on numerically controlled machine tools.

(4) CNC controller

The CNC control will interpret a CNC program and activate a series of commands in sequential order. As it reads the program, the CNC control will activate the appropriate machine functions, cause axis motion, and in general, follow the instructions given in the program. Along with interpreting the CNC program, the CNC control has several other purposes. All current model CNC controls allow programs to be modified (edited) if mistakes are found. The CNC control allows special verification functions (like dry run) to confirm the correctness of the CNC program. The CNC control allows certain important operator inputs to be specified separate from the program, like tool length values. In general, the CNC control allows all functions of the machine to be manipulated.

The background knowledge to the CNC machine construction is used as guidance of the HAVES system design and retrofit in the following sections.

3.5 HAVES system design

3.5.1 System considerations

To satisfy the HAVES test bed requirements proposed in section 3.3, a machine centre that integrates screw-pins adjustment and NC machining with vacuum forming machined is required. None of the standard NC machines has been integrated for vacuum forming operations thus making customisation of standard NC machines inevitable. Buying a standard new NC machine for customisation is considered vastly expensive for just a prototype, thus, a retrofit of an old machine would be a better option. A bridge (gantry) machine that is already available in the workshop is retrofitted for the HAVES design.

According to system functional requirement analysis and the proposed overall architecture, the following sections introduce the original filament lining machine, list of retrofit work content and describes hardware selection plus control.

3.5.2 The original Gantry Machine introduction

The gantry (bridge type) machine to be retrofitted shown in Figure 3-4 was originally designed as a filament lining machine, and it can be simplified as the concept shown in Figure 3-5.

Figure 3-4 filament lining machine (before retrofit)

The bridge has motion in the Y direction, and the tool holder which is mounted on the bridge, inheriting the motion of the bridge, will have its own motion along the bridge (X direction). The tool for lining is installed on the tool holding, inheriting motion in X and Y directions and has motion of its own in the Z direction and slow Z rotation movement (C). The original gantry machine comprises of:

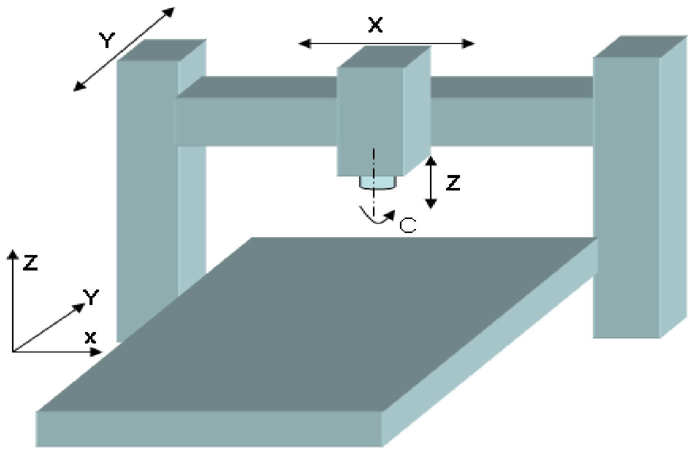


Figure 3-5 Motion of the gantry machine

Control system: CT FNC4 control (already broken);

Axes:

X axis -- Carriage across gantry

Y axis – Gantry dual drive, Y1 (Master), Y2 (slave)

Z axis – vertical, drives C axis up/down

C axis -- Rotary axis attached to Z axis saddle

Drives:

Drives for X, Y (Y1, Y2) and Z axes are all SEM dc servo motors with CT Maestro Drive 140x14/28A (4 off); drive for C axis is ECL dc permanent magnet servo motor with mini maestro drive, and used as a reliance drive.

Measurement feedback (Encoder)

X axis -- Sony Mag. SL110 tapes, 5V TTL

Y1, Y2 axes -- Sony Mag. SL110 tapes, 5V TTL

Z and C axes -- Heidenhain Rod TTL encoders

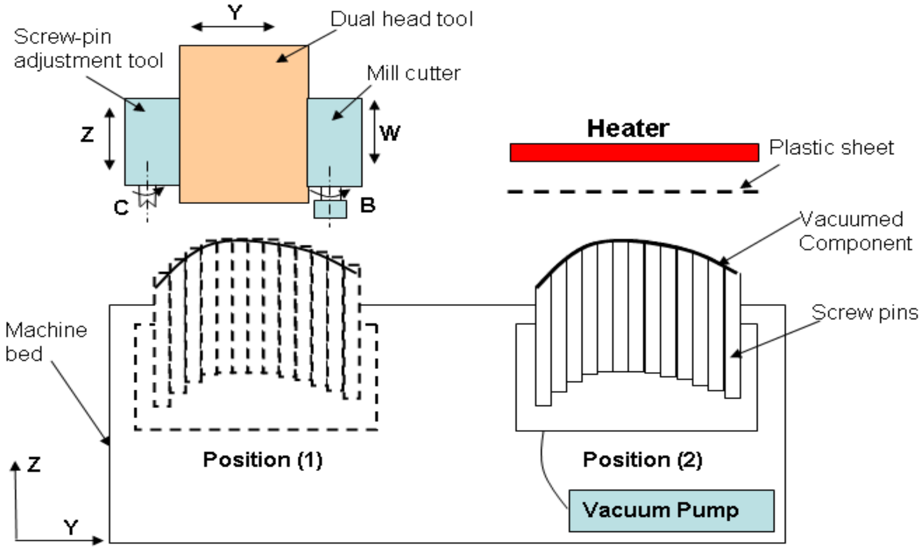
The machine is retrofitted for the purpose of HAVES test bed. The X, Y movement can be used for both screw-pin adjustment tool and the milling cutter. The Z and C axes can be reused for rotating the screw-pin adjustment tool. The current drive, carriage, measurement feedback and actuation mechanism system can be reused for the HAVES. However, a spindle is needed to hold one milling cutter and a vertical axis is required to move the spindle up and down. The original CNC controller was broken, and a new CNC controller should be employed. A vacuum forming system (heater, pump and its control and collection) are needed to fit within the machine. A summary of the reuse of the current machine and the retrofit contents are shown in table 3-2.

Table 3-2 Summary of reuse and retrofit contents

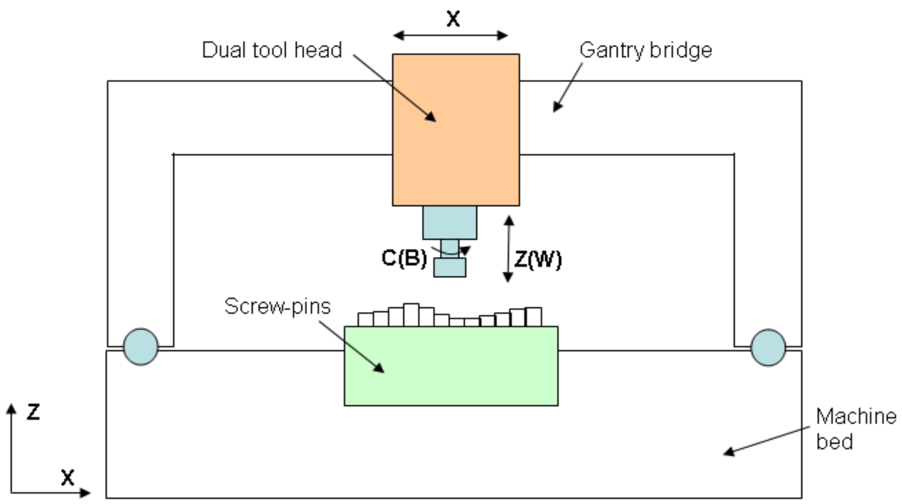
System requirement			**Original gantry machine**	**Retrofit**
Screw-pin tooling	motion	X	Yes	
		Y	Yes	
		Z	Yes	
		C	Yes	
		W	No	Motor taken from an unused machine, encoder purchased
		B	No	spindle, actuation mechanism
	Controller		Out of date	Purchase
Vacuum forming	Heater		No	Purchase
	Pump		No	Purchase
	Control		No	Purchase

3.5.3 Initial conceptual design

It is not feasible to integrate the screw-pin tooling and the vacuum forming in the same position, as the heater may be in the way of the motion of the screw-pin adjustment and milling machining. As shown in Figure 3-6, the



(a) Side view



(b) Front view

Figure 3-6 Conceptual design of the HAVES screw-pin batch is adjusted and machined at position (1) by the dual tool head and is moved to position (2) for component vacuum forming. Z axis saddle and W axis saddle are assembled together and mounted on the two sides of the gantry beam. The screw-pin adjustment tool and the mill cutter have the same movement in the XY plane. In general, holes are drilled on the mould for vacuum pressure to be applied to the plastic component. For the screw-pin tooling, there are already holes between screw-pins, thus, there is no need for the drilling operation, which is considered to be an advantage of the SPT.

The 3D detailed modelling of the HAVES is shown in Figure 3-7. The screw-pin tooling adjustment and machining position are located at the front of the support table and the vacuum forming device position is located at the rear of the support table. The total dimension of the support table is 3050mm length, 1200mm width and 940mm height. The span of the bridge is 2150mm.

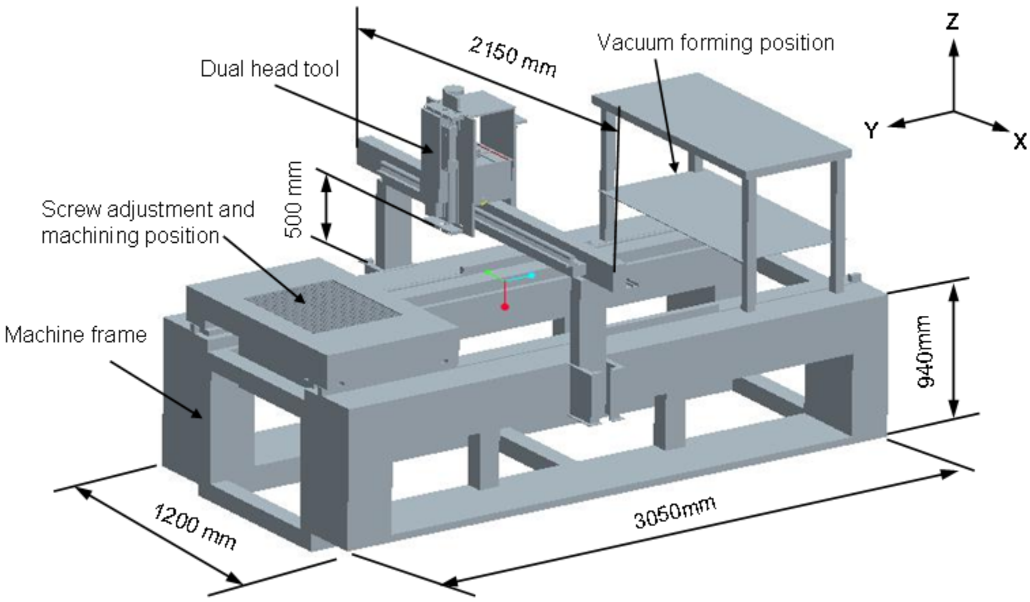


Figure 3-7 Machine frame for HAVES

3.6 Retrofit content

In order to satisfy the requirement of HAVES, the following retrofits of the original machine are needed:

1) Machine bridge

The bridge is too low for both tool adjustment and milling machining, and need customisation (see section 3.6.1).

2) Screw-pin tooling

The screw pin size and the covers are designed based on the overall size of the machine (see section 3.6.2).

3) CNC controller

The original control system CT FNC4 does not work any more, a new control system is purchased and integrated into the machine (see section 3.6.3).

4) Dual head and spindle

As shown in Figure 3-7, the machine concept shows that the screw-pin adjustment tool and milling cutter will be integrated into a dual tool head mounted on the bridge of the original machine. A spindle mounted on the dual tool head is needed to drive the milling cutter and it has to be purchased. The bridge can move in the Y direction. The dual tool head can move along the bridge (X direction). In this way, the screw-pin adjustment tool and the milling cutter share the motion in X and Y directions driven by the original machine (see section 3.6.4 and section 3.6.5).

5) Vacuum forming

The selection of the heater and the vacuum pump is based on the machine size. The vacuum forming is controlled by different controller from that of the machine in order to make the integration less complicated (see section 3.6.6).

3.6.1 Machine bridge

The machine bridge is used to support the dual tool head and driven by two servo motors. The original distance from the bottom edge of the gantry bridge to the machine bed surface was just 200mm as shown in Figure 3-4 and does not provide enough space for screw-pin tooling and screw pin adjustment. The maximum planned height of the component is 300mm, so one riser with 300mm height was added on each side of the gantry bridge as shown in Figure 3-8.

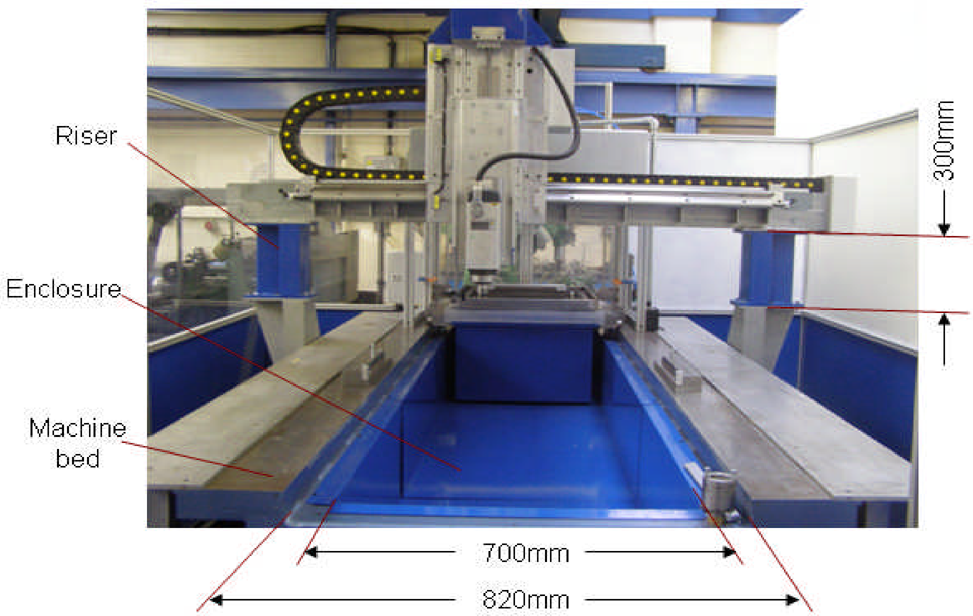
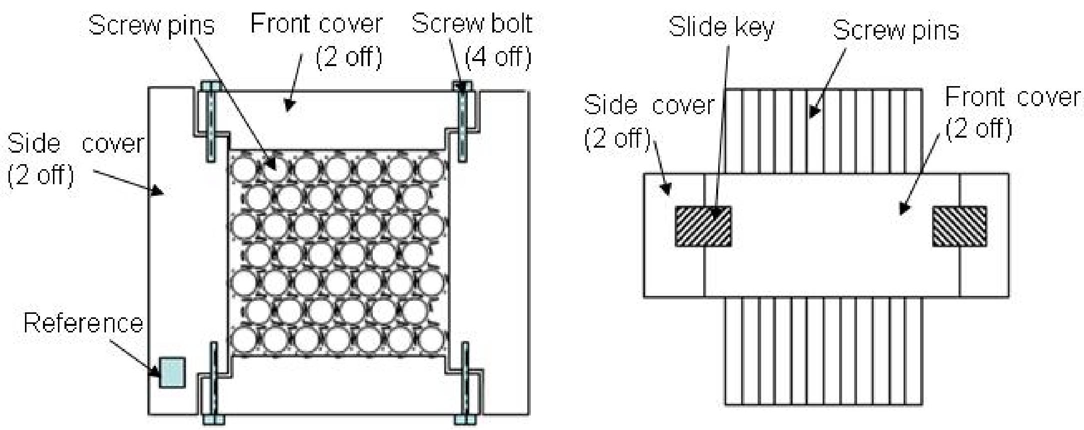


Figure 3-8 Machine bridge risers and enclosure

3.6.2 Screw-pin tooling

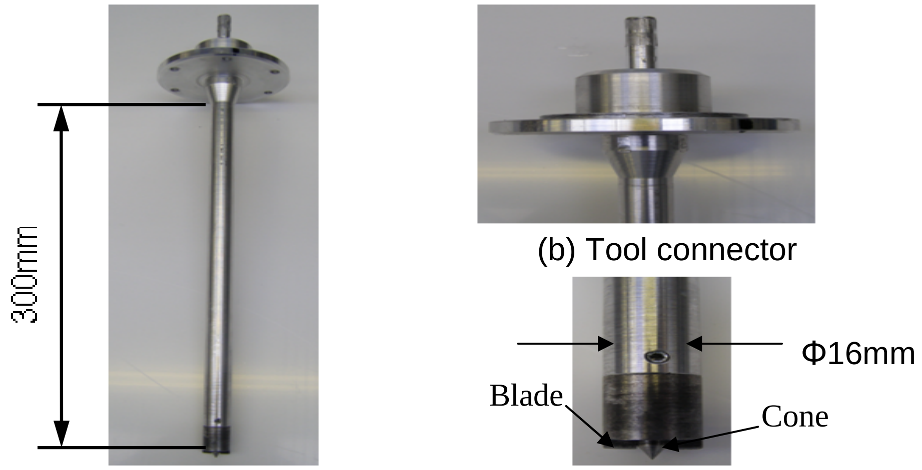
The screw-pin tooling comprises a plurality of screws arranged in an array pattern, and two side covers and two front-covers as shown in Figure 3-9. Four lock bolts are used to clamp the four covers with the array pattern of the screw-pins. There is a gap between the side cover and front cover, which allows justification between screw-pin adjustment and screw-pin machining by adjusting the screw-bolts. For easy screw-pin adjustment, the screw pin needs to be clamped relatively loosely, but still ensure that screw-pins are engaged properly, and in order to resist machining forces, the screw-pins have to be clamped firmly by the clamping bolts. Slide keys in Figure 3-9(b) are used to ensure the relative position between the four covers and the screw-pin array pattern. A square datum block mounted on top of one container block is used as position reference for the screw-pin array pattern. The prototype of the screw pin tooling developed in this research shown in Appendix A.1 is 19 rows and 20 columns with M20x300 screw-pins.



(a) Top view (b) side view

Figure 3-9 Design of screw-pin tooling

A customized adjustment tool is used to control the shape of the screw pin tooling. The diameter of the tool should be smaller than the diameter of screw to avoid interference between the adjustment tool and screw-pins. As shown in Figure 3-10, a small cone in the middle of the top end is used to locate the adjustment tool while the two blades near the cone are used to engage with the screw-pins and drive the screws to move. The screw-pin adjustment tool has a length of 300mm and a Φ16mm diameter.



(a) Adjustment tool (c) Tool tip

Figure 3-10 Screw-pin adjustment tool

3.6.3 Control system

Based on the analysis of system functional requirement and machine frame selection, the HAVES is required to control and manage 6 axes and one spindle shown in table 3-1. The drive and feedback measurement method for each axis are summarized and listed in table 3-3.

Table 3-3 Drives and feedback measurement methods for axes

Axis	**Drive**	**Feedback measurement**
X axis	SEM MT30R4-58	Sony linear magnescale SL110
Y axis (Y1, Y2)	SEM MT30R4-58	Sony linear magnescale SL130
Z axis	SEM MT22R2-24	Hengstler RS58-O/1024AS.41RB
C axis	ECL S644-3B/T	Hengstler RS58-O/1024AS.41RB
W axis	SEM MT22D2-19	Heidenhain Rod TTL encoder

In order to accommodate all functions of the HAVES, the CT FNC4 control used by the filament lining machine needs to be replaced by a new CNC control. The new CNC control should be compatible with existing hardware and keep pace with new computer technology. A series of CNC controls is investigated and compared and is shown in Appendix A.2.

Every investigated CNC control can be used to drive the HAVES. The Fagor CNC has the lowest price compared with others (the quotation is shown in Appendix A.3), although installation needs to be dealt with by ourselves. At the same time, the performance of the Fagor CNC was verified by the first European 5 axes waterjet machine in the workshop of The Nottingham Innovative Manufacturing Research Centre. The Fagor CNC was selected as the control for the HAVES.

The machine movements are controlled by Fagor 8055 CNC which is composed of a central unit module, a monitor module and a keyboard module. The central unit further includes a CPU module, an axis module and I/Os modules, etc. As shown in Figure 3-11, the Fagor 8055 CNC is required to control 5 axes (X, Y(Y1, Y2), Z, W, and C) and one spindle. Each axis includes several elements that should be managed by the CNC and they are detailed as follows:

1) X axis: one SEM ferrite brushed DC servo motor (model no. MT30R4-58, Appendix A.4), one Sony linear encoder (Appendix A.5), one reference switch and two limit switches;
2) Y axis: Y axis is a gantry axis and includes Y1 and Y2 two axes. The Y1 axis is called the main axis and its “Gantry” parameter set to “0”; the Y2 axis is called the slave axis and its “Gantry” parameter sets “Y1 axis” as its “master”. The Y1 axis and the Y2 axis must move together in synchronism with the parameter “MAXCOUPE” of the Y2 axis indicating the maximum

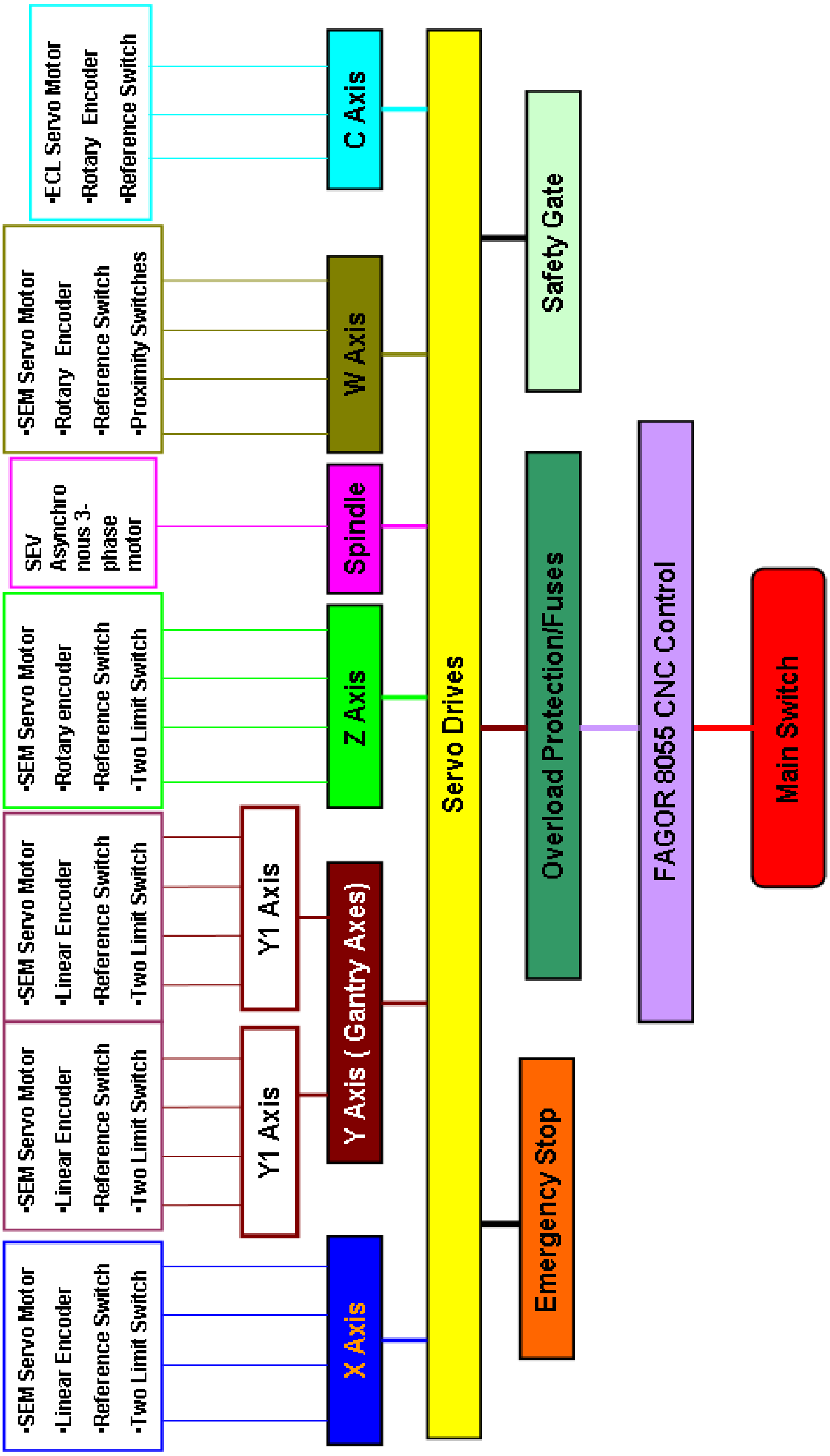


Figure 3-11 Axes and spindle control diagram in HAVES

allowed difference between the following errors of both axes. Only the movement of the Y1 axis needs to be programmed. The Y1 axis and the Y2 axis have the same control elements which include one SEM ferrite brushed DC servo motor (model no. MT30R4-58, parameters are shown in Appendix A.4), one Sony linear encoder (refer to Appendix A.6 for parameters), one reference switch and two limit switches;

3) Z axis: one SEM ferrite brushed DC servo motor (model no. MT22R2-24), one Hengstler rotary encoder and one reference switch and two proximity switches;
4) C axis: one ECL DC permanent magnet servo motor (model no.S644-3B/T), one Hengstler rotary encoder and one reference switch;
5) W axis: one SEM ferrite brushed DC servo motor (model no. MT22D2-19), one Heidenhain rotary encoder, one reference switch and two limit switches.

Besides controlling the spindle and the axes of the machine, the Fagor CNC also governs an emergency stop, a safety gate and overload protection.

3.6.4 Screw-pin adjustment tool (Z and C axes)

There are two axes working together to adjust the screw pins: Z axis and C axis. As shown in Figure 3-12, the Z axis comprises a drive motor (Appendix A.7), a pair of timing pulleys and a lead screw actuator (Appendix A.8); the C axis includes a drive motor (Appendix A.9), a gear reducer, a pair of timing pulleys and a screw-pin adjustment tool. As described in section 3.6.1, both axes retain the exsiting components from the filament lining machine. The Z axis is the original Z_0 axis, and the servo motor is the original one; a Hengstler rotary encoder (Appendix A.10) replaces its original encoder which does not work any more. The C axis uses existing components of C_0 axis except that its Heidenhain encoder is replaced by another Hengstler rotary encoder (Appendix A.10). Only the screw-pin adjustment tool is specially designed for reconfiguring tooling shapes.

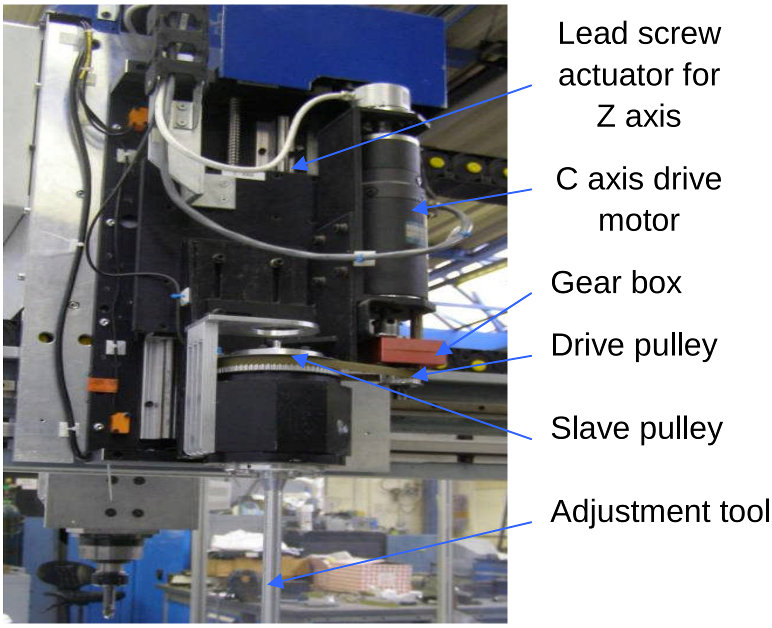


Figure 3-12 Tool head for screw-pin adjustment

The gear ratio of timing pulleys is 1:2 for the Z axis (Appendix A.11) and 1:3 for the C axis (Appendix A.12). The gear reducer's ratio for the C axis is 1:7 (Appendix A.13). The total gear ratio of the C axis r_c can be calculated as 1:21. The pitch of the Z axis is 5mm, and the pitch of C axis means the number of degrees the shaft rotates per encoder turn can be determined by:

$$P_c = 360^\circ \times r_c = 360^\circ / 21 = 17.142^\circ$$

Where P_c is the pitch of C axis; r_c is the gear ratio of C axis.

The maximum programmable feedrate F_0 is 99999.9999 degrees/min (Fagor Automation, 2006), the maximum speed of screw-pin adjustment v_{sp} can be calculated as:

$$v_{sp} = \frac{F_0 \bullet P_{sp}}{360 \times r_c} = \frac{99999.9999 \times 2.5}{360 \times 21} mm/\min = 33.07 mm/\min$$

Where P_{sp} is the pitch of screw-pins. Find the time t_{100} to adjust a screw pin for 100mm in $33.07 mm/\min$:

$$t_{100} = \frac{100}{v_{sp}} = \frac{100}{33.07} \min = 3.02 \min$$

3.6.5 Machining tool modular (W axis and spindle)

The machining tool module includes a drive motor, a Heidenhain Rod TTL encoder, a pair of heavy duty pulleys, a lead screw actuator, a router spindle and a milling tool as shown in Figure 3-13. It is a new part of the machine system, and everything needed to be purchased or found. The router spindle is provided to machine the screw-pin tooling in the W axis and mounted on the rear of the X axis beam. The drive motor is taken from an unused machine and used to drive a lead screw actuator for carrying the router spindle.

The pitch of the W axis is 5mm. An existing SEM MT22D2-19 DC servo motor is selected as the drive motor (Appendix A.14) and its stall torque is 3.5NM. To keep the speed of the drive motor, the gear ratio of the heavy duty pulleys is 1:1 (Appendix A.15). The lead screw actuator (Appendix A.16) uses an M24x5 lead screw and has 250mm stroke. A HEIDENHAIN rotary encoder (Appendix A.17) is employed to measure feedback of the W axis. To reduce the complexity and cost of the machine, a SEV air cooling spindle (Appendix A.18) that is designed for machining wood, plastic, aluminium, marble and glass materials of screw-pin tooling is selected. The selected electro-spindle is light and powerful and very suitable for machining with a high axial load.

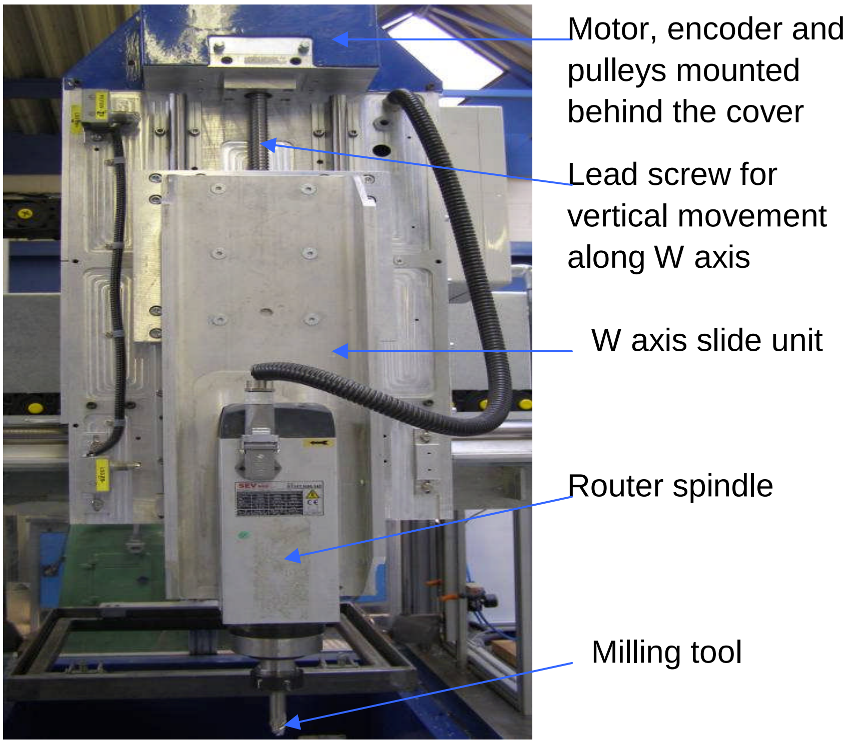


Figure 3-13 Machining tool head of HAVES

3.6.6 Vacuum forming system development

3.6.6.1 Background to vacuum forming process

Vacuum forming or thermoforming is a processing method in which a heated thermoplastic sheet is deformed and shaped over mould geometry by vacuum pressure (Lee, Virkler and Scott, 2001). This process is one of the most frequently used techniques for forming thermoplastic sheets. A variety of products ranging from simple shape cups to complex parts for the automotive, aerospace and electronic industries to highly complex refrigerator liners is presently vacuum formed (Kouba, Ghafur and Vlachopoulos, 1994).

The typical process steps can be identified as follows: clamping, heating with sheet level activated, pre-stretch, forming, cooling with air and spray mist, release and trimming. The key components of a typical vacuum forming system consist of clamp frame, heater, vacuum pump, etc. The clamp frame needs to be sufficiently powerful to handle the thickest material likely to be formed on the machine, up to 6mm. The heaters are generally infra-red elements mounted within an aluminum reflector plate. In order to obtain the best vacuum forming results, using any material, it is essential that the sheet is heated uniformly over its entire surface area and throughout its thickness. The vacuum pump is used to draw the air trapped between the sheet and the mould. The vacuum pump should be capable of maintaining a differential pressure of approximately 27”Hg (Formech, 2006).

3.6.6.2 Working process

Thus, the working process of the proposed vacuum forming system is scheduled as in Appendix A.19 and described as follows:

1) The plastic sheet is firmly placed between the clamp and the support frames;
2) The plastic sheet moves under the heater and the heater starts heating;
3) Once heated to forming temperature, the plastic sheet moves down driven by the cylinders to the top of the screw-pin tooling for moulding, and the heater is switched off at the same time;
4) The vacuum pump is started to evacuate air from the vacuum box and help the plastic sheet drape over the screw-pin tooling;
5) Once the vacuum gauge reaches a proper vacuum, the vacuum pump is stopped and the plastic sheet cooled;
6) The formed plastic sheet is released from the screw pin tooling under the help of a reverse airflow and unclamped from the clamping frame.

3.6.6.3 Key component selection

The concept design of the vacuum forming system is shown in Figure 3-14, and its essential component includes:

1) A heater to heat the plastic sheet to a specific temperature;

2) A vacuum pump to supply vacuum power for the vacuum forming process;

3) A clamp and support frame to hold the plastic sheet

4) Two cylinders to lift the plastic sheet up and down for heating and forming.

The selection of these components is detailed in the following sections.

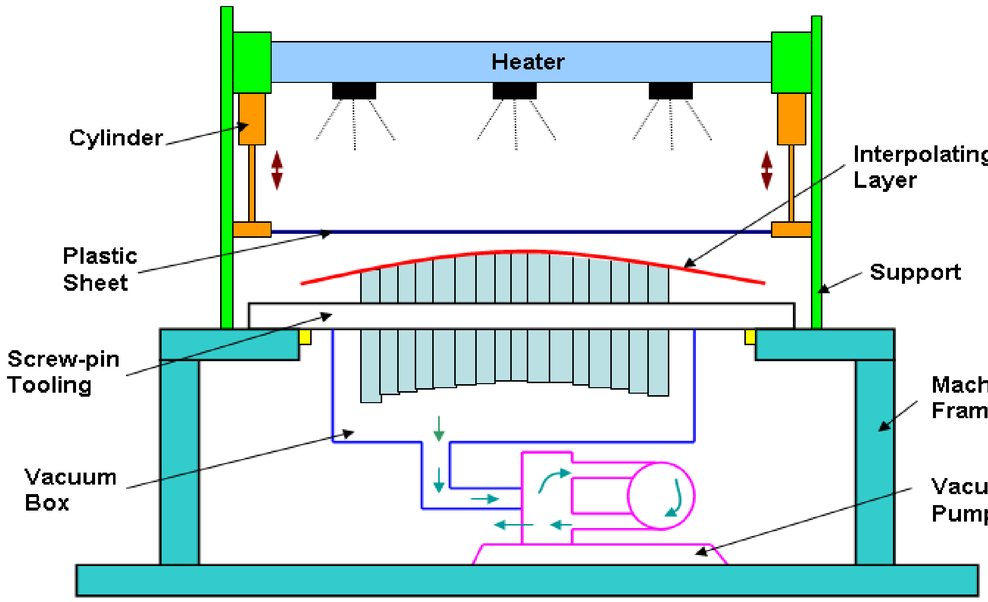
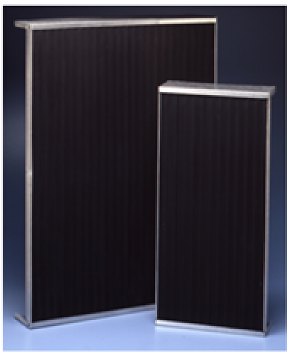


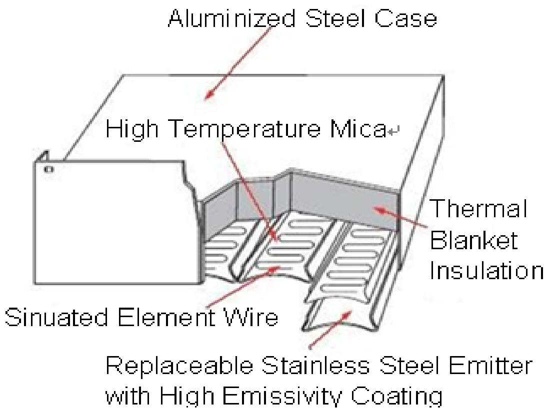
Figure 3-14 Vacuum forming system of HAVES

1. Heater selection

Before vacuum forming takes place, the plastic sheet needs to be heated by a heater. Uniform full surface heat sources that provide even heat over the plastic sheet will be ideal. Radiation heat transfer method is used to head the plastic sheet as the heat is transferred from a high temperature object to a low temperature object via electromagnetic waves. No medium (like a solid or liquid) is required to transfer heat energy and air is generally unaffected due to its transparent nature. It is the most energy efficient way of heating a planar surface (Throne, 1996).

A uniform radiation heater is shown in Figure (3-15); it is generally composed of a frame and several panels. The size of the heater should be smaller than the frame (800mm) and should leave enough space for the heater holder. The radiant heater RAYMAX® 1120 family from Watlow Company is a lightweight, yet sturdy and durable radiant heater panel and is ideal for our application. P2424AX081, a standard part of RAYMAX 1120 part family containing two standard panels, is selected due to its overall size. The detailed specification of P2424AX081 is shown in Table 3-4.





(a) Schematic (b) Internal structure

Figure 3-15 RAYMAX® 1120 radiant heater (Watlow, 2006)

Table 3-4 Parameters of RAYMAX® 1120 radiant heater

Code No.		P2424AX081
Overall Size (mm)	**Width**	619.1
	Length	641.4
Panel size	**Width**	609.6
	Length	609.6
Volts		415v, 3ph
Watts (w)		11520
Watt Density (W/cm^2)		3.1

2. Vacuum pump selection

In order to reproduce the detail features on the screw pin tooling, a vacuum pump is needed to suck the air out from between the heated plastic sheet and the vacuum box. Vacuum pump performance is measured in terms of vacuum levels, achievable flow rates and the cost of the pump. The vacuum level required to form a heated plastic sheet is approximately 0.83 bar (25" Hg); the required air flow rate should ensure rapid moulding before the heated plastic sheet temperature drops below its ideal forming temperature with the time for rapid moulding being about half a minute (C.R.Clarke, 2006). In other words, after the plastic sheet contacts the screw-pin tooling, the air trapped between the pump tank and the screw-pins should be sucked out after about 30 seconds.

As indicated in section 3.6.2, the prototype screw-pin tooling has 19 rows and 20 columns of standard M20 screw-pins, with 300mm length and 2.5mm pitch. As shown in Figure 3-16, let V_b be the volume of vacuum tank, it is:

$$V_b = 600mm \times 570mm \times 360mm = 0.123m^3$$

Initially, around 150mm length out of the 300mm length of screw-pin will be within the tank after shape adjustment, let V_P be the space in the tank occupied by screw-pins:

$$V_p = 370mm \times 300mm \times 150mm = 0.017m^3$$

therefore, the air volume to be sucked by vacuum forming V_a is:

$$V_a = V_b - V_p = 0.123m^3 - 0.017m^3 = 0.106m^3$$

The required air flow rate F_a should be:

$$F_a > \text{Volume/time} = 0.106/30\ m^3/sec$$

Based on 1CFM=4.71947 X10^4 m^3/s, we have:

$$F_a = (0.106/\ 30)/4.71947*10^4 CFM=7.769\ CFM$$

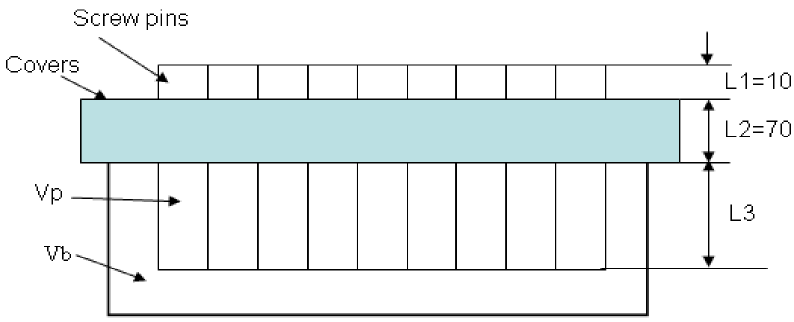


Figure 3-16 Vacuum space before screw-pin adjustment

The vacuum pump is therefore selected based on two parameters: vacuum level (=>25 HG) and flow rate (>7.769 CFM). Several types of pumps are looked into, and according to the performance comparison of vacuum pumps shown in Appendix A.20 made by GAST® Company, a rotary vane pump is selected for plastic sheet vacuum forming mainly due to cost consideration (about 50 percent less for a given displacement and vacuum level). The model 1423-1010-G626X of GAST® rotary vane vacuum pump is selected as part of the design system and its information is listed in table 3-5. The vacuum pump has 25"HG maximum vacuum and 13.2 CFM open air flow. The actual time needed for the vacuum forming is about 26 seconds (calculation details in Appendix A.21), which is the ideal time for the material to be formed before cooling down.

Table 3-5 GAST® rotary vane vacuum pump

Model Number	**Motor Voltage**	**RPM**		**Vac. level**	**Flow rate (CFM)**	**Net Wt. (kg)**
		60 cycles	**50 cycles**			
1423-1010-G626X	200-230	1725	1425	25 HG	13.2	24.7

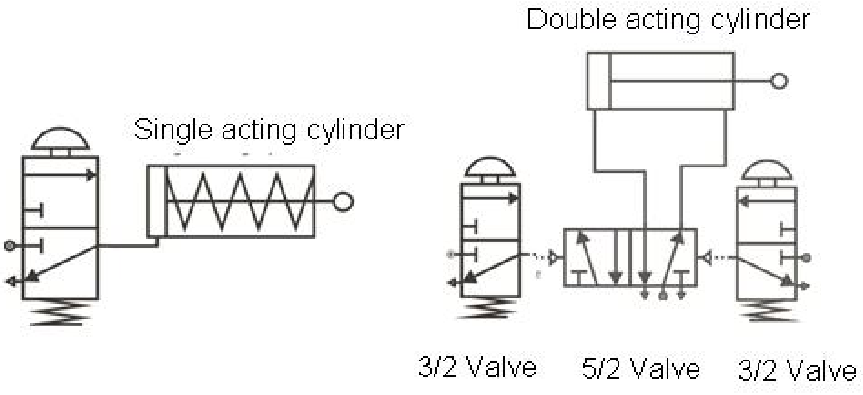
3. Selection of lifting cylinder

Plastic sheets need to be moved at two height levels for heating and vacuum forming as shown in Figure 3-14. A pair of pneumatic cylinders are employed for that purpose. There are generally two types of pneumatic cylinder: single acting cylinder and double acting cylinder as shown in Figure 3-17. In a single-acting cylinder, compressed air is used to push a piston out, and a spring to push it in again. The movement of a single-acting cylinder is normally controlled by a three-port valve - a type of simple switch which governs the flow of air. Double acting cylinders use the force of air to move in both extended and retracted strokes. They have two ports to allow air in, one for outstroke and the other for instroke. Two 3/2 port valves and one 5/2 valve are needed for the double acting cylinder.

The choice between a single acting cylinder and a double acting cylinder is based on whether or not the spring back of the cylinder is sufficient for the pistons of the two cylinders to retract to the original position, since the pistons of the cylinders are moving in a vertical direction. Even when retracting, they need to overcome the weight of the plastic sheet, and the clamping holder which is very heavy, therefore, a single acting cylinder is not feasible and two double acting cylinders are thus needed. The selection of a standard cylinder would be based on the load it can withhold and the stroke distance (distance between original position and fully extended position).

According to the clamp frame prototype shown in Figure 3-18, the frame movement distance is about 450mm; the author set the required stroke distance as 500mm. The total weight of clamp frame, support frame and plastic sheet is about 60kg, and each cylinder piston rod needs to take 30kg.

Typical safety factor of the cylinder 1.3 is used by the author, so the force used in calculation is about 40kg.



(a) Single acting cylinder (b) Double acting cylinder

Figure 3-17 Comparison of single and double acting cylinder

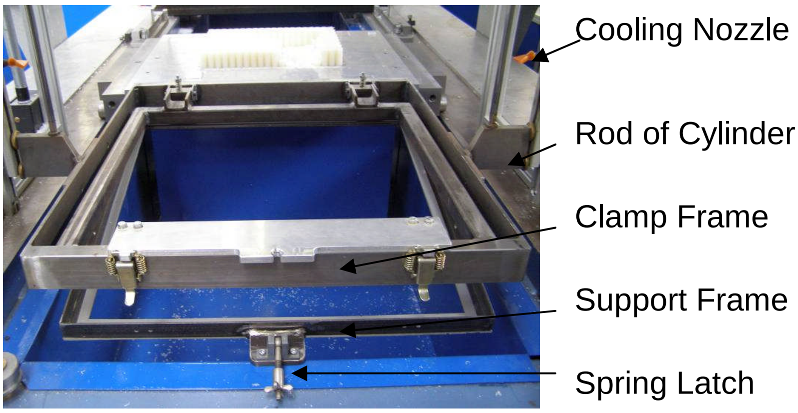


Figure 3-18 Clamping and movement suites for plastic sheet

According to the theoretical relationship between the thrust (outstroke) or pull (in stroke) of a cylinder and the effective area of the piston by the working pressure, the minimum size of the cylinder bore is 28.85mm (Appendix A.22). Based on the manual of Norgren cylinders (2006), the corresponding minimum diameter of the standard cylinder should be Φ32mm. Thus, a double acting, side port and flat end Norgren roundline cylinder RT/57232MF/500 is selected. Its parameters are listed in Appendix A.22.

4. Control structure

A PLC controller is needed in order to control the heater, pump and positioning of the plastic sheet. The purpose of the heater control is to set correct temperature and heating time on the heater to ensure that the plastic sheet is in the state ready for vacuum forming. It is conducted by using a thermo coupling sensor and displacement sensor and closed loop control system. The thermo coupling sensor is used to measure the temperature on the surface of the plastic sheet. The displacement sensor is employed to control the material sag of the plastic sheet. The closed loop control system will switch the heater on and off to maintain the heating temperature.

When a plastic sheet is heated the material will start to melt and the sheet will adopt an arc shape. The extent of the arc is an indication of the readiness of the material for the vacuum forming. Therefore the displacement sensor as shown in Figure 3-19 is used to measure the amount of drop the material has. Once the material drop achieves the pre-assigned value, the sensor will send a signal to the controller, the cylinders will start to move the plastic sheet down, and the pump will be turned on for the vacuum forming process.

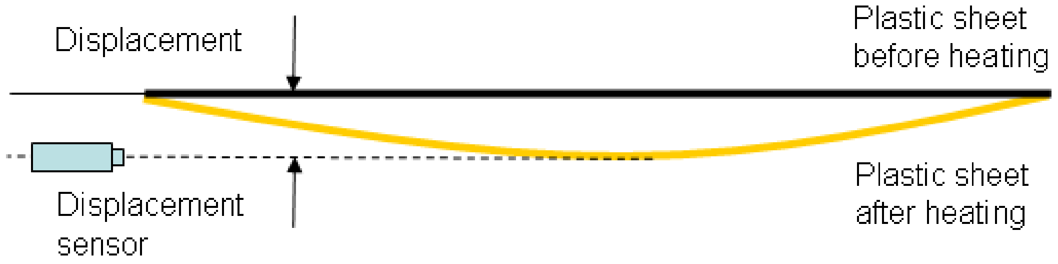


Figure 3-19 Displacement sensor

Figure 3-20 shows the control configuration of the vacuum system. A Watlow 1120 radiant heater is connected to the system via a DIA-A-MITE solid-state power controller. A Watlow PID controller 1/16 DIN driven by 240V power is used to remote control the heater temperature and the displacement sensor. The heater temperature is monitored by a thermocouple mounted under the heater. A DIN Rail Mounting Component Box System is applied to integrate the GAST rotary vane vacuum pump into the system. A PLC controller driven by 24V power is assembled with the control paned to connect/disconnect power, turn on/off the heater, switch on/off vacuum pump, set manual/auto operation method, and also it works together with two-way compact solenoid valves and pneumatic valve to control the movement of the Norgren roundline cylinder.

As part of the control system, the control panel as shown in Figure 3-21 helps users to remotely control the heater, vacuum pump and cylinders. There are five buttons, one heater light and one temperature controller in the control panel and each button has two working conditions:

1) Cylinder button: 0 cylinder up, 1 cylinder down;

2) Vacuum pump button: 0 vacuum forming off, 1 vacuum forming on;

3) Heater button: 0 heater off, 1 heater on;

4) Start button: 0 starts off, 1 start on;

5) Operation button: 0 manual control, 1 auto control.

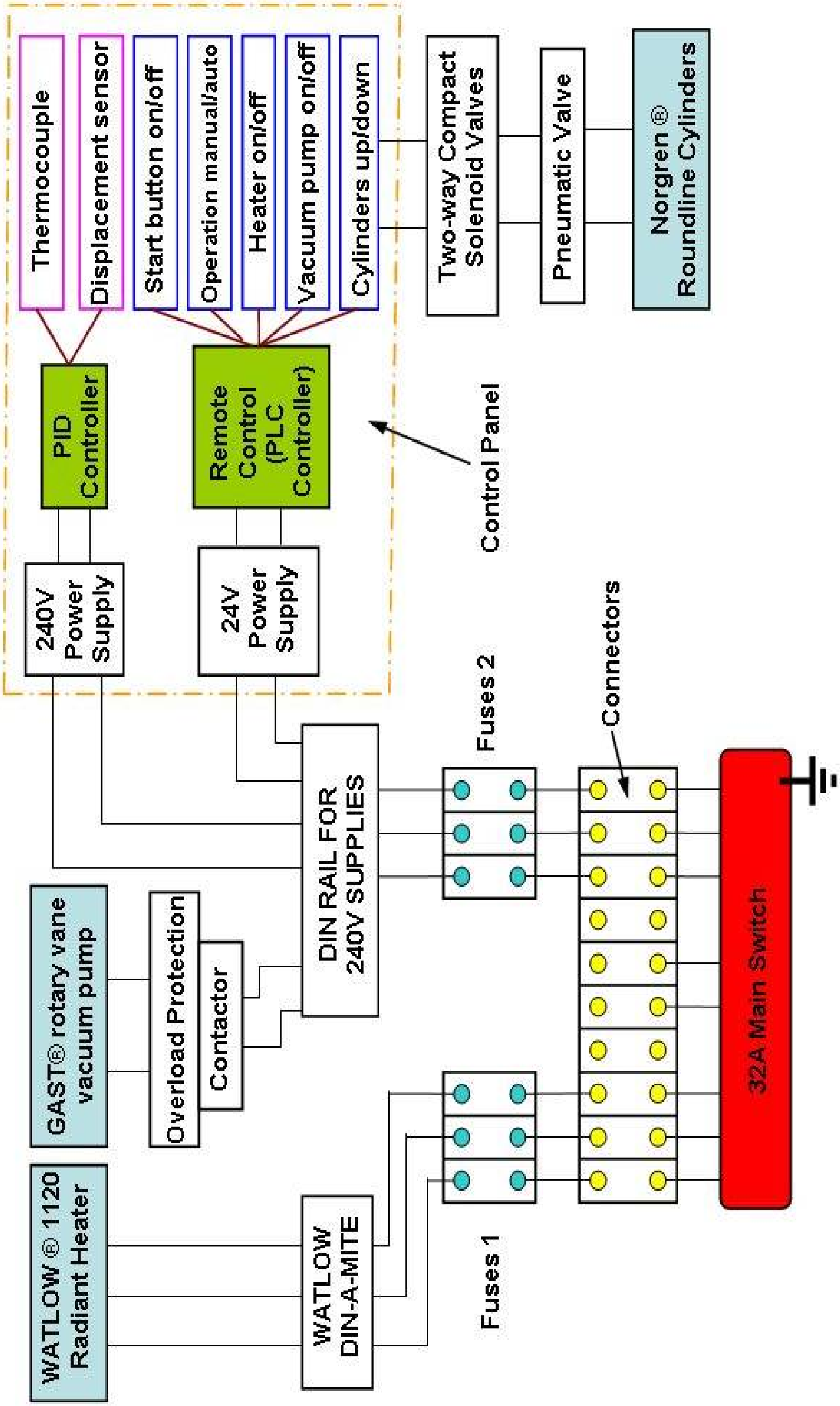


Figure 3-20 Concept structure of vacuum forming control system

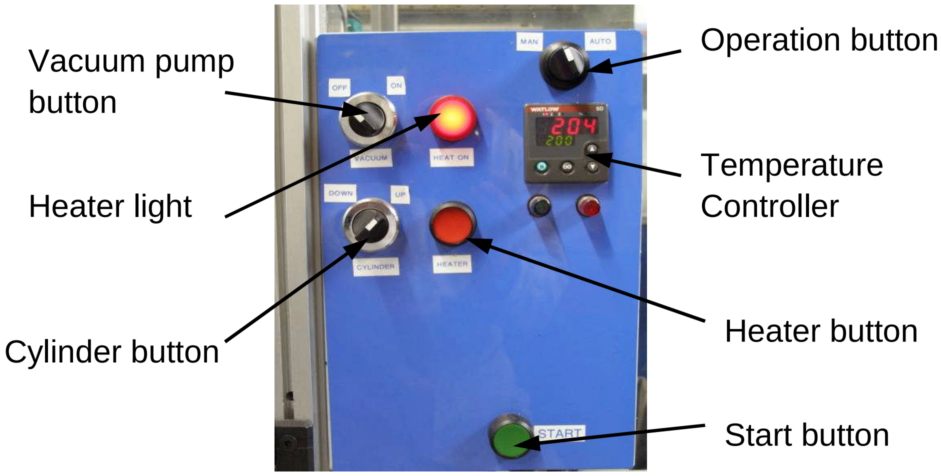


Figure 3-21 Control panel for vacuum forming system of HAVES

3.7 Digitizing and inspection device

3.7.1 GOM ATOS II-400 digitizing system

In order to establish the relationship between the real component produced by vacuum forming and its CAD model, an efficient 3D coordinate measuring device is needed to digitize the component surface. A GOM ATOS (Advanced Topometric Sensor) II-400 digitizing system is selected to fill this requirement and works as part of the HAVES test bed. The GOM ATOS II-400 digitizing system is a non-contact, high mobility digital optical measuring system, which can efficiently be used for design, CAD construction, NC manufacturing, and quality assurance (GOM mbH, 2004).

As shown in Figure 3-22, the GOM ATOS II-400 digitizing system consists of the following units: a sensor head with a fringe projector and two high resolution cameras, a stand for secure and steady holding of the sensor head, a control unit for the power supply and for controlling the sensor head as well as PC interface, a rotary table for moving the object to be measured and

ATOS II-400 system application software with high performance computer (no display). The stand includes one horizontal axis and one vertical axis, and the horizontal axis can be rotated around the vertical axis. The camera head is mounted on the tip of the horizontal axis, and it can be transformed by sliding along two axes and rotating around the vertical axis.

The ATOS II-400 digitizing system is able to perform the measurement quickly and with a high local resolution. Each single measurement generates up to 1.3 million data points. The individual measurement images are merged via reference points and the measured data are polygonized and made available as point clouds, sections or polygon mesh. A few formats' CAD model (Appendix A.23) can be imported in the ATOS II-400 software and compared with the measured data. The file extensions that can be exported by the evaluation mode of ATOS II 400 system include IGES, VDA, STL, etc. (Appendix A.23).

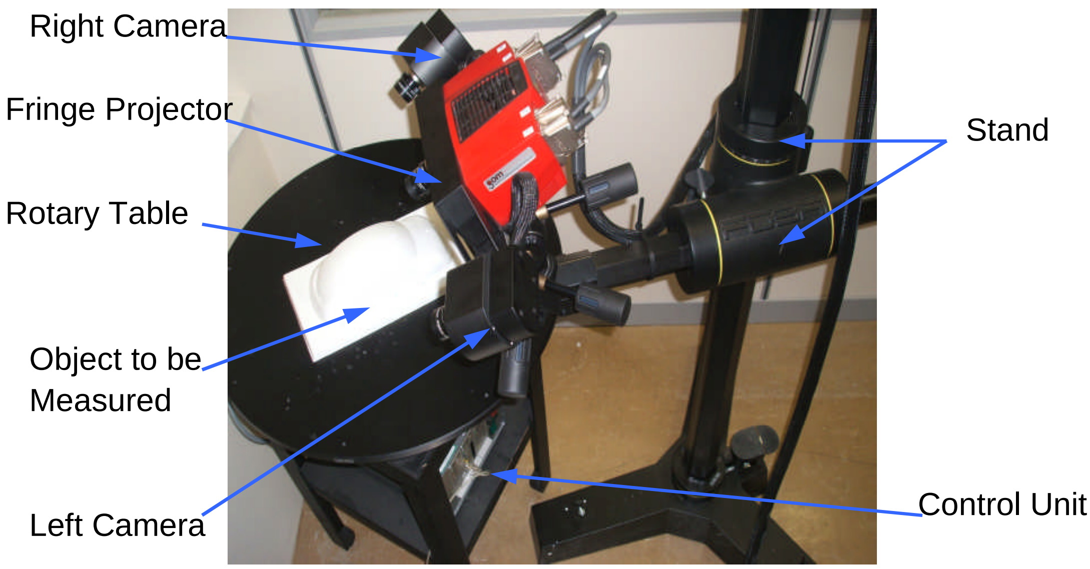


Figure 3-22 GOM ATOS II-400 digitizing system

3.7.2 Digitizing process

To carry out a standard measuring project using the ATOS II-400 system the developed digitizing process is necessary and is shown in Figure 3-23 and explained in the following paragraphs. The digitizing process is divided into three stages: measurement preparation, object measurement and post processing. Each stage includes several process steps, and a digitized surface model in IGES or STL format can be exported at the end of the measurement post processing.

In the preparation stage, the ATOS software is started and the control unit is switched on. To optimise the scan surface for overly dark, transparent or shiny components, the surface is sprayed with titan dioxide powder. The choice of reference point diameter depends on the measuring volume and should be identified by the ATOS system (Appendix A.23). The reference points which are placed on the object to be measured and/or in its vicinity can also help the individual measurements to be transformed into one common coordinate system. The selection of the sensor depends on the available sensor type, the size of the measuring object and the desired resolution of the measuring points (Appendix A.23). The angle relations of the lenses, the focus and the aperture need to be adjusted prior to initial commissioning of the ATOS system. The prepared system is calibrated by means of calibration panels.

In the measurement stage, a project is created in the ATOS software and the object is scanned with one or several measurements. The 3D data of the individual measurements are then available as point clouds. The unwanted measuring data can be deleted in a 3D object window and the left point cloud is converted into mesh triangles without overlapping.

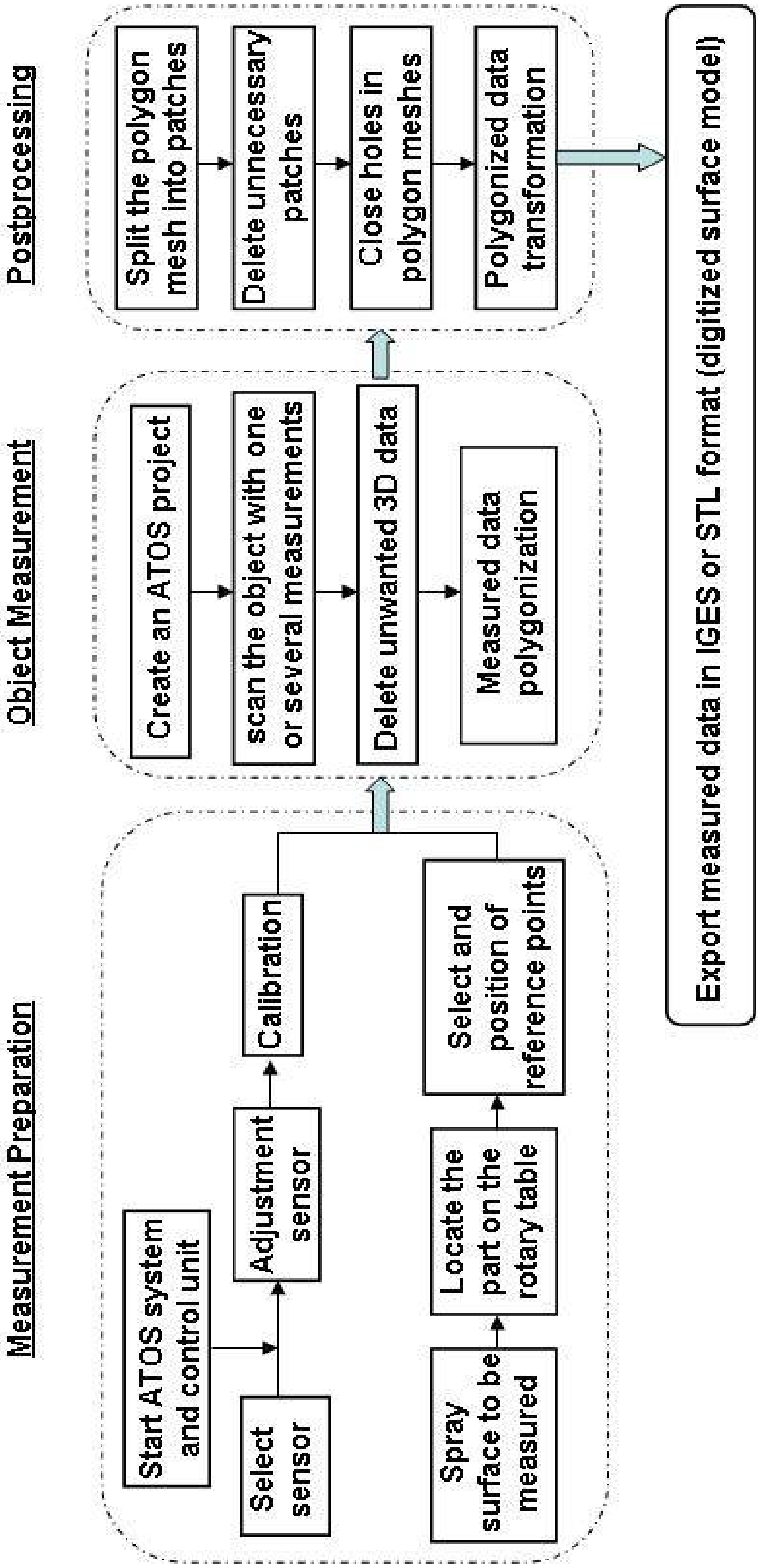


Figure 3-23 Digitizing process developed for ATOS II 400 system

The post-process stage is to further process and optimize the polygonized data. The polygon mesh is split into patches and the data of fixture, background or reference points are deleted. Holes in the polygon meshes are filled. The polygonized data are transformed into a new coordinate system which is defined with the help of 3D points or primitives. Thus, the ATOS data are in a defined coordinate system and ready for use in subsequent systems.

3.7.3 Digitizing component

In using the optical measuring system ATOS (Advanced Topometric Sensor), the geometry of objects that are produced by screw pin reconfigurable tooling can be digitized quickly with high local resolution and compared with the master data for quality evaluation. The ATOS systems consist mainly of the sensor comprising of two cameras, a projector and stand, the control unit for the sensor head and a high-performance PC.

For the digitization, markers are put on the object. The 3D-coordinates of these markers are determined using a high resolution digital camera and the ATOS software. The Project Mode of the ATOS software is used to create measuring projects, adjust and calibrate the sensor and record the measurements. The object to be measured is scanned by means of several individual measurements, and the transformed 3D data of these individual measurements are then available in a common 3D view.

3.7.4 Evaluation of components

The Evaluation Mode of the ATOS software is used to inspect the components produced by reconfigurable tooling. The original master data are superimposed on the measuring data of the digitized parts and compared with them. Based on this comparison, the user may check whether the tolerances have been met or in which area the part is deformed. The deviations can be displayed by means of colour polygon meshes or surface control points for defined measuring points.

3.8 Completed HAVES test bed

The finished HAVES is shown in Figure 3-24. Each functional modular and its control are displayed. The purchased components and materials are listed in Appendix A.24.

Figure 3-24 The completed HAVES

3.9 Gantry machine system calibration

3.9.1 CNC machine test

The aim of the test is to evaluate the accuracy of the constructed HAVES test bed. There is a series of evaluation procedures including basic evaluations, spindle/table travel evaluations and machining evaluations which need to be performed for commercial CNC machines, and each evaluation includes several technique parameters such as accuracy, cutting power, table flatness, squareness, etc. To simplify the evaluative procedures in this prototype, only circularity and squareness of axes are evaluated in this Chapter while accuracy and repeatability of axes will be discussed in Chapter 6 as part of the experiments.

1. Circularity

The circularity is the difference between the maximum outward deviation and the maximum inward deviation from the best-fit circle or arc through the captured data points (Renishaw, 1993). The best-fit circle is the best circle that passes through the captured data and can be shown in analysis plots by a circle of long dashed lines through the captured data. The larger the circularity value, the worse the performance of the machine.

The circularity of the HAVES test bed is tested by a Renishaw ballbar system as shown in Figure 3-25. The ballbar kit includes magnetic centre mount, ball joints, transducer, ballbar extensions (50mm, 150mm and 300mm, to allow various test diameters), serial interface unit, magnetic tool cup and ballbar software. During the test, data will be captured as the machine moves the Ballbar in the XY plane through a 360° data capture arc in a clockwise direction round the centre mount. The ballbar length is 150mm, axes' feedrate 3000mm/min, and sampling rate 18.75 per sec. The corresponding programme for the test is listed in Appendix 4-25. A polar plot of the captured data from Ballbar analysis software is shown in Figure 3-26.

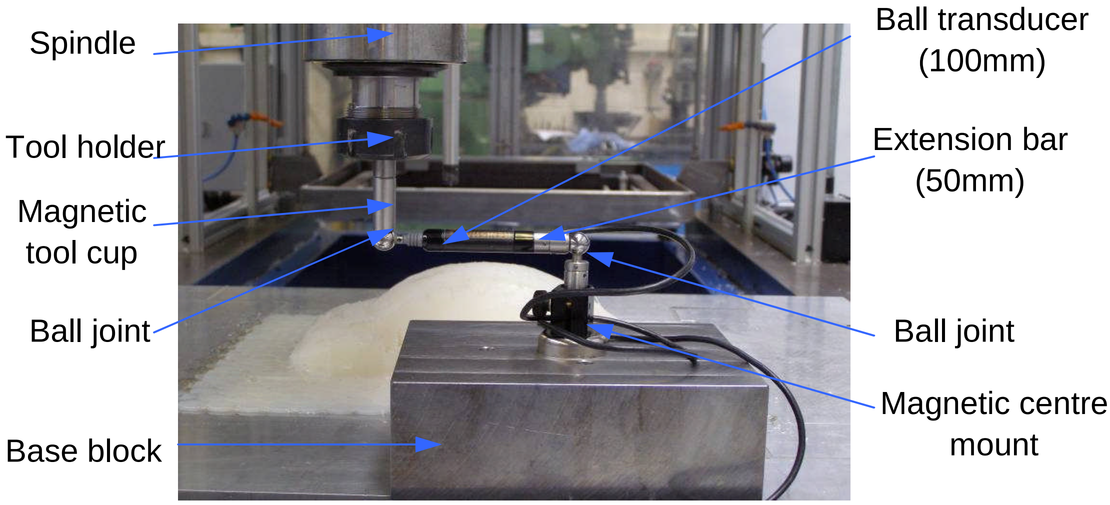


Figure 3-25 Ballbar system set up for calibration

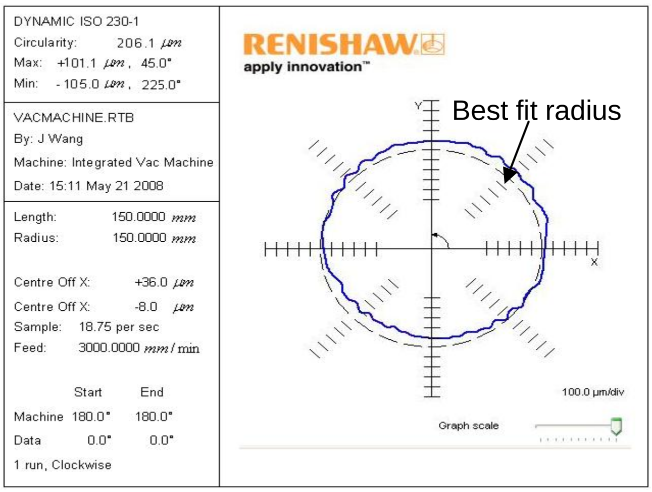


Figure 3-26 Data capture of the gantry machine circular test

The test results from the circularity are shown in table 3-6. The average circularity calculated according to ISO 230-1 is 218.9 μm; the maximum outward deviation and the maximum inward deviation from the best-fit circle are 124.6 μm in test 4 and -113.5 μm in test 5 separately. The circularity deviation of the HAVES test bed is larger than that of CNC machines (about 50 μm) on the market, but it does not effect the screw-pin tooling adjustment and the following machining, and is acceptable by experiments to be performed in Chapter 5.

Table 3-6 Circularity test results

TEST	Max. outward deviation (um)	Max. inward deviation (um)	Circularity (um)
1	+101.1	-105.0	206.1
2	+107.3	-102.9	210.2
3	+113.5	-109.3	222.8
4	+124.6	-98.4	223.0
5	+117.8	-113.5	231.3
Avg.	112.9	-106.0	218.9

2. Squareness

The squareness is the angle between the two axes in the test plane, less 90^0. Practically, if a 1 metre square block is machined, as indicated in Figure 3-27 below, the squareness error is equal to θ (Renishaw, 1993).

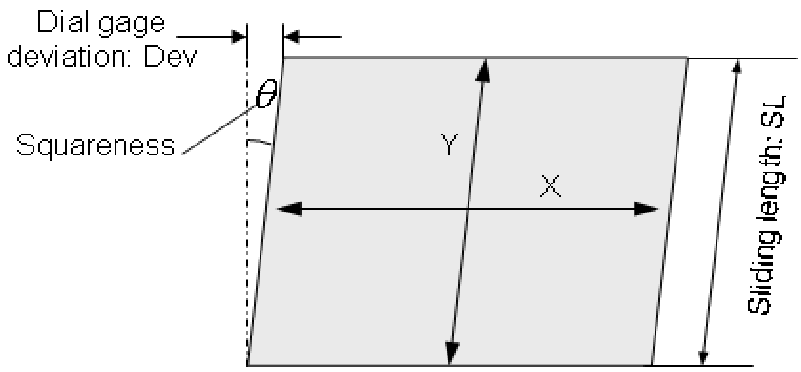


Figure 3-27 Squareness error

The squareness is measured by sliding on a 450mm fixture base with a dial gauge which is mounted on the machining tool head through a magnetic base. The sliding speed towards each target position is 500mm/min and sliding length SL is 400mm. The tests are repeated at five different locations in the machine's working volume. The deviations of the readings of the dial gauge are recorded in Table 3-7 and its corresponding squareness is calculated by:

$$Sin\theta = Dev / SL$$

thus:

$$\theta = Arc\sin\frac{Dev}{SL}$$

The table 3-7 shows the squareness between x and y planes of the HAVES test bed. The average dial gauge deviation is 1.10mm, and the corresponding squareness is 0.15°; the minimum dial gauge deviation is 0.86mm and its squareness is 0.12°; the maximum dial gauge deviation is 1.36mm and its squareness is 0.19°. The squareness deviation of the HAVES test bed is larger than that of CNC machines (about 56 μm/m for the UK's Bridgeport machine) on the market, but it does not effect the screw-pin tooling adjustment and the following machining, and is acceptable by experiments to be performed in Chapter 5.

Table 3-7 Squareness test results

TEST	**Dial gauge deviation (mm)**	**Squareness (degree °)**
1	1.20	0.17
2	1.08	0.11
3	1.36	0.19
4	0.86	0.12
5	1.02	0.15
Avg.	1.10	0.15

3.9.2 Heater calibration

In order to heat a plastic sheet correctly and obtain the best vacuum forming results, it is necessary to calibrate the WATLOW Heater and build a relationship between the temperature of the heater controller and the real temperature of the plastic sheet. The set up of the calibration experiment for the WATLOW Heater as shown in Figure 3-28 comprises of a test plate with holes, 8 K-Type Thermocouples, PICO TC-08 Thermocouple Data Logger and software, the WATLOW Heater and its controller.

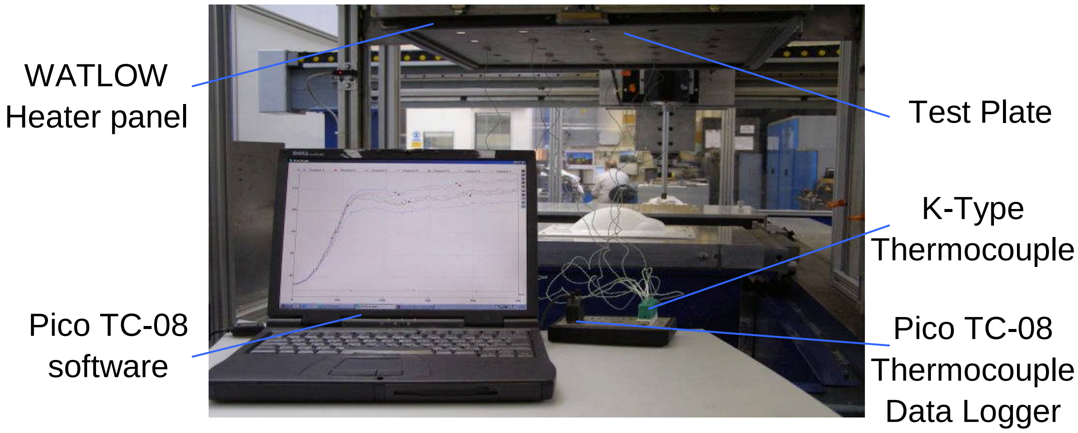


Figure 3-28 Experiment set up for WATOW heater calibration

The Pico TC-08 is a complete thermocouple input device for use with a computer (Pico, 2005); it is used to collect and analyse data from the K-Type thermocouple. The experiment is to discover the temperature evolution of each K-Type thermocouple in the test plate at different control set temperatures. The forming temperature of most thermoplastic is between 140°C and 200°C; the control set temperature should be higher than the forming temperature because of the 50mm distance between the heater thermocouple and the plastic sheet. The selected controller setting temperature is between 200°C and 380°C. The total record time is 500 seconds and the data are captured every 2 seconds for each experiment.

The positions selected for temperature measurement are shown in Figure 3-29. Position 1 is the centre of the sheet and positions 2 to 5 are located in the middle area of the sheet; position 6 is situated on the side area of the sheet and position 7 is located outside of the sheet. In PICO system, Channel 1 to channel 6 stand for thermocouple temperatures of point 1 to point 6 separately, and channel 7 stands for ambient temperature (Appendix A.26).

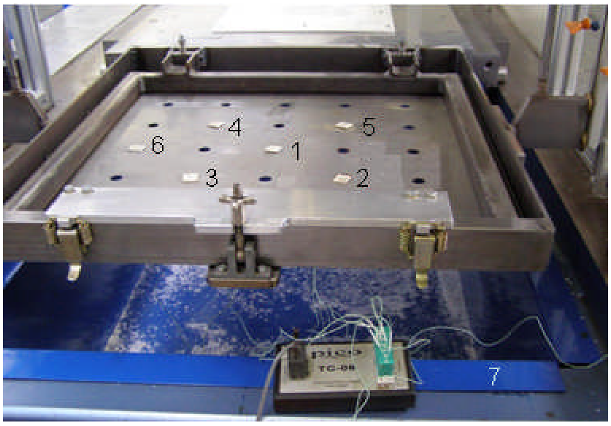


Figure 3-29 Point locations for WATOW heater calibration

Figure 3-30 shows the temperature evolution of testing points in the test plate when the heater controller temperature is set at 320° C. For the first 180s of the heating, the temperature of the test positions showed a sharp rise from environment temperature. There was a steady increase after 180s. The temperature at 180s can be called the critical inflexion temperature (C.I.T.). Among heated thermocouples, position 1 has the highest C.I.T. temperature and position 6 has the lowest C.I.T. temperature. The C.I.T. temperatures of position 2 to 5 are nearly the same and its average temperature is called working temperature on the plastic sheet which is between 130°C and 165°C in Figure 3-30.

Each heater controller setting temperature has its corresponding plastic sheet working temperature and their comparison is listed in table 3-8. These calibration results are used as reference in experiments performed in Chapter 5.

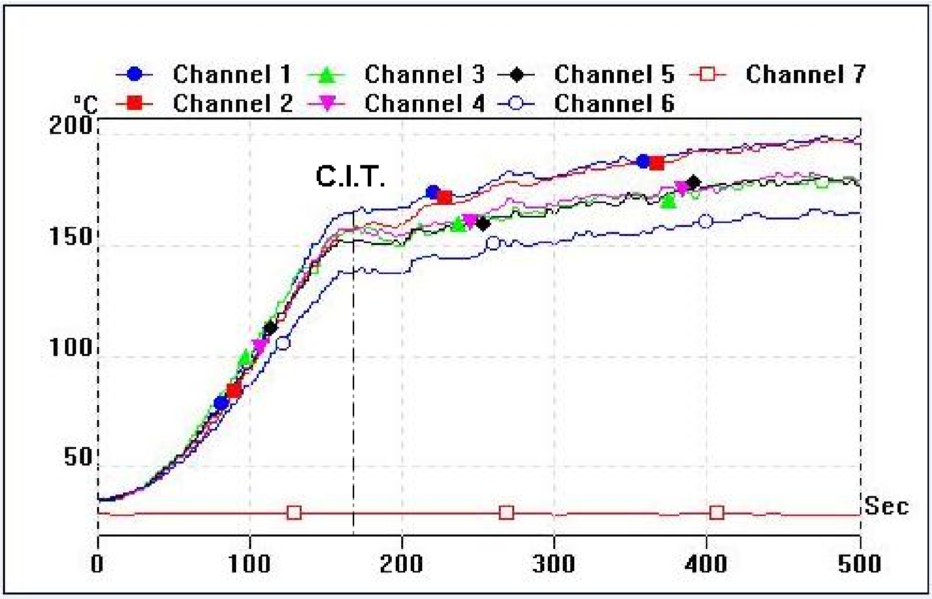


Figure 3-30 Temperature evolution of thermocouples in the test plate

Table 3-8 Comparison table of heater calibration

Heater controller setting temperature (°C)	**Working temperature on plastic sheet (°C)**
200	85
210	90
220	97
230	101
240	105
250	112
260	120
270	125
280	130
290	138
300	145
310	150
320	155
330	160
340	170
350	180
360	190
370	196
380	200

3.10 Summary

This chapter illustrates the concept of the SPT and proposes the development architecture of the HAVES test bed based on the SPT. This chapter has also analysed system development basic requirements of the HAVES test bed which include screw-pin adjustment, surface machining, vacuum forming and component evaluation. The conceptual design is presented and a gantry machine is selected to be retrofitted to construct the proposed system. The retrofit contents include a dual tool head, a machine bridge, SPT, CNC control, spindle and vacuum forming. The GOM ATOS II-400 digitizing system is employed to evaluate the components and the system communicates with the HAVES test bed by internet. The selection of some key components of the system such as driving motors, the heater, the vacuum pump, etc. are also illustrated. On the finished HAVES system, the CNC axes' circularity and squareness are tested and its heater's calibration is performed.

CHAPTER 4

METHODOLOGY FOR AUTOMATIC SHAPE ADJUSTMENT OF SCREW-PIN TOOLING

4.1 Introduction

The previous chapter explained the hardware construction of the vacuum forming machine using screw-pin tooling. This chapter will focus on the support software development which enables screw-pin adjustment to represent the different component geometry with minimal human interference. Firstly, procedures and methodology of the digital tooling generation are introduced. The methodology treats the adjustment of screw-pin tooling as a mapping process between component surface model and screw pin array pattern. Secondly, surface models are imported into FEA software (i.e. ABAQUS/CAE) to generate a customized analysis input file, which consists of many thousands of elements and nodes of information needed by this kind of research work. General layout, main instructions and creation procedures of the customized analysis input file are also introduced. Thirdly, a point processor is constructed to store digital screw pin tooling. Finally, a tooling shape controller is developed and applied to generate the CNC program and simulation program.

4.2 Procedures of digital tooling generation

In order for the screw-pin tooling to be reconfigurable for different component geometry with minimal human interference, it is important for the screw pins to be automatically adjusted to appropriate positions to represent different component geometry. The purpose of the chapter is to develop the software support system to enable reconfigurable tooling.

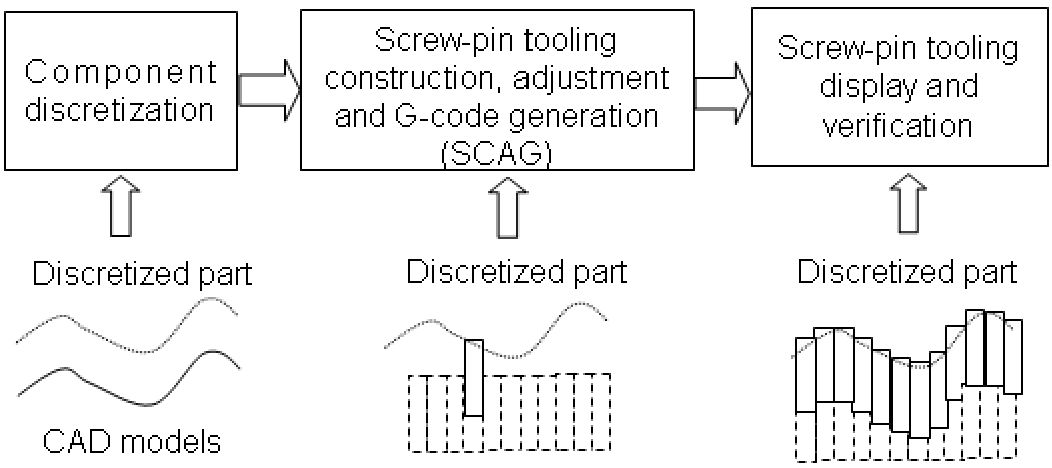


Figure 4-1 Procedures of digital tooling generation

As shown in Figure 4-1, the support software system includes three models: component discretization, screw pin tooling construction, adjustment and G code generation (**SCAG**), and screw-pin tooling display and verification (**SPT-Demo**). The Component discretization model is discretizes components (CAD model or physical model) in order to obtain the component geometry information; The SCAG model is developed to automatically adjust the screw-pin position to represent the component geometry; The SPT-Demo is used to generate 3D screw-pin geometry within commercial CAD software, so that user can assess whether or not the position of the screw pin can represent the component geometry.

4.3 Methodology for shape control

The adjustment of reconfigurable pins according to component geometry is a mapping process from the component surface model to the pin array pattern. A detailed and complete description of this mapping process needs to be made because of the following requirements:

- No expressions are given for the general mapping process;
- There is little research addressing the technique that can be widely used to find each pin position in different types of reconfigurable tooling;
- There is a lack systematic knowledge for supporting software development of tooling shape control.

The mapping process description includes three components: surface and point cloud model description, screw pin tooling description and adjustment description.

In the following description, the centre of the coordinate system on the component is put on the centre bottom position as shown in Figure 4-2 and is aligned with the coordinate system of the screw-pin array pattern.

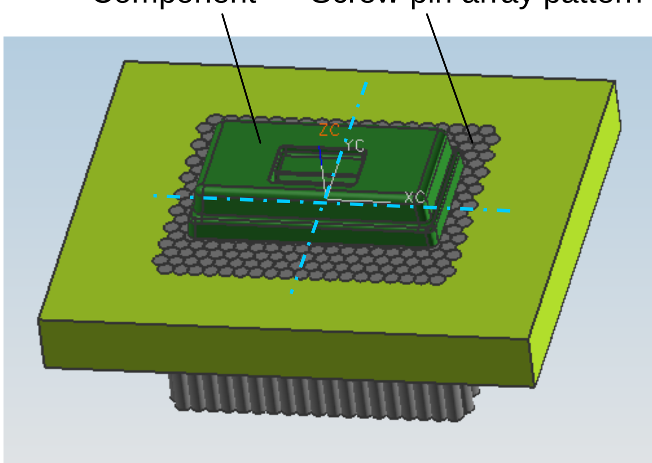


Figure 4-2 Coordinate systems of component and SPT

4.3.1 Design model description

1. Surface model description

A general 3D surface is described by NURBS surface (Piegl, 1991) as follows:

$$S(u,v)=\sum_{a=0}^{l}\sum_{b=0}^{k}R_{a,b}(u,v)P_{a,b}=\frac{\sum_{a=0}^{l}\sum_{b=0}^{k}\omega_{a,b}P_{a,b}B_{a,p}(u)B_{b,q}(v)}{\sum_{a=0}^{l}\sum_{b=0}^{k}\omega_{a,b}B_{a,p}(u)B_{b,q}(v)} \quad (4\text{-}1)$$

Where

S: geometry model surface;

$R_{a,b}(u,v)$: rational basis functions;

$P_{a,b}$: 3D control points;

$\omega_{a,b}$: weights of $P_{a,b}$;

l and k: numbers of control points in the u and v directions;

$B_{a,p}$: normalized B-splines of degree p in the u directions;

$B_{b,q}$: normalized B-splines of degree q in the v directions.

Based on the above formula of principle of surface modeling, an arbitrary complex three-dimensional surface model can be formed by using $m\times n$ array pattern NURBS patches and this can be described in a mathematical form as:

$$\mathbf{S}=\mathbf{S}^{11}\cup\mathbf{S}^{12}\cup\ldots\cup\mathbf{S}^{1n}\cup\ldots\cup\mathbf{S}^{ij}\ldots\cup\mathbf{S}^{mn}=\cup_{\mathbf{i=1}}^{\mathbf{m}}\cup_{\mathbf{j=1}}^{\mathbf{n}}\mathbf{S}^{\mathbf{ij}} \quad (4\text{-}2)$$

Where S^{ij} denotes a surface patch of geometric model. For example, a car surface model and its component patches as demonstrated in Figure 4-3.

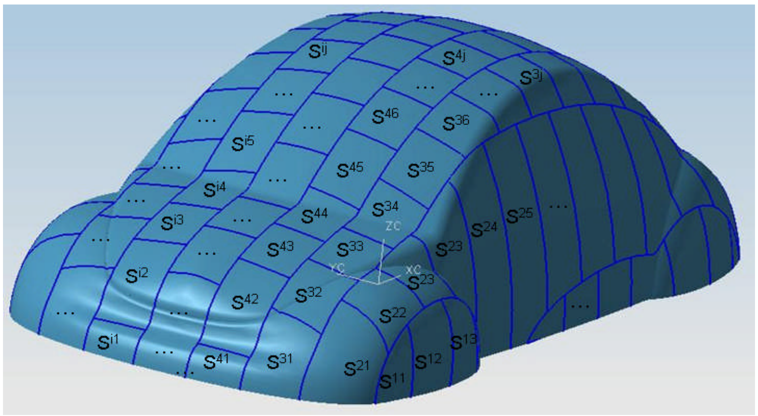


Figure 4-3 Surface model and component patches

2. Point cloud model

The component surface S needs to be represented by discrete point cloud N; the discretization process is written as:

$$\mathbf{S} = \mathbf{N} \tag{4-3}$$

The point cloud model can be expressed using point sets as follows:

$$\mathbf{N} = \mathbf{N^{11}} \cup \mathbf{N^{12}} \cup \cdots \cup \mathbf{N^{ij}} \cdots \cup \mathbf{N^{mn}} = \cup_{\mathbf{i=1}}^{\mathbf{m}} \cup_{\mathbf{j=1}}^{\mathbf{n}} \mathbf{N^{ij}} \tag{4-4}$$

$$\mathbf{N^{ij}} = \mathbf{N_1^{ij}} \cup \mathbf{N_2^{ij}} \cup \cdots \cup \mathbf{N_e^{ij}} \cdots \cup \mathbf{N_t^{ij}} = \cup_{\mathbf{e=1}}^{\mathbf{t}} \mathbf{N_e^{ij}} \tag{4-5}$$

Where $N^{ij} \subset S^{ij}$ and $N_e^{ij} \in N^{ij}$, it can be obtained that $N_e^{ij} \in S^{ij}$; N represents all the nodes that build the surface model; N^{ij} represents nodes in the ith row and jth column surface area; N_e^{ij} represents a node in the ith row and jth column surface area; t represents the total number of nodes in the N^{ij} point set.

4.3.2 Screw pin tooling description

For a tooling comprised of $m \times n$ screw pins, the working surface of the tooling S_T is represented by $m \times n$ discrete points and can be expressed as a function of the heights of all screw pins:

$$S_T = f1(P_{11}, P_{12}, \cdots, P_{ij}, \cdots, P_{mn}) \quad i \in [1, m], j \in [1, n] \tag{4-6}$$

$f1$ is a mapping function from screw pin domain to tooling working surface domain. Since both S_T and P_{ij} are discrete, we can get:

$$S_T = S_T^1 \cup S_T^2 \cup \cdots \cup S_T^{ij} \cdots \cup S_T^{mn} = \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} S_T^{ij} \tag{4-7}$$

$$\begin{aligned} f1(P_1, P_2, \cdots, P_{ij}, \cdots, P_{mn}) &= f1(P_1) \cup f1(P_2) \cup \cdots \cup f1(P_{ij}) \cdots \cup f1(P_{mn}) \\ &= \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} f1(P_{ij}) \end{aligned} \tag{4-8}$$

Where P_{ij} represents the screw pin at the ith row and the jth column in the array pattern; S_T^{ij} is the z-coordinates of the screw pin sampling points, and it represents part of the working surface of the tooling. From Equation (4-7) and Equation (4-8), it can be obtained:

$$S_T^{ij} = f1(P_{ij}) \tag{4-9}$$

$$S_T = \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} S_T^{ij} = \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} f1(P_{ij}) \tag{4-10}$$

4.3.3 Adjustment description

The adjustment of screw pin tooling from one component surface model to another includes two steps:

STEP1, calculate the final screw pin heights according to design model;

STEP2, determine the move distance of each screw pin, and adjust it to the desired shape.

1. Screw pin height calculation

By sampling the spatial surface S , the shape surface in screw pin tooling can be expressed with Equation (4-11):

$$S_T = f2(S) \tag{4-11}$$

Where $f2$ is geometry mapping function from component surface models to screw pin tooling working surface. Substitute Equation (4-3), (4-4), (4-5) into Equation (4-11), the S_T can be expressed as:

$$\begin{aligned} S_T &= f2(N) \\ &= f2(\bigcup_{i=1}^{m} \bigcup_{j=1}^{n} N^{ij}) \\ &= f2(\bigcup_{i=1}^{m} \bigcup_{j=1}^{n} (\bigcup_{e=1}^{t} N_e^{ij})) \end{aligned} \tag{4-12}$$

Substitute Equation (4-10) into Equation (4-12),

$$\begin{aligned} \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} f1(P_{ij}) &= f2(\bigcup_{i=1}^{m} \bigcup_{j=1}^{n} (\bigcup_{e=1}^{t} N_e^{ij})) \\ &= \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} f2(\bigcup_{e=1}^{t} N_e^{ij}) \end{aligned} \tag{4-13}$$

Then we obtain:

$$f1(P_{ij}) = f2(\bigcup_{e=1}^{t} N_e^{ij}) \tag{4-14}$$

The following equation can be derived:

$$P_{ij} = f1^{-1}(f2(\bigcup_{e=1}^{t} N_e^{ij})) \tag{4-15}$$

From Equation (4-15), $f1^{-1}(f2)$ is defined as a mapping function from point cloud domain to screw pin height domain. It can be detailed according to screw pin tooling application methods as follows:

$$P_{ij} = \begin{cases} Max(\bigcup_{e=1}^{t} N_e^{ij}) \ ; & \text{Sacrificial application} \\ Min(\bigcup_{e=1}^{t} N_e^{ij}) \ ; & \text{Filler application} \\ Mid(\bigcup_{e=1}^{t} N_e^{ij}) \ ; & \text{Centre line} \end{cases} \tag{4-16}$$

The application methods of screw pin tooling will be introduced in Chapter 5.

2. Adjustment distance determination of screw pin tooling

Adjustment means for adjusting the axial position of each screw pin from their current position to a new one, such that the upper surfaces of the elements define approximately the said desired surface contour. Let S_n represent new component geometry; let S_c be the current component geometry; let ΔP_{ij} be adjustment distance of P_{ij}, let $f3$ represent a mapping function from S_c to S_n; and let S_T^n represent screw pin tooling working surface used to produce S_n; Then we can obtain:

$$S_n = f3(S_c, \Delta P_{ij}) \tag{4-17}$$

$$\Delta S_T = S_T^n - S_T^c \tag{4-18}$$

ΔS_T is also expressed as:

$$\Delta S_T = \Delta S_T^{11} \bigcup \Delta S_T^{12} \bigcup \cdots \bigcup \Delta S_T^{ij} \cdots \bigcup \Delta S_T^{mn} = \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} \Delta S_T^{ij} \tag{4-19}$$

S_T^c represents screw pin tooling working surface used to produce S_c; ΔS_T represents the difference between S_T^n and S_T^c.

Substitute Equation (4-9) into Equation (4-18), ΔS_T can be written as:

$$\begin{aligned}\Delta S_T &= (\bigcup_{i=1}^{m} \bigcup_{j=1}^{n} f1(P_{ij}^n)) - (\bigcup_{i=1}^{m} \bigcup_{j=1}^{n} f1(P_{ij}^c)) \\ &= \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} (f1(P_{ij}^n) - f1(P_{ij}^c))\end{aligned} \tag{4-20}$$

Where P_{ij}^n represents pin position for the new design model; P_{ij}^c represents pin position for the current design model. Using Equation (4-19), we can deduce:

$$\bigcup_{i=1}^{m} \bigcup_{j=1}^{n} \Delta S_T^{ij} = \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} (f1(P_{ij}^n) - f1(P_{ij}^c)) \tag{4-21}$$

According to Equation (4-9), we have

$$f1(\Delta P_{ij}) = f1(P_{ij}^n) - f1(P_{ij}^c) \tag{4-22}$$

It can be simplified as:

$$\Delta P_{ij} = P_{ij}^{n} - P_{ij}^{c} \tag{4-23}$$

Where P_{ij}^{n} and P_{ij}^{c} are calculated using Equation (4-16).

4.4 Support software framework

The purpose of software development is to integrate different software platforms including CAD/CAM (Unigraphics), Finite Element Analysis software (Abaqus), scanning software (Gom) to receive, analyze and filter data information from CAD/CAM or reverse engineering system, to control hardware movement, to adjust the SPT's shape. The software is composed of two packages, namely A package for pin adjustment and B package for simulation. The A package was developed with Microsoft Visual Basic with the purpose of processing coordinate geometry information, creating the screw-pin tooling, calculating the amount of SPT movement and generating NC code for the movement accordingly. Package B is developed with Graphics Interactive Programming to simulate screw-pin movement within Unigraphics Solutions' CAD system and verify the results visually. It can help users to understand the working process and check the final shape of the SPT.

As mentioned before, the SPT generation is conducted in three steps and the detail of the framework is shown in Figure 4-4.

Part1: Component discretization

In order to obtain the component position information in response to the screw-pin array pattern, it is essential to discrete the 3D component surfaces. There are two types of discretization: discretization of a 3D CAD model and discretization of a 3D physical model. The discretization of a 3D CAD model is also called mesh generation, which is the same to that of Finite Element Analysis, therefore it is conducted within FEA software (ABAQUS/CAE). Discretization of a 3D physical model, employed when CAD models are not available, is conducted through scanning using Gom scanner. More detailed information about part discretization can be seen in section 4.5.

Part 2: Screw-pin tooling construction, adjustment, evaluation and G code generation (SCAG)

SCAG is developed within a visual basic environment. The purpose is to read the generated file from the component discretisation process, construct or retrieve a screw-pin array pattern, calculate the amount of adjustment of the screw-pin, generate G code, and output the screw-pin array pattern. Please refer to section 4.6 for details.

Part 3: Display and verification

A customised menu on the CAD software (Unigraphics) using GRIP is developed to read the screw pin array pattern file and generate 3D solid screw-pin tooling, and the difference between component geometry and the screw-pins can be seen from the CAD software easily. Please refer to section 5.7 for details.

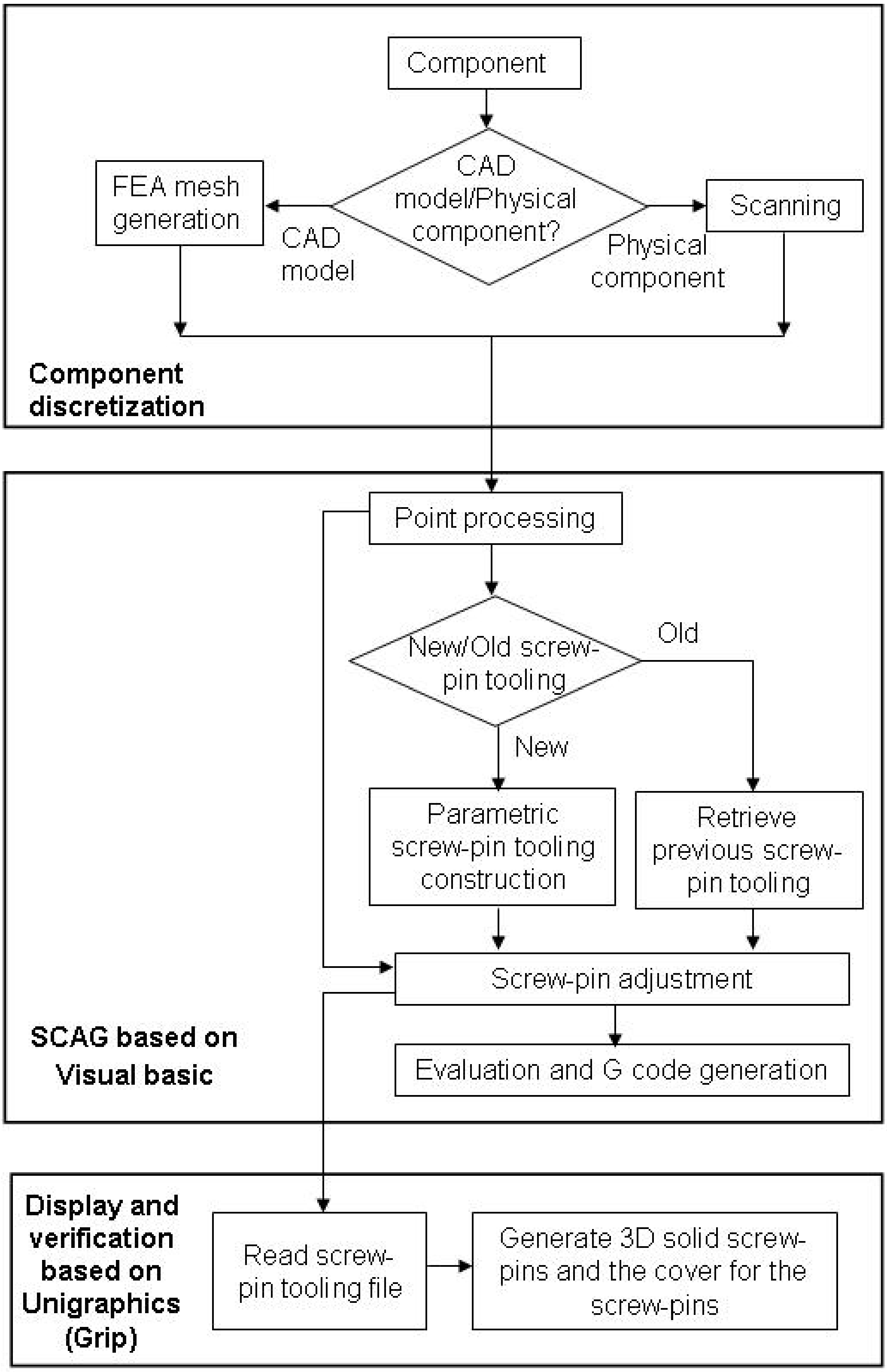


Figure 4-4 Software framework

4.5 Component geometry discretization

Two types of component discretisation are considered. The first one is the discretisation of 3D CAD models which is the procedure of breaking down the 3D surface into a lot of small pieces and extracting the position information of each piece. The discretization of the 3D CAD model is the same as the mesh generation of Finite Element analysis and requires the point coordinates of the model for further application, thus, the FEA software (i.e. ABAQUS) is employed for the job. The second type of component discretisation deals with a situation when the CAD model is not preferable or not available. The physical 3D part is digitalised through a scanner (GOM system) and the point cloud file containing the point information is generated.

4.5.1 Three-dimensional CAD model discretization

4.5.1.1 Abaqus/CAE introduction

Abaqus/CAE is a complete Abaqus environment that provides a simple, consistent interface for creating, submitting, monitoring, and evaluating results from Abaqus/Standard and Abaqus/Explicit simulations (Abaqus, 2007). Abaqus/CAE is divided into modules, where each module defines a logical aspect of the modeling process; for example, defining the geometry, defining material properties, and generating a mesh. As you move from module to module, you build the model from which Abaqus/CAE generates an input file that you submit to the Abaqus/Standard or Abaqus/Explicit analysis product. The analysis product performs the analysis, sends information to Abaqus/CAE to allow you to monitor the progress of the job, and generates an output database. Finally, the Visualization module of Abaqus/CAE can be used to read the output database and view the results of the analysis

4.5.1.2 Analysis input file

An analysis input file is generated to represent a model when a job associated with the model is submitted for analysis in Abaqus/CAE (Abaqus, 2007). The analysis input file is an ASCII file with an extension of **.inp**; it can be viewed and edited using a text editor in the Abaqus/CAE working directory. This file helps users communicate with the ABAQUS analysis modules and it must be created first. In this research, the contents of the input file are analyzed by a Point Processor developed in Virtual Basic (see section 4.6.1) instead of ABAQUS analysis modules.

What the Point Processor requires is the node numbers and node coordinates of a geometric model. To satisfy this requirement, the analysis input file used by the Point Processor includes three main sections: the title section, the part section and the assembly section. The part section can further be divided into the node and element sections; and the assembly includes an instance section. Each section implements many keywords with required and optional parameters and data lines. The meshed domain of the geometric model may consist of many thousands of elements and nodes. Then, the node numbers, node coordinates, and node members forming each element can be listed in the input files with formats defined by keywords *node and *element.

The input file starts with a set of general instructions to ABAQUS. There are many lines in the input file which begin with a **. This is a comment marker and everything following a ** is ignored by the data processor. Other lines begin with a single * which denotes an ABAQUS keyword. The keywords such as heading, node, element, part and et al., contain the information to define the mesh. Some lines beginning with numbers or text are data lines, as required by ABAQUS keywords. For example, the geometry model in

Figure 4-5 can be coded using a customized analysis input file as shown in Figure 4-6. Which depicts 2D element types including S3 and S4R which are selected in this car analysis input file. For details on the ABAQUS Input file, please refer to the ABAQUS manual.

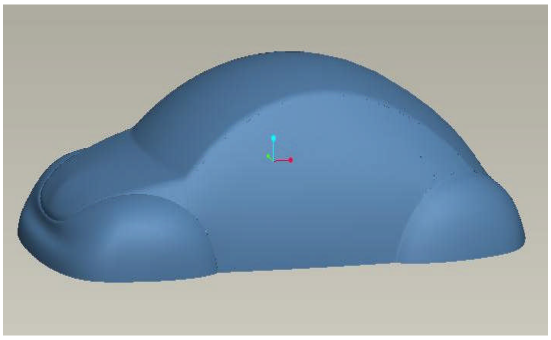


Figure 4-5 Car geometric model

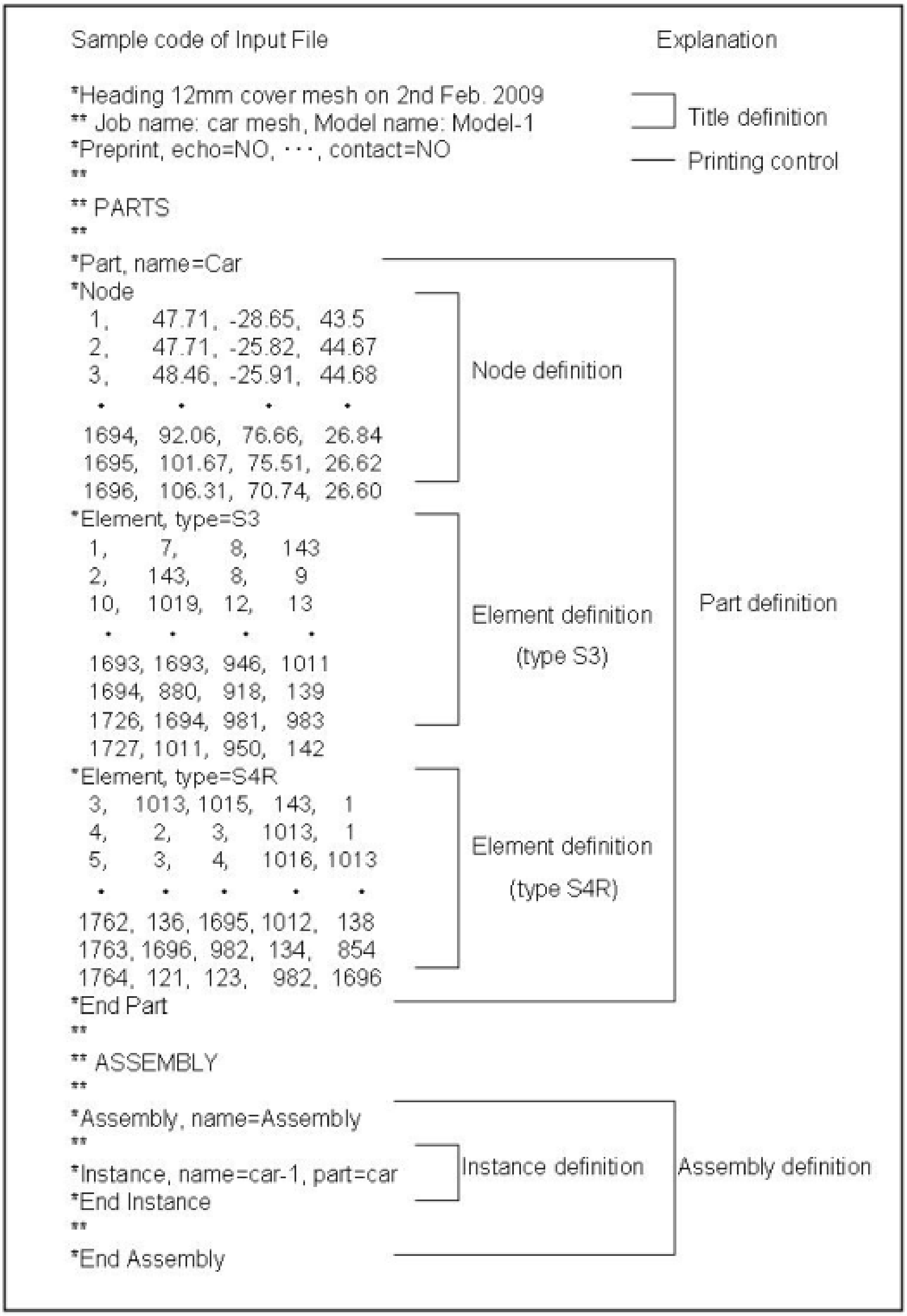
4.5.1.3 Creation procedure of Analysis Input File

The whole creation procedure of the Abaqus input file is illustrated in Figure 4-7 and some key issues are explained in detail as follows:

1. **Geometry repair**

In an ideal scenario, a geometry built by CAD software is used in FEA, so that the duplication of geometry modelling is eliminated. However, in the real world, the CAD generated geometry cannot or, in some cases, should not be directly used in FEA modelling. When a complex geometry is modeled in CAD software and used as input to FE software, the geometry information is transformed between different software representations. The disparity of the interpretation and data expression makes information loss inevitable.

When a body contains a lot of B-spline surfaces and small features, it is not unusual that after the geometry is inputted into FE software, some of the small surfaces are lost and parts of the B-spline surfaces are misinterpreted.




```
*Heading 12mm cover mesh on 2nd Feb. 2009
** Job name: car mesh, Model name: Model-1
*Preprint, echo=NO, ···, contact=NO
**
** PARTS
**
*Part, name=Car
*Node
  1,     47.71, -28.65,  43.5
  2,     47.71, -25.82,  44.67
  3,     48.46, -25.91,  44.68
   ·       ·       ·       ·
 1694,  92.06,  76.66,  26.84
 1695, 101.67,  75.51,  26.62
 1696, 106.31,  70.74,  26.60
*Element, type=S3
  1,      7,     8,   143
  2,    143,     8,     9
  10,  1019,    12,    13
   ·      ·      ·      ·
  1693, 1693,  946,  1011
  1694,  880,  918,   139
  1726, 1694,  981,   983
  1727, 1011,  950,   142
*Element, type=S4R
  3,   1013, 1015,  143,    1
  4,      2,    3, 1013,    1
  5,      3,    4, 1016, 1013
   ·      ·     ·     ·     ·
 1762,  136, 1695, 1012,  138
 1763, 1696,  982,  134,  854
 1764,  121,  123,  982, 1696
*End Part
**
** ASSEMBLY
**
*Assembly, name=Assembly
**
*Instance, name=car-1, part=car
*End Instance
**
*End Assembly
```

Figure 4-6 The composition of analysis input file (car.inp)

Even when the geometry can be transferred from CAD software to the FEA software without information loss, it is still unrealistic to generate the FE mesh directly, as the high-order surfaces (B-spline surface) might lead to element inconsistencies, and small features might cause highly distorted elements or failed mesh. Therefore, it is necessary to idealize the geometry in order to generate a feasible mesh. For example, Figure 4-8 illustrates a part imported from an IGES file. Two fillets of the imported part were converted to two balls by Abaqus/CAE and required repair.

A Geometry Repair toolset in the Part module is provided to edit or repair the geometry of the imported part. The tools can be used to repair edges, faces, an entire part, or regions of a part that make it invalid or imprecise. Abaqus/CAE stores most of the repair operations as features.

The repair process of the above imported part can be conducted in two steps: removing discontinuous surfaces and creating a new surface:

1) Removing face

Faces including chamfers, fillets, and holes can be selected from an imported part. Abaqus/CAE looks for adjacent faces that define a feature. The entire feature or only the selected faces can be removed, as shown in Figure 4-9(a).

2) Creating face

A face can be created on an imported part by selecting one or more edges of the new face. Abaqus/CAE loops through the adjacent edges and calculates the location of the new face. Abaqus/CAE creates the new face as a shell, as shown in Figure 4-9(b).

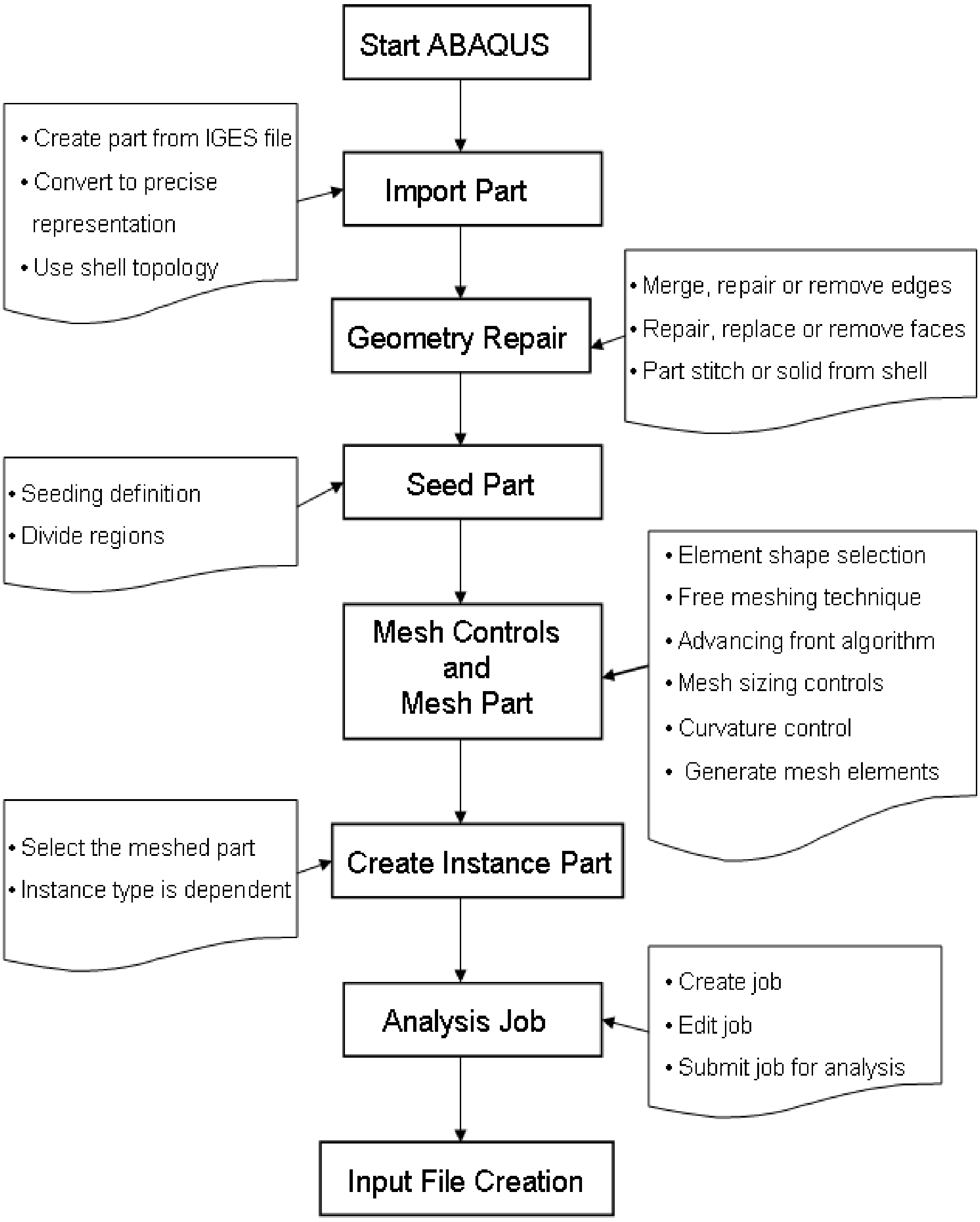


Figure 4-7 General creation procedure of Abaqus input file

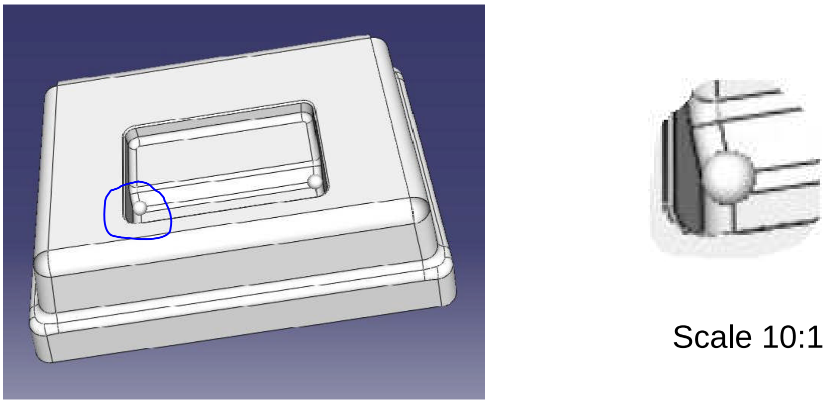


Figure 4-8 Imported part with features to be repaired

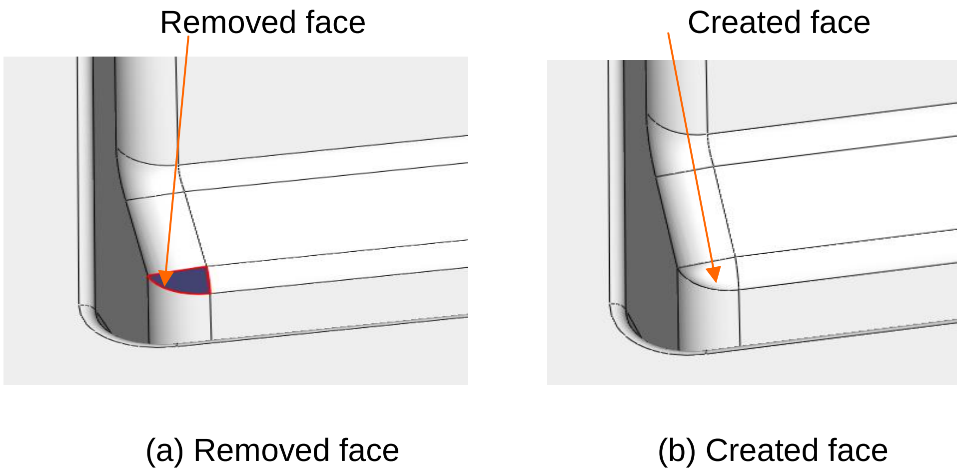


Figure 4-9 Surface repairing of imported model

2. Part seeding

Part seeding is influenced by two elements: seed density and curvature control, which are illustrated as follows:

1) Seed density

Seeds are markers that are placed along the edges of a region to specify the target mesh density in that region. Abaqus/CAE creates seeds only along edges and generates meshes that match the seeds as closely as possible.

The seeds can be distributed uniformly along an edge and appear in white.

The seed density can be controlled by specifying average element size for the entire part or number of elements desired along an edge. Figure 4-10 shows part seeds of the imported Rectangular Cover part, whose part size is 230x168x62mm and average element size is 8mm.

2) Curvature control

To avoid the problem of inadequate seeding around small curved features, Abaqus/CAE applies curvature control when it seeds a part. Curvature control allows Abaqus/CAE to calculate the seed distribution based on the curvature of the edge along with the target element size.

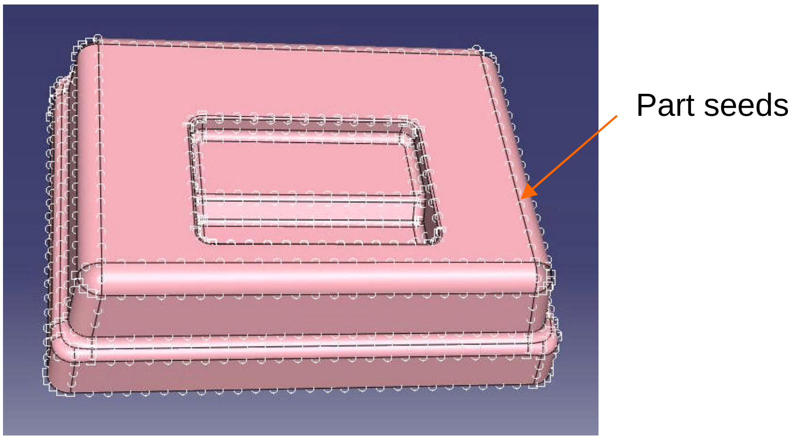


Figure 4-10 Part seeds in the imported part

The deviation and minimum size factors can be configured to realize curvature control. The deviation factor is a measure of how much the element edges deviate from the original geometry; specifying a minimum size factor prevents Abaqus/CAE from creating very fine meshes in areas of high curvature that have no interest in modeling.

3. Mesh controls and part meshing

Mesh characteristics are controlled by mesh density, element shape, meshing technology and mesh algorithm. During mesh generation, nodes are generated first, then the element type and element connectivity are specified (Abaqus, 2007).

1) Mesh density

As mentioned in part seeding, mesh density is specified by seeds along the edges of the model. Both the mesh density along the boundary of the region and the mesh density in the interior of the region are determined by the seeds along the edges of the region.

2) Meshing algorithm

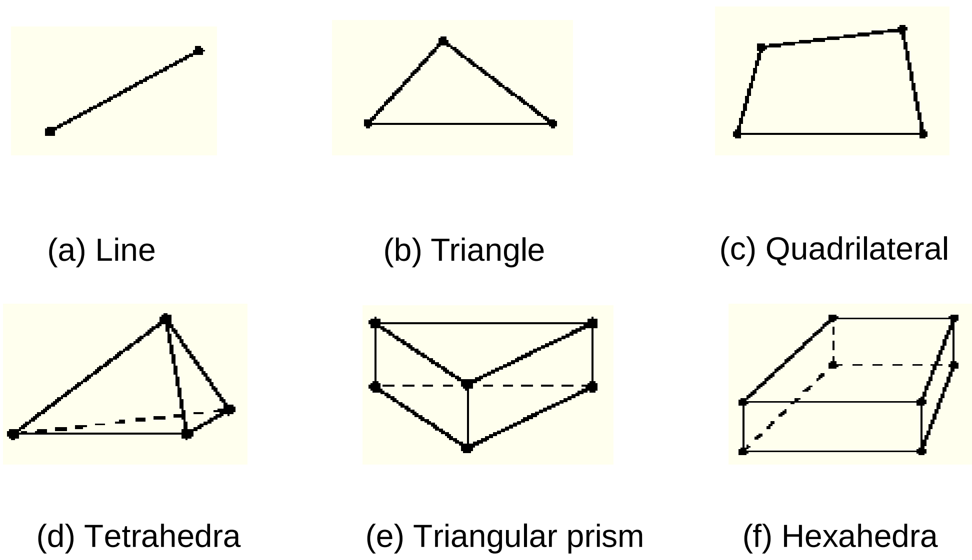
There are two meshing schemes to generate a mesh in Abaqus/CAE: the medial axis algorithm and the advancing front algorithm. The medial axis algorithm first decomposes the region to be meshed into a group of simpler regions. The algorithm then uses structured meshing techniques to fill each simple region with elements. The advancing front algorithm generates quadrilateral elements at the boundary of the region and continues to generate quadrilateral elements as it moves systematically to the interior of the region. The elements generated by the advancing front algorithm will always follow the seeding exactly for quadrilateral-dominated meshes.

The medial axis algorithm may modify the original seeds along some of the surface edges. This modification may distort the mesh by causing element shear. Compared with the medial axis algorithm, the advancing front algorithm has no mesh shear and can produce a more uniform mesh. So the advancing front algorithm is selected to control mesh production.

3) Mesh element shape

There are six different mesh element shapes as shown in Figure 4-11: line, triangle, quadrilateral, tetrahedral, triangular prism and hexahedra in Abaqus/CAE (Abaqus, 2007). Three types of element shape can be used for two-dimensional regions: triangle, quadrilateral, and quad-dominated. Quad-dominated primarily uses quadrilateral elements, but allows triangles in transition regions. Every mesh region has one or more element types assigned to it by default. Each element type corresponds to an element shape that can be used in that region.

The advancing front algorithm typically produces a higher quality mesh when it uses quadrilaterals and includes triangles in tight regions, so a Quad-dominated element shape is selected as the element shape for a mesh region. Meshing with the Advancing front algorithm and the Quad-dominated element shape typically produces a more robust mesh with less element shearing for surfaces.



(a) Line (b) Triangle (c) Quadrilateral

(d) Tetrahedra (e) Triangular prism (f) Hexahedra

Figure 4-11 Mesh element shapes

4) Meshing technique

There are three types of meshing technique used to mesh surfaces or solids in Abaqus/CAE. These are free, structured and sweep (Abaqus, 2007). The free meshing technique is used to mesh a surface with quadrilateral or quadrilateral-dominated elements; the structured meshing technique is applied to simple two-dimensional regions (planar or curved) or to simple three-dimensional regions that have been assigned the Hex or Hex-dominated element shape option; the swept meshing technique is used to mesh a solid region with hexahedral or hexahedral-dominated elements. Since parts used in this research are all complex shells, the free meshing technique is selected to generate meshes. In summary, mesh controls setup can be listed as table 4-1. After set up of all mesh attributes, Abaqus/CAE starts to mesh parts and thus mesh information can be obtained.

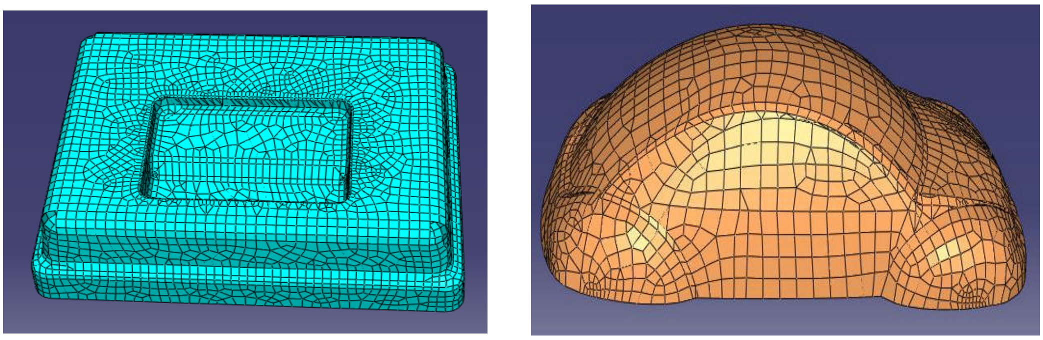
Table 4-1 Mesh controls

Dimensionality	**Element Shape**	**Algorithm**	**Technique**
Two-dimensional	Quad-dominated	Advancing front	Free

5) Mesh information and example statistics

Mesh information includes mainly the following messages: a) the name of the part or part instance; b) the number of nodes and elements in the part or part instance; c) the number of elements for each element shape.

Figure 4-12(a) and Figure 4-12(b) are two examples of free meshes generated with Quad-dominated elements by the advancing front algorithm. Mesh statistical information of Figure 4-12 is listed in Table 4-2 and Table 4-3 respectively, based on which, the approximate global size 1mm is selected to produce an analysis input file for both the cover and car models for 10mm screw-pin array pattern. This is because if the size of an element is more than 1mm, the component may be over coarsely meshed and if it is less than 1mm, there is a huge amount of data to be processed.



(a) Cover (b) Car

Figure 4-12 Free mesh generated with Quad-dominated elements

Table 4-2 Summary of Cover mesh information

Approximate global size(mm)	Number of nodes	Number of elements	Quadrilateral elements (S4R)*	Triangular elements (S3)**
10	1882	1960	1714	246
8	2428	2494	2254	240
5	4418	4457	4217	240
2	22058	22104	21620	484
1	86219	86739	84917	1822
0.5	364436	367639	359671	7968

Table 4-3 Summary of Car mesh information

Approximate global size (mm)	Number of nodes	Number of elements	Quadrilateral elements (S4R)*	Triangular elements (S3)**
10	1709	1781	1486	295
8	2017	2102	1781	321
5	3398	3479	3137	342
2	15841	15955	15362	593
1	60921	61409	59753	1656
0.5	202890	204023	199616	4407

* The quadrilateral mesh elements are assigned the S4R element type

** The triangular mesh elements are assigned the S3 element type

4.5.2 Three-dimensional physical component digitalisation

The aim of the digitalisation is to acquire point-cloud data of the physical component which is to be used by the SCAG software through a method known as reverse engineering. There are two types of digitizing methods for physical components: the contact and non-contact methods. The contact method, such as Mitutoyo Coordinate Measuring Machine (CMM), is suitable for digitizing simple or regular geometry parts where accurate description of dimensions and tolerances are needed. In contrast, the non-contact method, such as Advanced Topometric Sensor (ATOS) system by the GOM Corporation, is capable of capturing complex 3D free-forms which require a massive number of data points for their accurate description. In the following paragraphs, the Mitutoyo CMM will be used to illustrate the contact digitalisation and the ATOS system will be employed to introduce the non-contact digitalisation. To make the digitalized component easily accessible to the SCAG software, the point-cloud data will be stored in the ASCII format.

1. The Mitutoyo CMM (Euro_C_A121210):

The Mitutoyo CMM uses a Renishaw scan probe system to collect 3D data points of an object in space. It is supported by Geowin software which consists of several standard modules to digitize components. Every software module is designed to help users make comprehensive evaluations of measurements made by the CMM. By precisely recording the X, Y, and Z coordinates of the target, the Geowin software generates points for the construction of features and captures the coordinate data as an ASCII format file. The digitizing procedure of the Mitutoyo CMM can be summarized in the following steps:

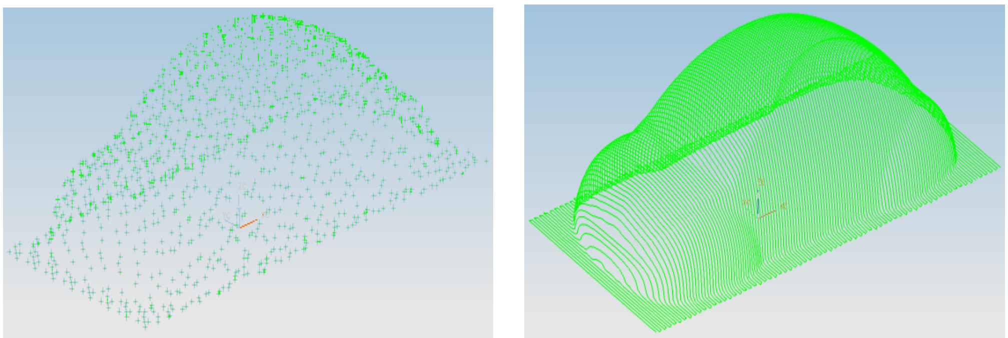
STEP1: Select output configuration of the Geowin software as ASCII format.
STEP2: Start the program, create a relevant coordinate system etc.
STEP3: Create and name a new ASCII file to store measured data.
STEP4: Select the required storage parameters.
STEP5: Measure all of the data required.
STEP6: Output measured data to the ASCII file and end the measurement.

When taking measurements with the touch probe of the CMM, only a finite number of points on the actual surface are sampled. The number of measurement points are determined by decimation and scanning pitch of the CMM program, and should have acceptable levels of accuracy. The decimation is the number of points per line and the pitch is the minimal distance between two lines. As the measurement pitch increases, the number of points on the scan surface decreases. The format of the output ASCII file is shown in Figure 4-13.

The digitized component can also be output as a neutral file format such as STEP or IGES. Figure 4-14(a) is an IGES model of the beetle car part in Figure 4-5 which is point by point scanned by the probe in the Mitutoyo CMM. Figure 4-14(b) is another IGES model of the beetle car part which, in Figure 4-5, is continuously scanned by the probe in the Mitutoyo CMM.

```
12.603 -101.839 47.571
12.603 -102.188 47.688
12.603 -102.332 47.734
…………………………..
222.603 -124.029 90.294
222.603 -124.018 91.562
222.603 -124.018 91.660
…………………………..
```

Figure 4-13 ASCII file format by the Mitutoyo Geowin



(a) Points (b) Curves

Figure 4-14 Curves and points obtained by Mitutoyo CMM

2. The ATOS system

The ATOS system is a widely used optical scanning device that can quickly acquire 3D point data from physical components. 3D scanning is easy and fast if the object to be measured fits the ATOS measuring volume or just overlaps slightly. During the measurement, a fringe pattern is projected onto the object surface and recorded by two cameras. Each single measurement generates up to 1.3 million data points. For a complete measurement of complex objects, the individual measurements are merged into a project. The system automatically determines the current sensor position and transforms the individual measurements into a common object coordinate system. The measured data can be exported as point clouds in the ASCII format. The amount of scanned data is decided by camera resolution and the number of scans.

The digitizing procedure of the ATOS system can be summarized as follows:

STEP1: Mount two selected ATOS sensors on a tripod positioned around the object and setup the sensors.

STEP2: Calibrate the ATOS system.

STEP3: Create a project and carry out a measurement.

STEP4: Store the measured data into the project.

STEP5: Delete unwanted 3D data.

STEP6: Polygonize the scan results.

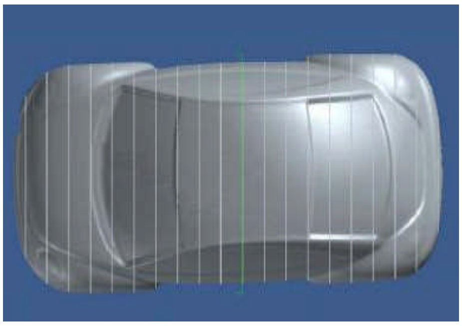
STEP7: Export the measured data in an ASCII format file.

The format of the output ASCII file by the ATOS is similar to Figure 4-13 and the scan result can also be output as a neutral format file such as STEP or IGES. Figure 4-15(a) is a physical leg component and Figure 4-15(b) is an IGES model of the leg scanned using the ATOS system.

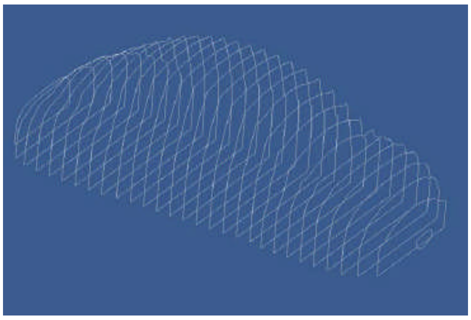
(a) Physical component (b) Digital model

Figure 4-15 Leg physical component and its digitalization

As shown in the Figure 4-15(b), there may be several million measuring points in the scan model. It is not a good idea to feed all of these points to the SCAG because of the potential for huge calculations. To filter out the overlapping scan point and other unnecessary data, sections are employed to simplify the scan model. Sections can be created in the scanned meshes as shown in Figure 4-16(a) using different methods such as plane, spline, 3D line, etc. Further editions such as the deleting or thinning of sections, filling in of gaps and changing the point density may be needed for the created sections. The finished sections are shown in Figure 4-16(b) and can be exported in the ASCII format. In this situation, the amount of scanned data depends on the number of sections, point density of the sections and the size of the physical component.



(a) Meshes and sections



(b) Sections

Figure 4-16 Scanned beetle car and its sections in ATOS system

4.6 Screw-pin construction, adjustment, and G code generation

Visual Basic is used to develop a user-friendly interface to allow users to process the output file from the previous discretisation process to obtain point position, make a decision of whether a new screw-pin array pattern or previous screw-pin array pattern should be used. If a new screw-pin array pattern is needed, it will be constructed parametrically, otherwise, the previous screw-pin array pattern will be retrieved. After this process, the amount of screw-pin adjustment will be calculated based on the height difference between the screw-pin array pattern and the component geometry; assessment is then made about whether the screw-pin array pattern is suitable for the component or not. If yes, then G code for the Fagor CNC controller is generated automatically, otherwise, it will feedback to the user so that the user can modify the screw-pin array pattern to avoid problems occurring in downstream stages. In summary, the SCAG is composed of five parts:

1) Point processing: to process the FEA file and scanned component file to obtain point (node) coordinate position.
2) Parametric screw-pin array pattern construction: allows user to retrieve previous SPT or construct new SPT.
3) Screw-pin adjustment: calculate the amount of adjustment of each screw-pin; saving and retrieving screw-pin array pattern.
4) Evaluation: to assess whether or not the overall size of SPT and the remaining length of individual pins are sufficient for the new component.
5) G code generation: Automatic generation of G-code for the screw pin adjustment for the Fagor controllers.

The SCAG programmes are listed in **Appendix B.1** and **Appendix B.2**.

4.6.1 Point processing

The output file from the component discretization process may contain points coordinate positions as well as other information, e.g. for the FEA file, it contains an element list and material properties amongst others. The point processing program is developed to read the component discretization file and obtain point position information and ignore other irrelevant information. The point processor includes two parts: 1. Point processing for FEA *.inp file; 2. Point processing for point cloud ASCII file *.asc generated by the scanner and explained in detail below.

1. Point processing for FEA input file

The Visual Basic programme opens the inp file that is generated by ABAQUS and reads line by line of the inp file before processing it. As shown in Figure 4-17, the node definition starts with “* Node” in the first line, and is followed by a series of lines, each of which contains node identity numbers and x, y, z coordinate values of a node; “,” is used to separate them; “*” means end of the node definition. The flow chart of the program to read a FEA input file is shown in Figure 4-18. **Pt** (x,y,z) and is a node position variable.

```
* Node
ID number, X Value, Y Value, Z value
*
```

Figure 4-17 Format of node definition in input file

2. Point processing for scanning data ASCII file

The format for the created ASCII file in reverse engineering is expressed in Figure 4-19. Each line of the ASCII file contains x, y, z coordinate values of a node and every value in each line is separated by a space. The point processor of the SCAG reads the ASCII file line by line from the beginning to the end. Figure 4-20 shows the flow chart of the SCAG program to read an ASCII file. **Pt** (x,y,z) is a node position variable.

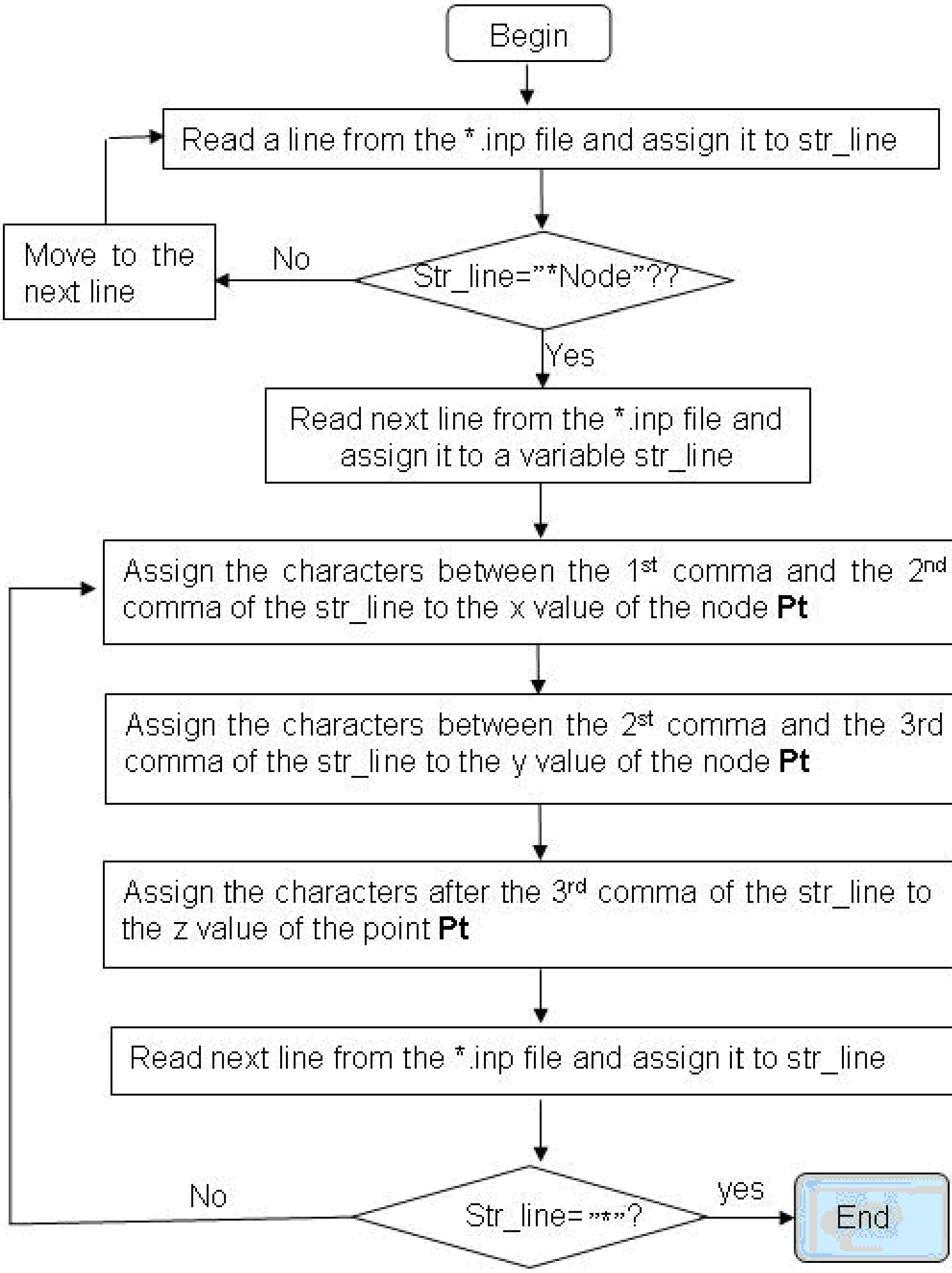


Figure 4-18 Flow chart of input file reading

X_0 Value Y_0 Value Z_0 value

X_1 Value Y_1 Value Z_1 value

……….. ………. ……….

Figure 4-19 Format of ASCII file

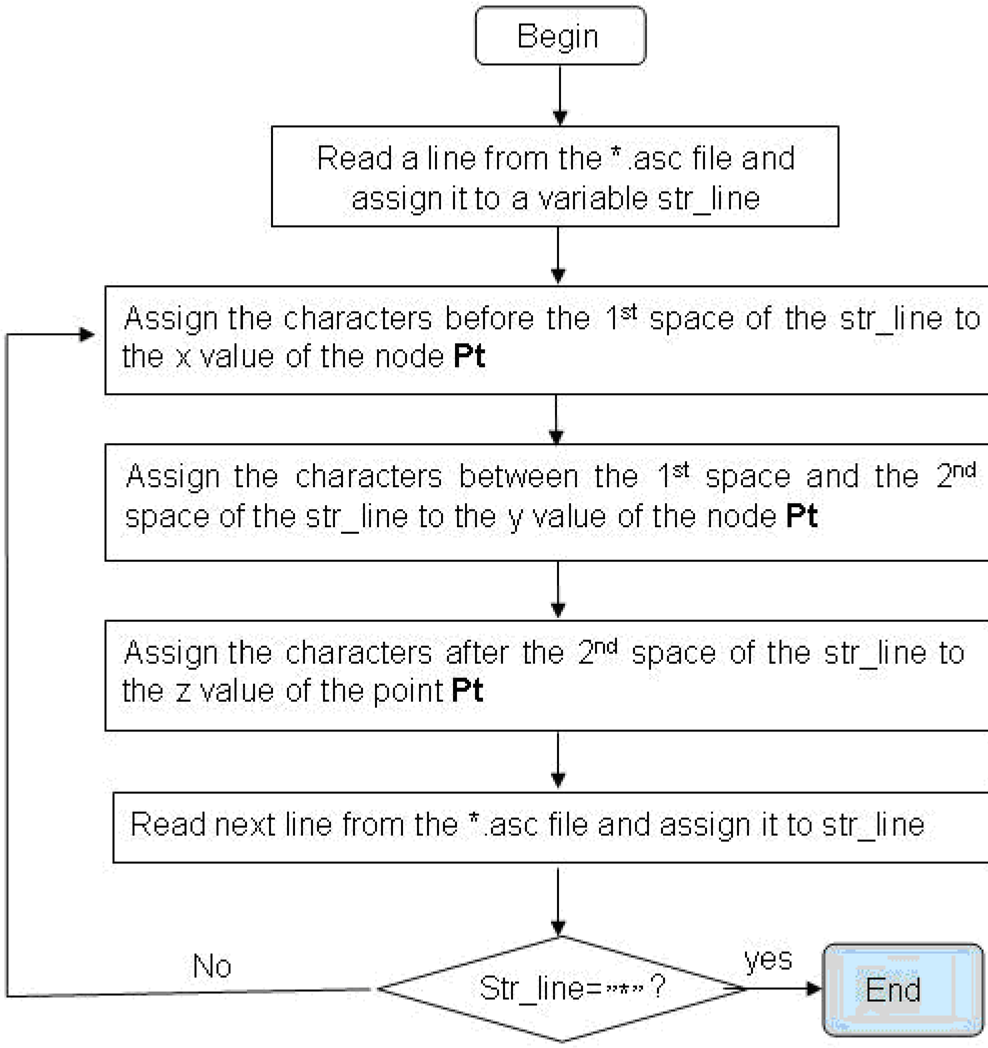
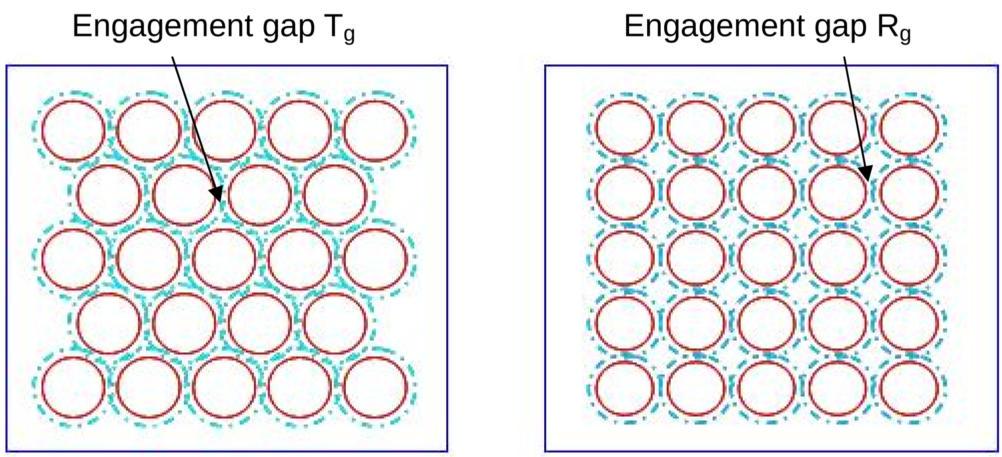


Figure 4-20 Flow chart of ASCII file reading

4.6.2 Parametric screw-pin array pattern construction

1. Screw pins engagement methods

There are two engagement methods for a set of screw pins packed in a tooling: a rectangular and triangular pattern (as shown in Figure 4-21).



(a) Triangular pattern (b) Rectangular pattern

Figure 4-21 Screw pins engagement methods

In Figure 4-21, T_g is the engagement gap among screw pins in a triangular pattern and R_g is engagement gap among screw pins in a rectangular pattern. These two engagement patterns induce different gap sizes which are reflected on the surfaces produced by the tooling. For example, as for a set of M20 screw pins, T_g is about 0.5mm and R_g is about 6mm. The size of the screw pin gaps is very important, since it will affect product surface quality. Compared with a rectangular pattern, a triangular pattern has smaller gaps and produces smoother product surface, and is selected for screw pins packing.

2 Screw pin design

All screw pins of the SPT should have the same dimensions to allow for tooling reconfigurability. To select the right screw pin size, the following factors should be considered:

- Screw pin diameter: the diameter of the screw pins should be bigger than the diameter of the adjustment tool to avoid interference between them and standard metric screws such as M20, M24 and M30 should be selected to minimize the cost and lead time of their fabrication.
- Screw pin length: the length of the screw pin is determined by adding the height of maximum pin extension above the top surface of the container and pin length staying in the container; standard length should be selected.
- Screw pin gaps: gaps between screw pins should be minimized to reduce possible dimples on the produced component surface and the smaller pins can result in higher surface resolution and adequate die shape fidelity.
- Screw pin loads: a screw pin must be strong enough to withstand the buckling and bending loads incurred while forming thermoplastic components.
- Set up time: the CNC machine is employed to set the shape of the screw pin tooling and the adjustment time depends on the number of the screw pins. The bigger the screw pin number, the longer the set up time. The reconfigurable tooling size and the machine bed size of the system are used to determine the number of the screw pins in the tooling.

3 Screw pin tooling parameters

In this thesis, all of the screw pins employed in a tooling have the same size. The parameters of a screw pin tooling include rows (**ROWpin**) and columns (**COLpin**) of screw pin, pin diameter (**Dpin**), length (**Lpin**) and pitch (**Ppin**).
The distance between two screw-pin central axes in the x direction and in the

Y direction, designated as Xpin and Ypin as shown in Figure 4-22, are needed in order to identify the screw-pin axis position, and are determined by the pin diameter (**Dpin**) and the Pitch (**Ppin**).

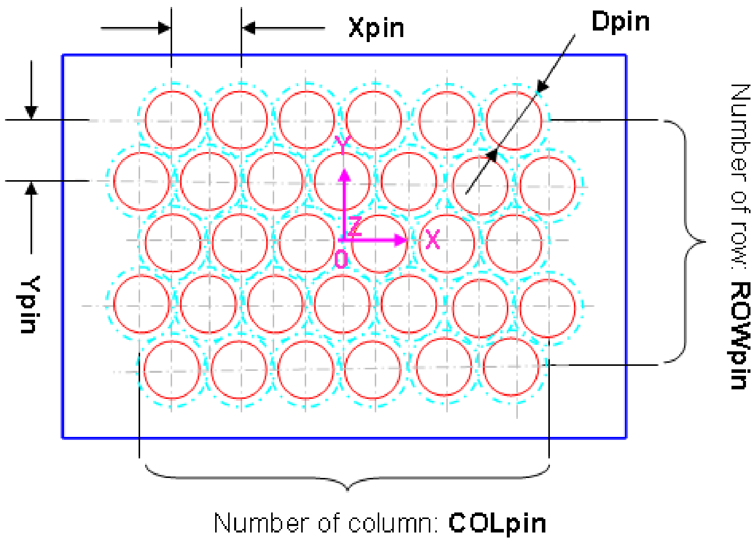


Figure 4-22 Parameters used by screw pin tooling*

* Screw pin pitch and length parameters are not displayed in the Figure 4-22.

ISO 68-1 general-purpose external metric screw threads ("M" series threads) are used for the screw-pin array pattern. As shown in Figure 4-23, each thread is characterized by its major diameter ***Dpin*** and its pitch ***P***. ISO metric threads consist of a symmetric V-shaped thread. In the plane of the thread axis, the flanks of the V have an angle of 60° to each other.

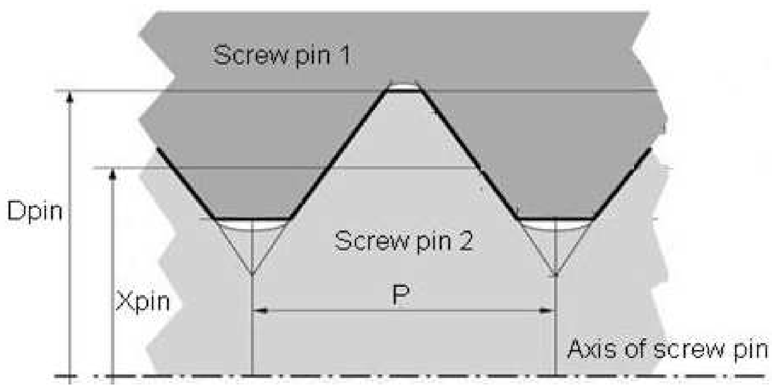


Figure 4-23 "M" series threads engagement

When two identical external screws are meshed together, the distance of the screw pin in the X direction Xpin is:

$$Xpin = Dpin - 2 \cdot \frac{3}{8} \cdot H = Dpin - \frac{3\sqrt{3}}{8} \cdot P \approx Dpin - 0.65 \times P$$

As detailed in Figure 4-24, the **Ypin** can be calculated as below:

$$Ypin = \sqrt{Xpin^2 - (Xpin/2)^2} = \frac{\sqrt{3}}{2} * Xpin = \frac{\sqrt{3}}{2} * (Dpin - 0.65 * P)$$

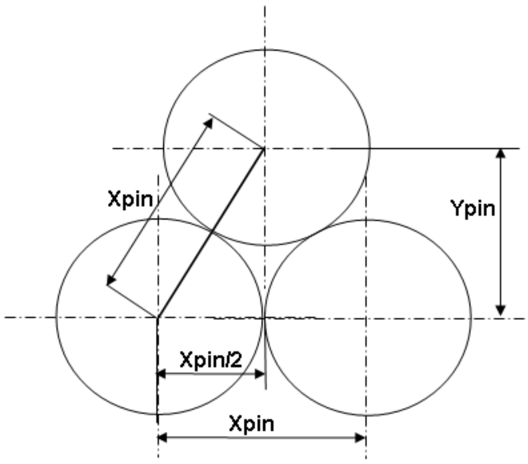


Figure 4-24 Distance calculation between central axes in the Y direction

4. Construction of the screw-pin array pattern

Let **Pnt** (i,j) be the point position on the top of the screw-pin central axis position on the ith row and jth column of the screw-pin array pattern, **Pnt**(i,j) is defined as a structure containing x, y, z0, z1, max, min, rl variables in visual basic as below.

Dim **Pnt**(i,j) as structure

{ X as double, Y as double, Z0 as double, Z1 as double, max as double, min as double, rl as double, A as double}

Where: **Pnt**(i,j).X, **Pnt**(i,j).Y are the X, Y coordinate values of the screw-pin P_{ij}, **Pnt**(i,j).Z0 and **Pnt**(i,j).Z1 are the Z coordinate of the screw-pin P_{ij} before adjustment and after adjustment; **Pnt**(i,j).max and **Pnt**(i,j).min are the maximum and minimum Z values of the patch of the components for the screw-pin P_{ij} to be adjusted to, **Pnt**(i,j).rl is the remaining length of the screw-pin **Pnt**(i,j) and **Pnt**(i,j).A is the amount of adjustment that the screw-pin P_{ij} will be moved.

As shown in Figure 4-25, the coordinate system is put in the centre of the screw-pins tooling, and the X and Y position of the screw-pin P_{ij} are functions of i and j, and are relevant to whether or not Rowpin and Colpin are odd or even:

$$\mathbf{Pnt}(i,j).y = j \times \mathbf{Ypin} - (\mathbf{Rowpin} - 1)/2 \times \mathbf{Ypin} \qquad j \in [\mathbf{0}, \mathbf{Rowpin - 1}];$$

There is one more pin in the odd row than in the even row, e.g. three pins in the 1st and 3rd row and four pins in 0th row and 2nd row as shown in Figure 4-25 (d). The function of the x coordinate value of pnt(i,j) is:

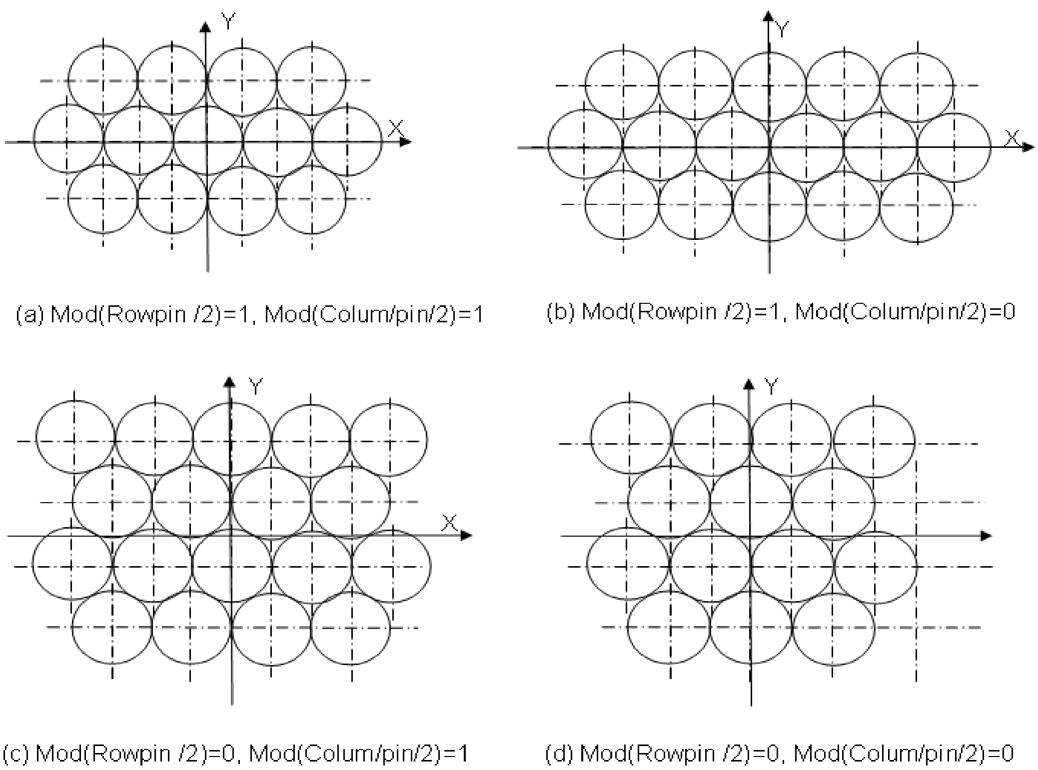


Figure 4-25 Coordinate system and pin array pattern

If I is odd

$$\mathbf{Pnt}(i,j).x = i \times \mathbf{Xpin}-(\mathbf{Colpin}-1)/2 \times \mathbf{Xpin} \qquad i \in [0, \mathbf{Colpin}-1];$$

Otherwise:

$$\mathbf{Pnt}(i,j).x = i \times \mathbf{Xpin}-(\mathbf{Colpin}-2)/2 \times \mathbf{Xpin} \qquad i \in [0, \mathbf{Colpin}-1]$$

When a new screw-pin array pattern is generated, the **Pnt**(i,j).z is assigned as zero:

$$\mathbf{Pnt}(i,j).z0=0$$

After the construction of the screw-pin array pattern, it is necessary to construct the screw pin container parametrically. As shown in Figure 4-26, the screw-pin container is defined by its length Xc, width Yc and height Zc. The edge of the screw-pin cover is 50mm away from the nearest pins, the thickness Zc is assigned as 1/5 of the pin length, therefore:

$$X_C = \mathbf{Xpin} \times (\mathbf{COLpin-1}) + \mathbf{Dpin} + 100$$

$$Y_C = \mathbf{Ypin} \times (\mathbf{ROWpin}-1) + \mathbf{Dpin} + 100$$

$$Z_C = \mathbf{Lpin}/5$$

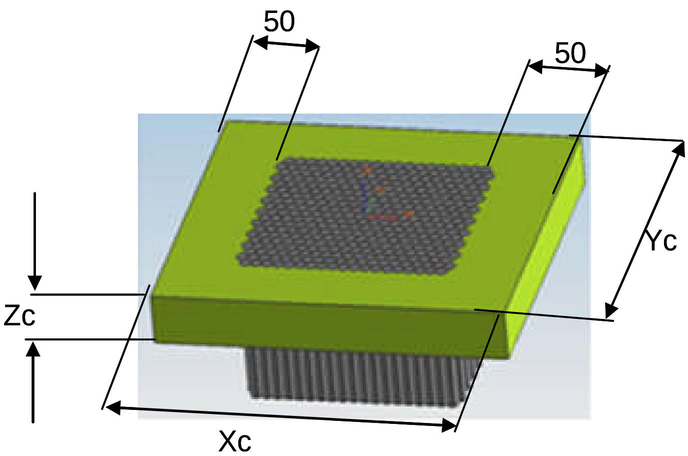


Figure 4-26 Screw-pin container

As shown in Figure 4-27, assuming there are **p** points on the component and **Pt**^{k}(x,y,z) to be the k_{th} point within the area of the P_{ij}, $k \in \mathbf{[0, p-1]}$, then:

$$\mathbf{Pnt}(i,j).X - \mathbf{Xpin}/2 \le \mathbf{Pt}^k.x \le \mathbf{Pnt}(i,j).X + \mathbf{Xpin}/2$$

$$\mathbf{Pnt}(i,j).Y - \mathbf{Ypin}/2 \le \mathbf{Pt}^k.y \le \mathbf{Pnt}(i,j).Y + \mathbf{Ypin}/2$$

And :

$$\mathbf{Pnt}(i,j).\mathrm{min} = \min(\mathbf{Pt}^0.Z, \ldots, \mathbf{Pt}^k.Z, \ldots, \mathbf{Pt}^p.Z)$$

$$\mathbf{Pnt}(i,j).\mathrm{max} = \max(\mathbf{Pt}^0.Z, \ldots, \mathbf{Pt}^k.Z, \ldots, \mathbf{Pt}^p.Z)$$

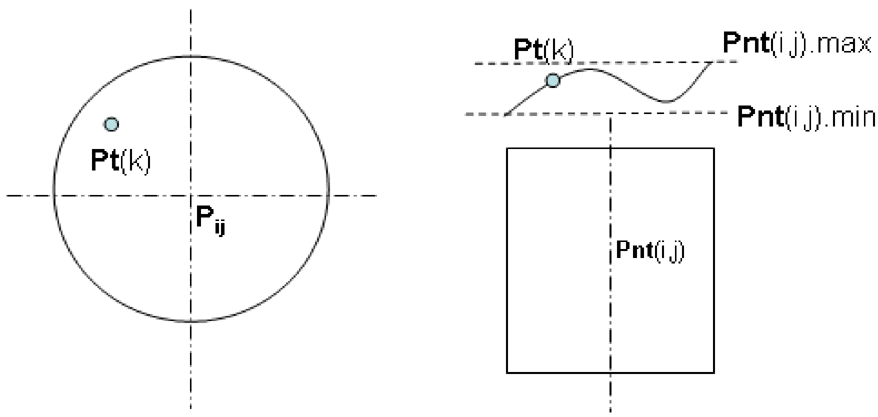


Figure 4-27 Points on the component

The screw pin array pattern, designated as **SPX,** is constructed as below:

SPX={**Dpin**, **Ppin**, **Lpin**, **PXmax**, **PXmin**, **PYmax**, **PYmin**, **Xc**, **Yc**, **Zc**, **Type**, **Pnt**(0,0), …,**Pnt**(i,j),…,**Pnt**(**Rowpin-1**, **Colpin-1**)}

Where: **PXmax**, **PXmin**, **PYmax**, **PYmin** are the maximum and minimum coordinate values in X and Y of the whole screw-pin array pattern respectively

PXmax=max (**Pnt(0,0).**X**, …, Pnt(i,j).**X**,… Pnt**(**Rowpin-1**, **Colpin-1**).X)

PXmin=min (**Pnt(0,0).**X**, …, Pnt(i,j).**X**,… Pnt**(**Rowpin-1**, **Colpin-1**).X)

PYmax=max (**Pnt(0,0).**Y**, …, Pnt(i,j).Y,… Pnt**(**Rowpin-1**, **Colpin-1**).Y)

PYmin=min (**Pnt(0,0).**Y**, …, Pnt(i,j).Y,… Pnt**(**Rowpin-1**, **Colpin-1**).Y)

As shown in Figure 4-28, two situations are considered: sacrificial and filler. In the case of sacrificial, the screw-pins are machined back to the component geometry. In order to take off minimal material from the screw pin, it is important for the screw-pin to be adjusted to a level just above the maximum height of the component within the area of the screw-pin, whilst in the case of the filler, as additional filler material needs to be added, in order for this to be minimal and later taken off, it is important for the screw-pins to be adjusted to the minimal height of the component within the area of the screw-pin, then:

Pnt(i,j).z1 =**Pnt(i,j).**max for sacrificial

Pnt(I,j).z1 =**Pnt(i,j).**min for filler

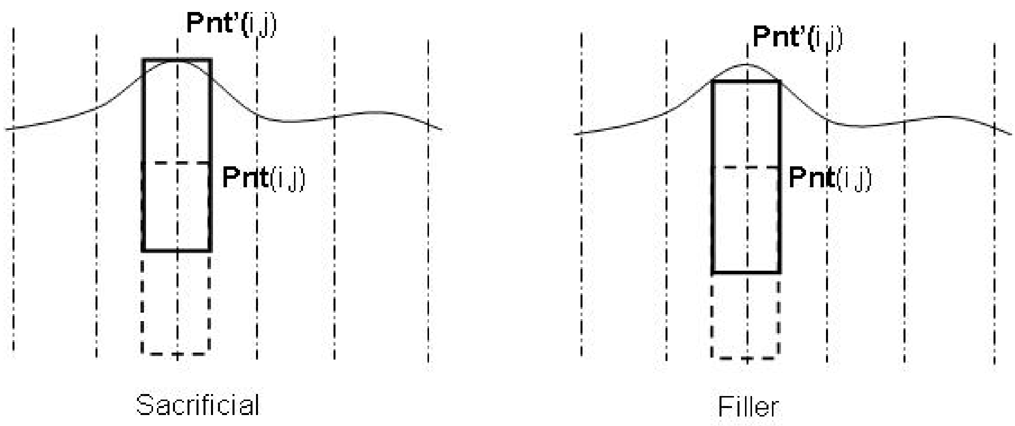


Figure 4-28 Sacrificial and filler solutions

4.6.3 Screw-pin adjustment calculation

1. Screw-pin adjustment for new screw-pin array pattern

When a point of component, defined as **Pc (x,y,z)**, is read by the programme, it is processed to identify which screw-pin area the position is located in.

Assuming that **Pc (x,y,z)** is located within the area of **Pnt**(m,n), then:

Pnt(m,n).X-**Xpin/2** ≤ **Pc.x** ≤ **Pnt**(m,n).x+**Xpin/2**

Pnt(m,n).Y-**Ypin**/2 ≤ **Pc.y** ≤ **Pnt**(m,n).y+**Xpin**/2

Let **Round**(v) be the mathematical function that returns the nearest integer of a real number v. e.g. Round(4.3)=4, Round(4.6)=5, then:

n= **Round**(**Pc**.y/**Ypin**+(**Rowpin**-1)/2)

if n is odd

m=**Round**(**Pc**.x/**Xpin**+ (**Colpin**-1)/2)

otherwise

m=**Round**(**Pc.**x/**Xpin**+(**Colpin**-2)/2)

The maximum value and minimum value of the **Pc**(x,y,z) in the area of screw-pin **Pnt**(m,n) can be obtained from the iteration as below:

If **Pnt** (m.n).max <**Pc**.z then **Pnt**(m,n).max=**Pc**.z

If **Pnt**(m,n).min >**Pc**.z then **Pnt**(m,n).min=**Pc**.z

The overall size of the component is also calculated as below and will be used for the evaluation (See section 4.6.4). Let **CXmax**, **CXmin**, **CYmax** and **CYmin** be the maximum and minimum X coordinate values, and the maximum and minimum Y coordinate values of all the points on the components, the iterations for obtaining **CXmax**, **CXmin**, **CYmax** and **CYmin** are:

If **CXmax** <**Pc**.x then **CXmax**=**Pc**.x

If **CXmin**>**Pc**.x then **CXmin**=**Pc**.x

If **CYmax**<**Pc**.y, then **CYmax**=**Pc**.y

If **Ymin** > **Pc**.y, then **CYmin**=**Pc**.y

The detailed programme flowchart for construction of a new screw-pin tooling is demonstrated in Figure 4-29.

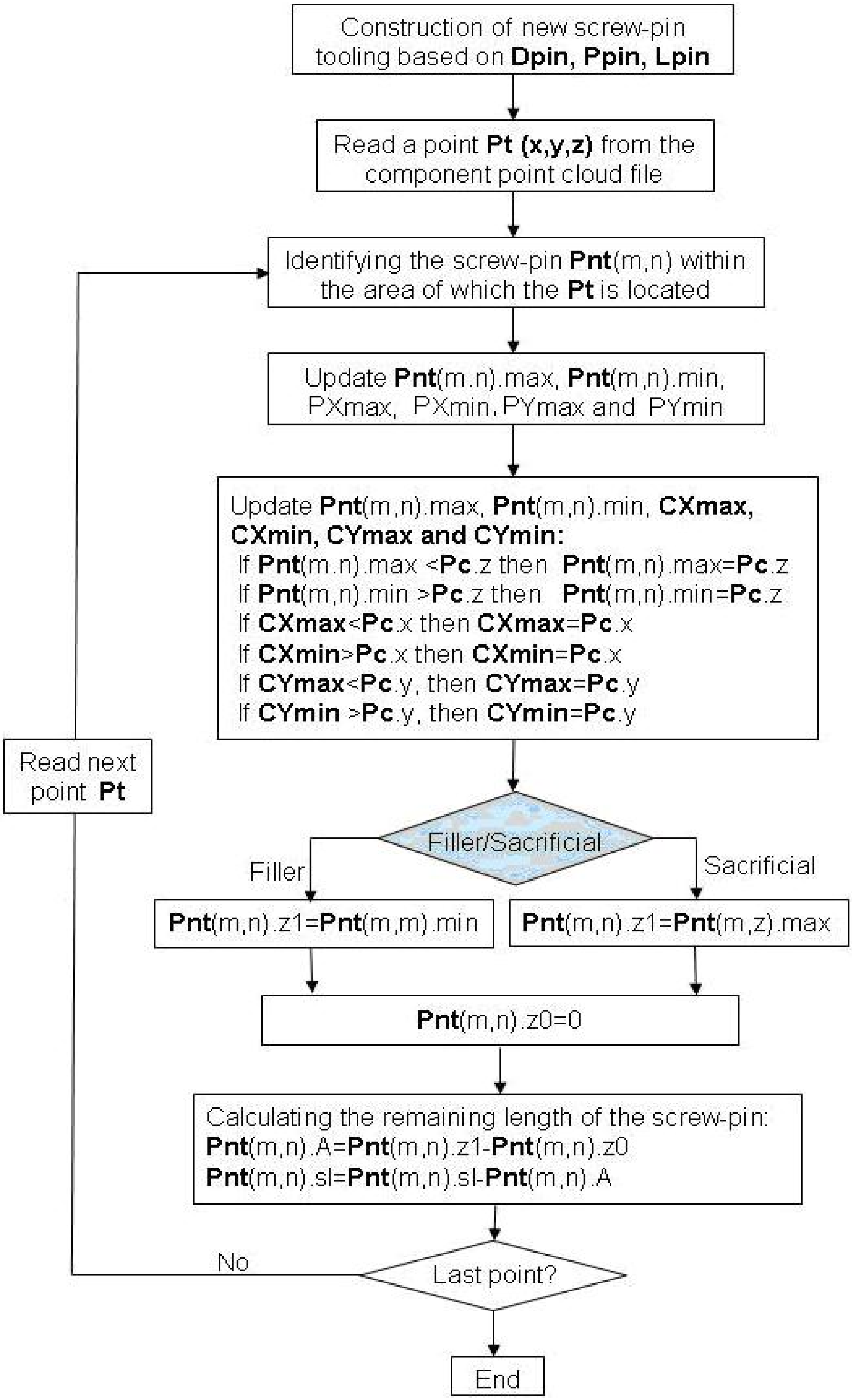


Figure 4-29 New screw pin tooling construction

2. Screw-pin adjustment for old screw-pin array pattern

As shown in Figure 4-30, the amount of pin adjustment for the new component is dependent on the types of operation: filler or sacrificial on the new component as well as on the current component. Let the $\mathbf{Pnt}^{(0)}$ (i,j) and $\mathbf{Pnt}^{(1)}$ (i,j) be the **Pnt**(i,j) for the current and new components respectively.

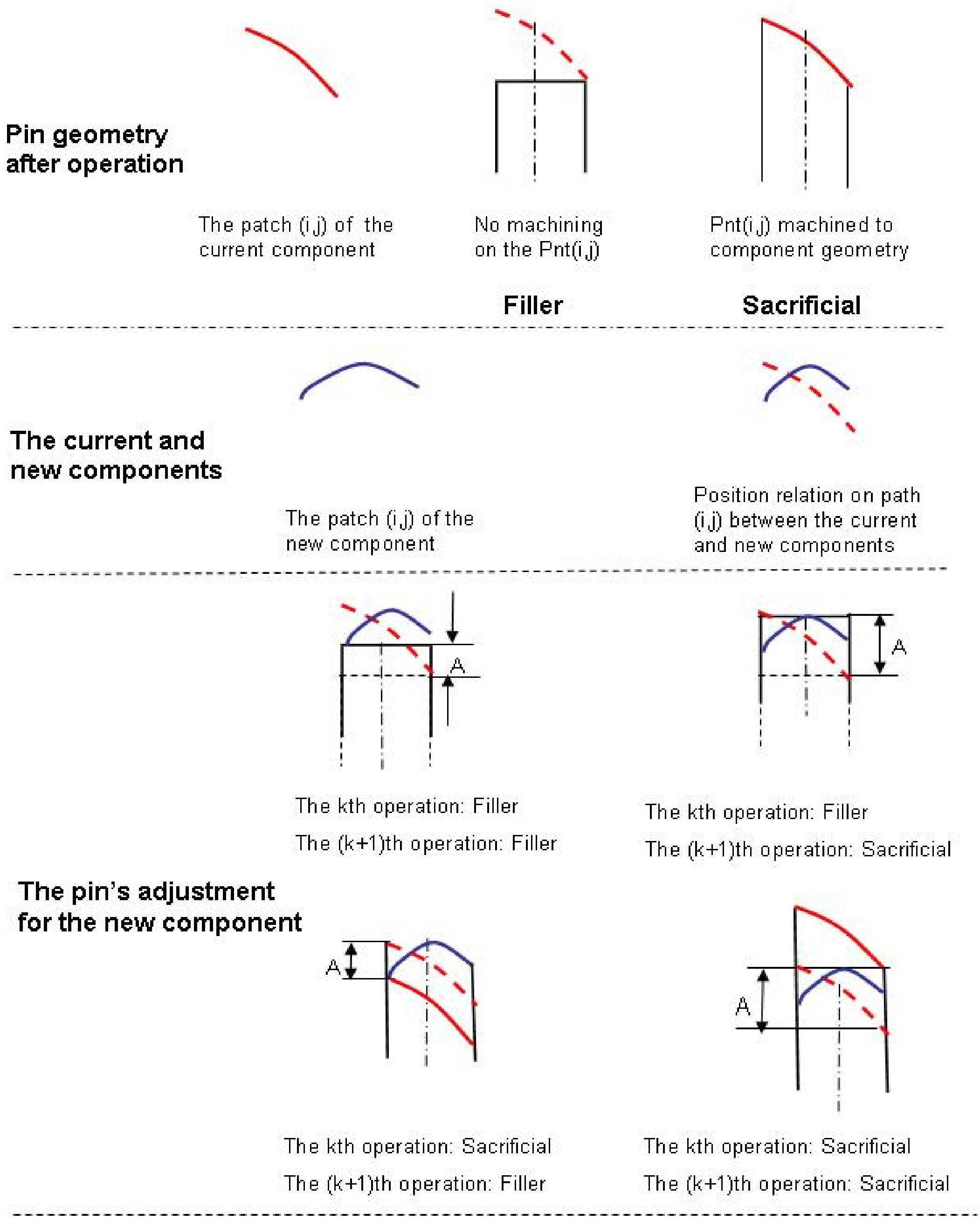


Figure 4-30 Pin adjustment for new component

If filler operation is undertaken for the new component, the screw-pin $\mathbf{Pnt}^{(1)}$ (i,j) needs to be moved to the minimal height regarding the $(i,j)^{th}$ patch of the component, then the screw pin position after adjustment is:

$$\mathbf{Pnt}^{(1)}(i,j).z1 = \mathbf{Pnt}^{(1)}(i,j).min$$

If the operation for the current component is filler, the screw pin should be adjusted to the minimal height of the (i,j)th patch of the current component and there is no machining of the pin.

$$\mathbf{Pnt}^{(1)}(i,j).z0 = \mathbf{Pnt}^{(0)}(i,j).min$$

If the operation for the current component is filler, and the operation for the new component is sacrificial, then:

$$\mathbf{Pnt}^{(1)}(i,j).z1 = \mathbf{Pnt}^{(1)}(i,j).max$$

If the operation for the current component is sacrificial, the screw pin is at the maximum height position of the $(i,j)^{th}$ patch of the k^{th} component. However, since the screw-pins will be machined to conform to component geometry, if the filler operation is undertaken for the new component:

$$\mathbf{Pnt}^{(1)}(i,j).z0 = \mathbf{Pnt}^{(1)}(i,j).min$$

The amount for adjustment is:

$$\mathbf{Pnt}^{(1)}(i,j).\mathbf{A} = \mathbf{Pnt}^{(1)}(i,j).z1 - \mathbf{Pnt}^{(1)}(i,j).z0$$

The remaining length of each screw-pin after adjustment is:

$$\mathbf{Pnt}^{(1)}(i,j).sl = \mathbf{Pnt}^{(1)}(i,j).sl - \mathbf{Pnt}^{(1)}(i,j).\mathbf{A}$$

4.6.4 Evaluation

The purpose of this evaluation is to assess whether or not the previous screw-pin tooling should be employed again or whether a new screw-pin array pattern be used. The evaluations are: the component size should be smaller than that of the overall screw-pin tooling size and the remaining length of each individual pin should be sufficient for the amount of adjustment. The component is put on top of the screw-pin tooling as shown in Figure 4-31. Where **p** is the total number of discretized points of the components; then the evaluation needs to check:

$$\mathbf{XcMax} < \mathbf{SPT}.PXmax+\mathbf{Xpin/2}$$

$$\mathbf{XcMin} < \mathbf{SPT}.PXmin+\mathbf{Xpin/2}$$

$$\mathbf{YcMax} < \mathbf{SPT}..PYmax + \mathbf{Ypin/2}$$

$$\mathbf{YcMin} < \mathbf{SPT}.\ PYmin + \mathbf{Ypin/2}$$

If part of screw-pin inside the tooling container is less than half of the height of the container, the screw-pin is considered to be not sufficiently rigid enough to be moved any further, therefore evaluation for remaining length is:

$$\mathbf{Pnt}\ (i,j).\ sl\ \mathbf{-Pnt}(i,j).\ z\ 1> \mathbf{Zc}/2$$

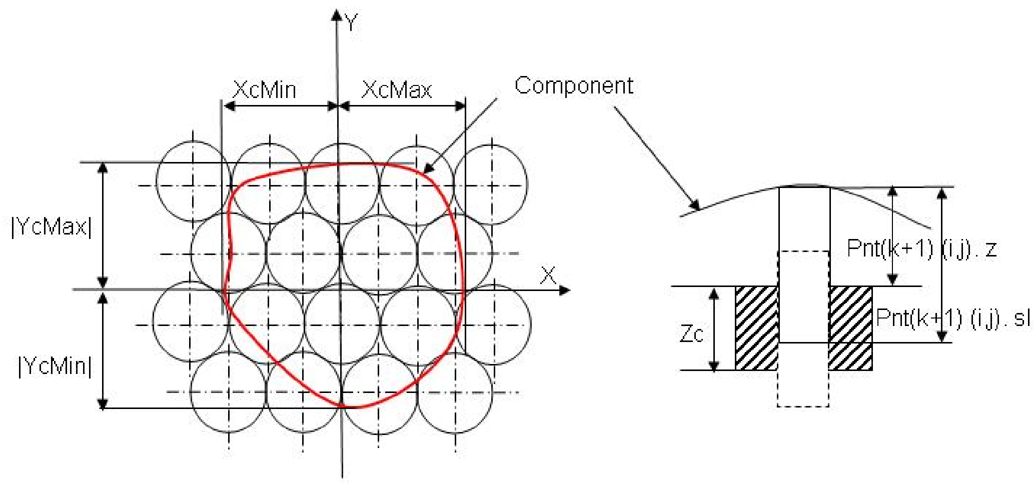


Figure 4-31 Evaluation of screw pin tooling

4.6.5 Screw-pin tooling saving and retrieving

After the calculation of the amount of adjustment of each screw-pin, it is important to save it to a text file in a certain format so that it can be retrieved later. The information of the whole screw-pin tooling includes: component name, screw-pin tooling name, **Dpin**, **Ppin**, **Lpin**, **PXmax**, **PXmin**, **PYmax**, **PYmin**, **Xc**, **Yc**, **Zc Colpin**. The type of operation (filler or sacrificial) are saved in the first line in this order, then it is followed by information about the individual screw-pin, including **Pnt**(0,0).ID, **Pnt**(0,0).X, **Pnt**(0,0).Y, **Pnt**(0,0).Z0, **Pnt**(0,0).Z1, **Pnt**(0,0).Max, **Pnt**(0,0).Min, **Pnt**(0,0).A, Pnt(0,0).sl in this order. as shown in Figure 4-32.

Component name, screw-pin matrix name, **Dpin**, **Ppin**, **Lpin**, **PXmax**, **PXmin**, **PYmax**, **PYmin**, **Xc**, **Yc**, **Zc**, Type of operation

Pnt(0,0).X, **Pnt**(0,0).Y, **Pnt**(0,0).Z0, **Pnt**(0,0).Z1, **Pnt**(0,0).Max, **Pnt**(0,0).Min, **Pnt**(0,0).A, **Pnt**(0,0).sl

Pnt(0,1).X, **Pnt**(0,1).Y, **Pnt**(0,0).Z0, **Pnt**(0,1).Z1, **Pnt**(0,1).Max, **Pnt**(0,1).Min, **Pnt**(0,1).A, **Pnt**(0,1).sl

...

Pnt(i,j).X, **Pnt**(I,j).Y, **Pnt**(i,j).Z0, **Pnt**(i,j).Z1, **Pnt**(i,j).Max, **Pnt**(i,j).Min, **Pnt**(i,j).A, **Pnt**(i,j).sl

Figure 4-32 Screw-pin tooling file for component

In order to reconstruct the screw-pin for a different component, it is necessary to retrieve the screw-pin configuration for the previous component; it is conducted according to the format specified above. When reading a line from the screw-pin array pattern file, it is necessary to identify the pin position regarding the array pattern, and is based on the ID number. Let Int() be the mathematical function to get the integer of the number, e.g. Int(10.8)=10, **Pnt** be the screw-pin point that is being read, then:

i= Pnt(i,j).Y/ Ypin

j= Pnt(i,j).X/Xpin

After the position of the screw-pin is identified, the other variables can be assigned to the **Pnt**(i,j).

4.6.6 Fagor CNC G-code generation

The G-Code, or preparatory code or function, are functions in the numerical control programming language. The G-codes are the codes that position the tool and do the actual work, as opposed to M-codes that manage the machine; T for tool-related codes. S and F are tool-Speed and tool-Feed, and finally D-codes for tool compensation. The programming language of Numerical Control (NC) is sometimes informally called G-code.

The G-code for the screw-pin **Pnt**(i,j) to be adjusted from $\mathbf{Pnt}^{(0)}$(i,j).z1 position for the current component to $\mathbf{Pnt}^{(1)}$(i,j).z1 position for the new component can be generated by the programme without human interference based on screw-pin array pattern files (detailed in section 4.5.5).

1. G-Code file format

The Fagor CNC program for screw pin tooling adjustment includes one main program **(Appendix B.3)** and a subroutine **(Appendix B.4)** which is a canned cycle. The file number for both of the programs must always have 6 digits and the extension. The first line of the main program must start with the % character, the comment associated with the file and the program attributes. To end the first line, RT (return) or LF (LINE FEED) characters should be sent separated by a comma. Following the first line, the file blocks are programmed. These will all be programmed according to the programming rules indicated by the Fagor CNC manual (2006). M30 is used to the end of the program with a return to the first block. The outline of the Fagor CNC main program for screw pin tooling is expressed in Figure 4-33.

The G code file shown in Figure 4-33 contains coordinate values of the screw pins, preparatory functions (G codes), variables e.g. P1 and P2 and subroutine, which are introduced in the following paragraphs.

Code of Fagor CNC Program	**Explanation**
%SCREW PIN ADJUSTMENT, MX, RT	; Start CNC program
G71 G90 G94	; Programming units' definition
G0X -110.688Y 79.880	; Rapid travel to starting point
(P6=100)	; Assigns the value 100 to the variable "P6"
G1X -110.688Y 79.880WP6 F10000	; Move tool tip to retract plane at start point
(PCALL 10, P1= 2.841, P2= 35.384)	; Call to subroutine 10.
G1X -92.240Y 79.880WP6 F10000	
(PCALL 10, P1= 2.505, P2= 51.932)	
G1X -73.792Y 79.880WP6 F10000	Move each pin to desired position by calling subroutine 10
(PCALL 10, P1= 2.572, P2= 51.913)	
……………………………………..	
………………………………………..	
G1X 92.240Y -79.880WP6 F10000	
(PCALL 10, P1= 2.150, P2= 52.314)	
G1X 110.688Y -79.880WP6 F10000	
(PCALL 10, P1= 2.878, P2= 35.052)	
G0W100	; Execute rapid traverse to retrace plane
M30	; End of program with return to the first block

Figure 4-33 Outline of the Fagor CNC main program

2. Coordinate axis

The four machine axes, as shown in Table 4-4, are used by the Fagor CNC program. X and Y axes are used to control the tool position in the X, Y direction of the coordinate frame; Z is used to specify the top position of the screw-pins (equivalent to Z for the normal CNC machine). The C axis indicates the rotational angle in order for the screw-pin to be moved to the required position.

Table 4-4 Coordinate axes

Axis	Description
X	X coordinate value on the main work plane of the machine
Y	Y coordinate value on the main work plane of the machine
Z	Screwing height direction
C	Rotational angle of screw-pin/tool (unit: degree)

3. Preparatory functions (G codes)

Preparatory functions are programmed using the letter G followed by up to 3 digits (G0-G319) (Fagor Automation, 2006). They are always programmed at the beginning of the body of the block and are useful in determining the geometry and working condition of the CNC. Table 4-5 lists all the G functions used by the CNC program for screw pin adjustment, and further description is made in the following paragraphs.

Table 4-5 G functions used in the CNC (Fagor Automation, 2006)

Function	Meaning
G0	Rapid traverse
G1	Linear interpolation
G04	Dwell
G71	Programming in millimetres
G90	Absolute programming
G91	Incremental programming
G92	Coordinate preset
G94	Feed rate in millimetres per minute

1) G0: the movement of axes is a rapid traverse and is executed at the rapid feedrate indicated in the axis machine parameter "G0FEED". Independently of the number of axes which move, the resulting path is always a straight line between the starting point and the final point.

2) G1: the movements programmed after G01 are executed according to a straight line and at the programmed feedrate "F". When two or three axes move simultaneously the resulting path is a straight line between the starting point and the final point. The CNC calculates the feedrate of each axis so that the resulting path is the "F" value programmed.

3) G71: when working in G71, figure from 0.00001 to 99999.9999 in millimetres is allowed in program and is called format+/-5.4.

4) G90: when working in absolute coordinates, the point coordinates refer to a point of origin of the established coordinates, often the part zero.

5) G91: when working with G91, the numerical value programmed corresponds to the movement information for the distance to be travelled from the point where the tool is situated at that time. The sign in front shows the direction of movement.

6) G92: when a zero offset is carried out via Function G92, the CNC assumes the coordinates of the axes programmed after G92 as new axis values. No other function can be programmed in the block where G92 is defined.

7) G94: feedrate in mm/min. The relationship between the feedrate of the axis component and the programmed feedrate "F" is as follows:

$$Feedrate\,component = \frac{Feedrate\,F \times Movement\,of\ axis}{\mathrm{Re}sulting\ programmed\,movement}$$

It can be further expressed as:

$$F_x = \frac{F \cdot \Delta x}{\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}}$$

$$F_y = \frac{F \cdot \Delta y}{\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}}$$

$$F_z = \frac{F \cdot \Delta z}{\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}}$$

4. Variables

Variables are applied to pass values from the main program to subroutine or vice versa. There are six variables from P1 to P6 used in the CNC program. The unit of P1, P2, P3, P4 and P6 is mm, and the unit of P5 is degree. In the program, a value or an expression can be assigned to each variable.

Table 4-6 Variables used in Grip program

Variables	Description
P1	Current screw pin Z coordinate
P2	Length to be adjusted
P3	Tool tip position for changing feed rate
P4	Tool tip position for starting adjustment
P5	Degrees to be adjusted
P6	Retract plane height

The variables in table 4-6 can be illustrated in Figure 4-34. The feature with a broken line is a screw pin before adjustment, and the feature with a solid line is the adjusted screw pin. The tool needs to have the screw-pins inserted before being rotated, that is why P4 is slightly lower than P1.

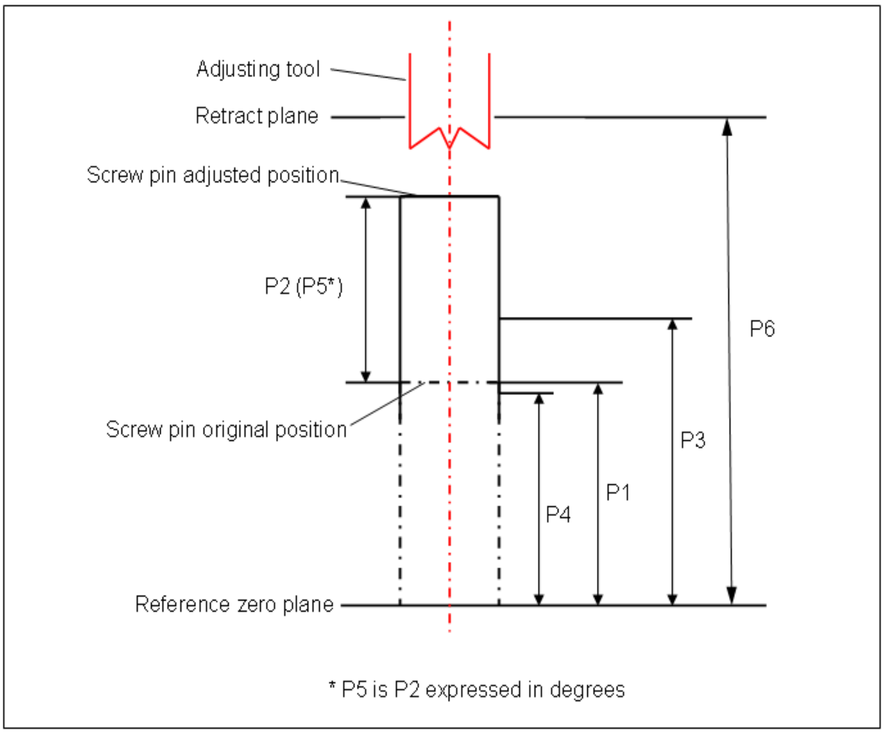


Figure 4-34 Variables used in Grip program

5. Subroutine construction and commends

A subroutine is a part of a program which, being properly identified, can be called from any position of a program in order to be executed. A subroutine can be kept in the memory of the CNC as an independent part of a program and be called one or several times, from different positions of a program or different programs. Only sub programs stored in the CNC's RAM can be executed.

1) Calling Subroutine from the main program

The mnemonic "PCALL" makes a call to the subroutine indicated by means of a number or by means of any expression that results in a number. In addition, it allows up to a maximum of 26 local parameters of this subroutine to be initialized. These local parameters are initialized by means of assignment instructions.

The subroutine construction can be expressed as:

(PCALL(expression), (assignment instruction), (assignment instruction)…))

2) Comments

Any kind of information can be incorporated into all blocks in the form of a comment. The comment is programmed at the end of the block, and should begin with the character ";".If a block begins with ";" all its contents will be considered as a comment, and it will not be executed. Empty blocks are not permitted. They should contain at least one comment.

3) Subroutine format

A subroutine is defined by using the "SUB" instruction at the beginning while the mnemonic "RET" indicates the finish of the subroutine. Between the "SUB" and the "RET", there is a set of program blocks. In the Fagor controller, the subroutine is identified with an integer which also defines the type of subroutine, either general or OEM. The range of general subroutines is "SUB 0000" to "SUB 9999" and the range of OEM (manufacturer's) subroutines "SUB 10000" to "SUB 20000".

A canned cycle expressed in Figure 4-35 is developed to adjust the height of a single screw pin. It is used as a subroutine called by the main program shown in Figure 4-33. By repeated use of the canned cycle, all the screw pins in a tooling can be produced.

Code of canned cycle	**Explanation**
(SUB 10)	; Definition of subroutine 10
G92 C0	; Preset current position as zero
(P3=P1+10, P4=P1-1.5, P5=((P2/2.5)*360))	; Assign values to P3, P4, P5
G1WP3F3000	; Tool tip move to P3
G1WP4F100	; Tool tip move to P4
G04 K2	; Dwell
G91G1WP2CP5F5000	; Incremental move P2
G90G1WP6F3000	; Straight positioning at P6
(RET)	; End of subroutine

Figure 4-35 Canned cycle for screw pin adjustment

In the canned cycle, variable P1, P2 and P6 are assigned in the main program. P3, P4 and P5 are calculated based on P1 or P2 value. The adjusting tool moves to the P3 position first and then to the P4 position. From the P4 position, the adjusting tool moves the screw up until it reaches the P2 position, and then rapidly back to the retract plane. Please see Figure 4-36 for a better understanding of this process.

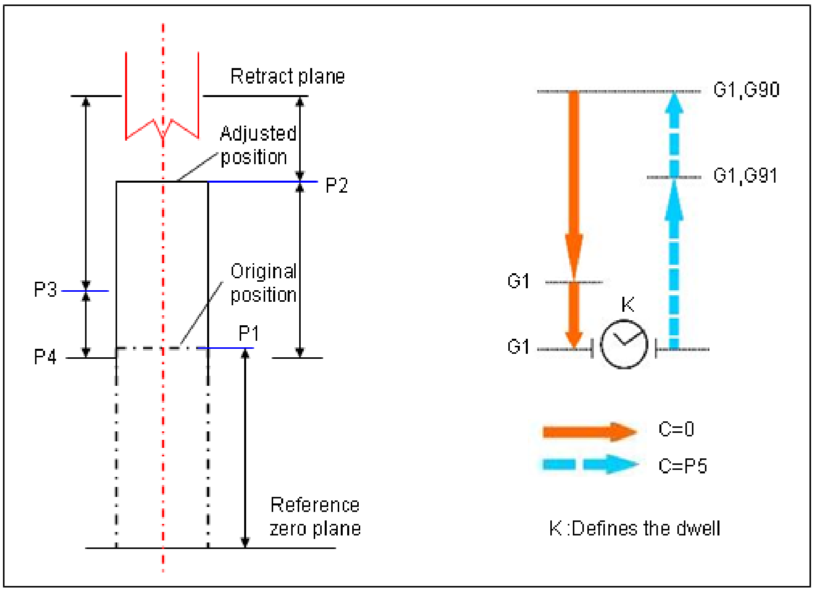


Figure 4-36 Diagram of canned cycle of screw pin adjustment

6. VB Programme for the G code generation

The programme for the automatic generation of G code is shown in Figure 4-37.

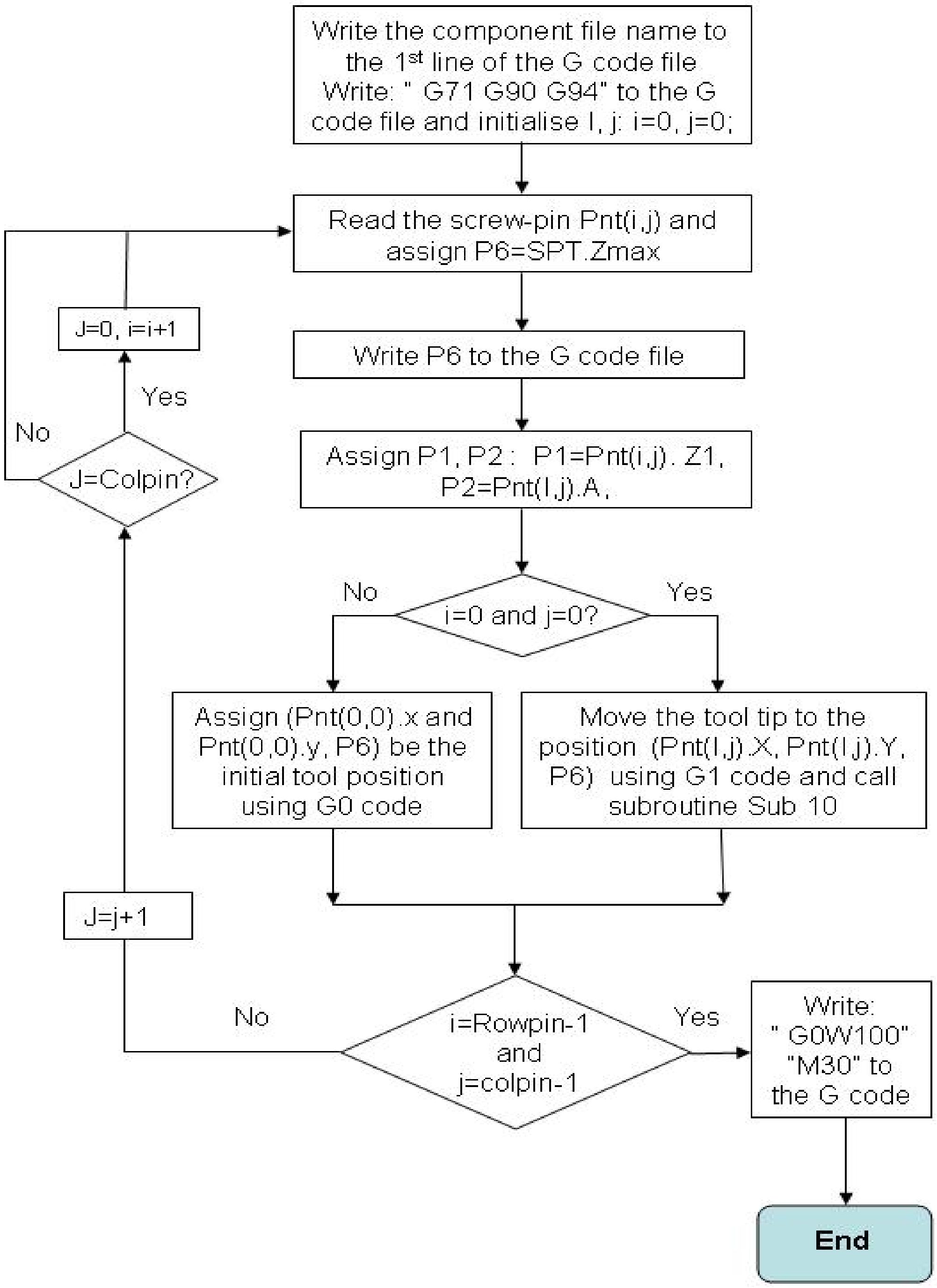


Figure 4-37 G code generation flowchart

4.6.7 Introduction to the screw-pin construction, adjustment and evaluation interface based on Visual Basic

The interface is a user-friendly interface which allows the user to process the file generated by FEA software and scanning software. As shown in Figure 4-38, it includes 4 sections: point processor, screw-pin construction, pin adjustment and evaluation and G code generation. The point processor interface contains the description, selection of file formats, and allows the user to select the component point cloud file quickly.

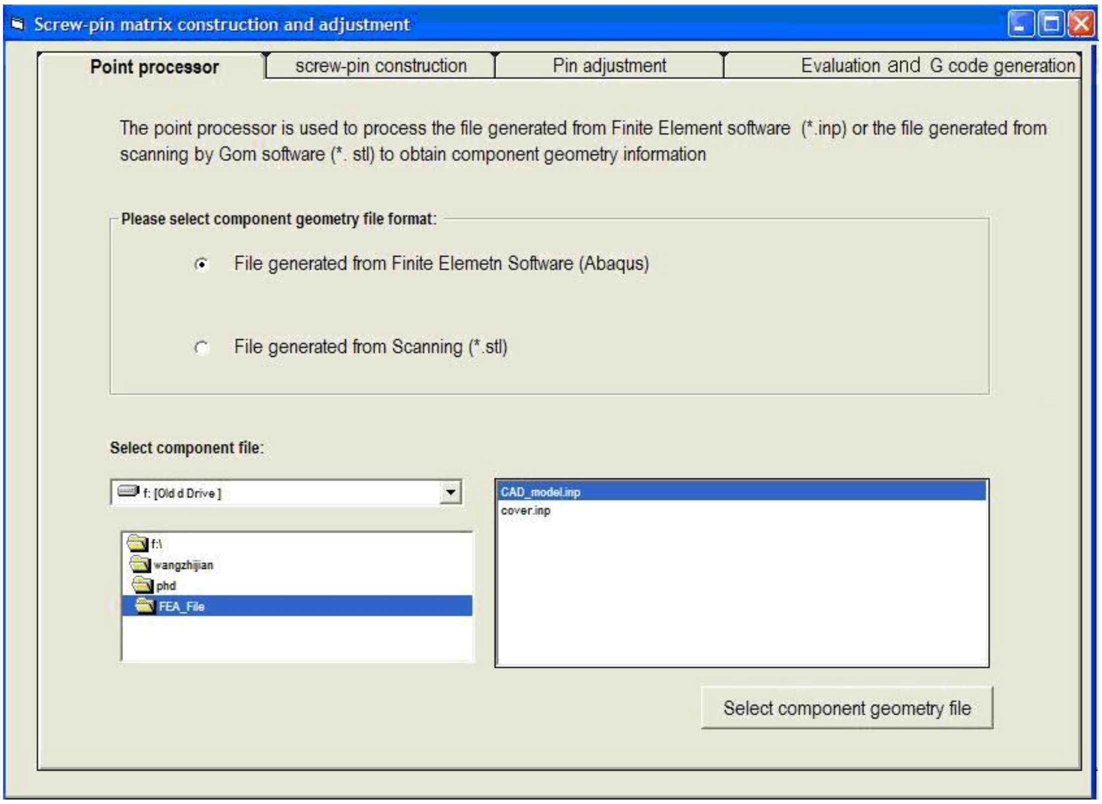


Figure 4-38 Point processor interface of SCAG

In Figure 4-39, the left hand side of the screw-pin array pattern construction interface allows the user to retrieve the old screw-pin array pattern for the component, whilst the right hand side of the screw-pin array pattern construction interface is for the user to construct a new screw-pin array pattern.

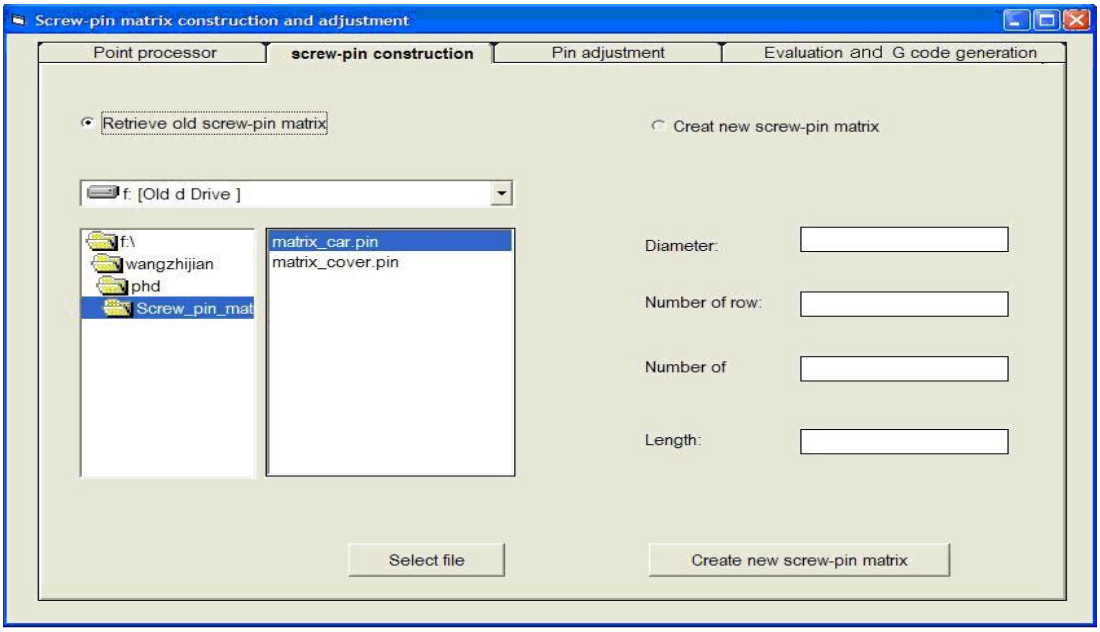


Figure 4-39 Screw-pin array pattern construction interface of SCAG

Pin adjustment section (shown in figure 4-40) allows the user to select the adjustment type, either filler or sacrificial, calculate the amount of the adjustment of each individual screw-pins and save the file to the user specified destination.

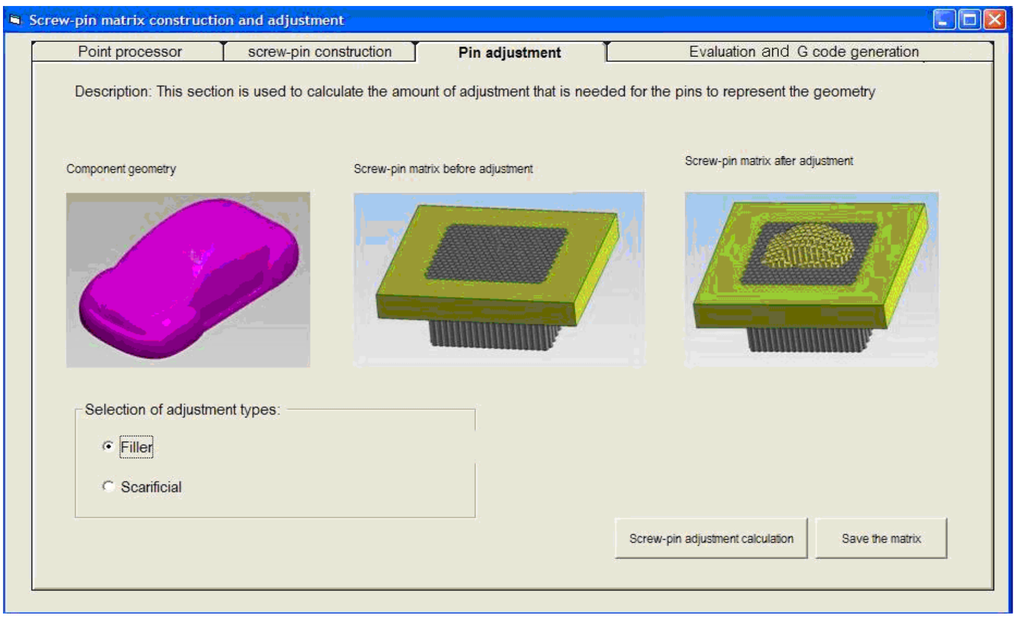


Figure 4-40 Pin adjustment section of SCAG

The evaluation and G code generation section (shown in Figure 4-41) firstly evaluates whether or not the screw-pin array pattern is appropriate for the component based on the overall size of the component and screw-pin array pattern and the remaining length of the individual pins. The component file name and screw-pin array pattern file name are automatically shown here once the user has identified the names in previous sections. If there is a problem, the interface will prompt messenger so that the user is aware of the problem. After the evaluation and screw-pin array pattern is appropriate for the component, G code will automatically be generated for the Fagor CNC control.

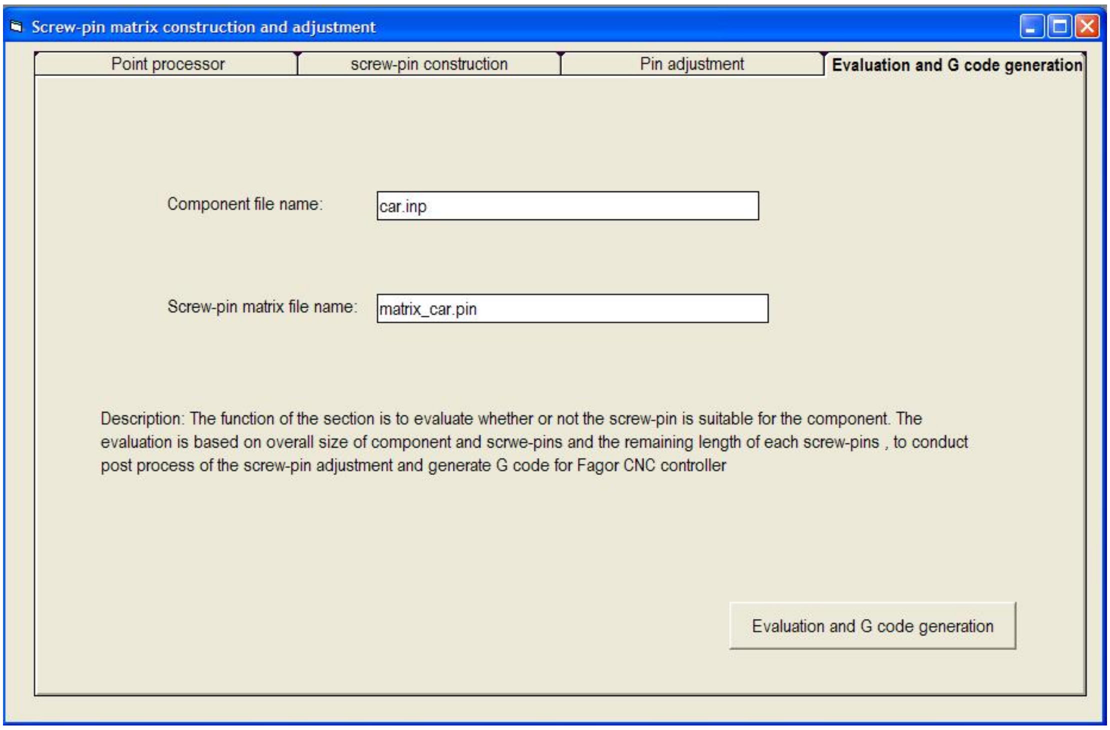


Figure 4-41 Evaluation and G code generation section of SCAG

4.7 Screw-pin array pattern display and verification

After the calculation of adjustment of the screw-pin tooling and generation of G code, it may be necessary to display the screw-pins within in a CAD/CAM environment to verify whether or not the screw-pins are in the correct positions before any physical machining takes place in order to prevent any collision or failure in the machine execution stage.

The geometry and the final position of the screw-pin are generated automatically based on the screw-pin array pattern file by the program developed within the Unigraphics/Grip environment.

4.7.1 Introduction to Unigraphics /GRIP

GRIP is an acronym for Graphics Interactive Programming. It is a programming language developed by Unigraphics Solutions. GRIP is used to create C language—like programs to automate most operations in Unigraphics NX and its associated modules (Unigraphics NX, 2004). The procedure for creating and running a GRIP program is similar to that of C program and includes creating, compiling, linking, running and debugging programs.

Many operations that can be performed interactively in Unigraphics NX can be performed by using a GRIP program. Commands are available to create geometric and drafting objects, control system parameters, perform file management functions and modify existing geometry. GRIP also provides interactive commands to control entity selection, menu option selection, data entry, text entry and the Generic Point Sub function. In some cases, GRIP can perform advanced, customized operations, in a more efficient manner than using interactive NX (2004). It can simplify repetitive operations by automatically performing operations that might take many interactive steps, e.g. lead-in, lead out of cutter position and rotation of the screw pins.

A GRIP program is created by using an operating system editor, typically after entering the GRIP Advanced Development Environment (GRADE, shown in Figure 4-42). The GRADE is a separate, executable program that allows a variety of GRIP program development functions to be performed from the operating system. GRADE facilitates edit, compile and link to create a GRIP executable file.

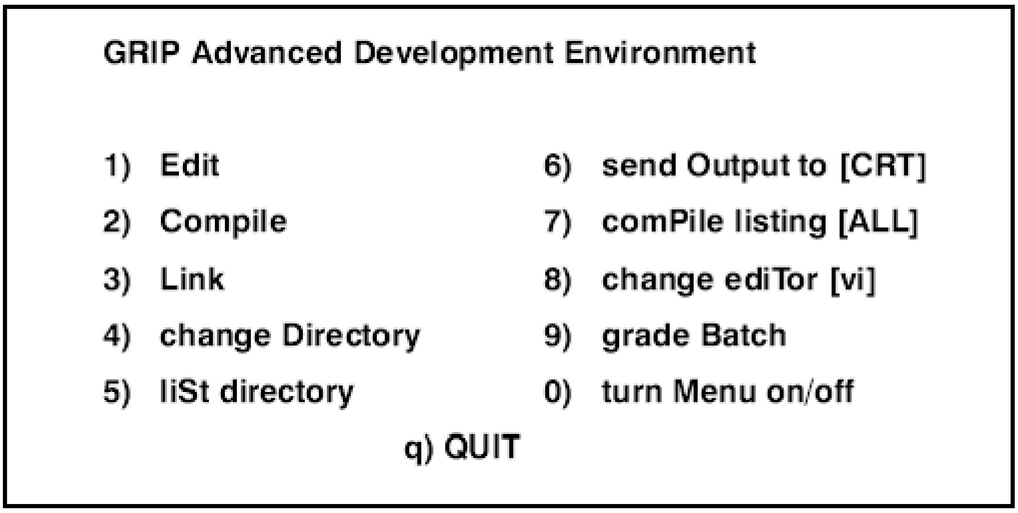


Figure 4-42 GRIP Advanced Development Environment

A GRIP source program is composed of a series of statements in the GRIP language. Generally, a GRIP program can be organized into five major areas, as shown in Figure 4-43. Each area has related GRIP language commands.

4.7.2 Screw pin tooling shape controller

1. Container creation

The container is used to clamp all the screw pins of the tooling and is designed as a rectangular block with a hollow core. The following statements are used to create a parametric container of a given size.

BLOCK1=SOLBLK/ORIGIN,-X_C/2,- Y_C/2,- Z_C/2,SIZE,X_C,Y_C,Z_C

&COLOR(BLOCK1)=&ORANGE

Where: X_C=**SPX**.Xc

Y_C=**SPX**.Yc

Z_C=**SPX**.Zc

Grip sample program	Explanation
ENTITY/LN,CR,PT NUMBER/mm(3) STRING/str(20),NAME(30)	**Declaration Statements**
DATA/mm,27,08,10 A=3 str='James Bond'	**Initialization Statements**
$$ Input student name L5: TEXT/'Student Name', NAME,rsp JUMP/L5:, L30:,,rsp $$ Open Point Constructor l10: GPOS/'Define First Point', x1,y1,z1, rsp JUMP/l10:,trm:,,,,rsp	**Interactive Statements**
PT=POINT/1,1 $$ draw point LN=LINE/0,0,0,x1,y1,z1 $$ draw line CR=CIRCLE/0,0,5 $$ draw circle	**Processing Statements**
L30: HALT	**Termination**

Figure 4- 43 GRIP program outline

X_C represents the length dimension of the container block, Y_C is its width dimension, and Z_C is its height dimension. The edges of the container block are aligned with the axes of the Work Coordinate System. A container created by the GRIP program is shown in Figure 4-44

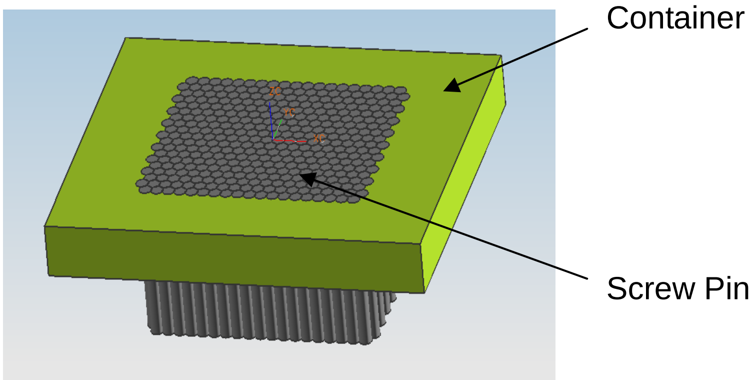


Figure 4-44 Screw pin tooling produced by the GRIP program

2. Screw pins creation

Each screw pin is simplified by a cylinder in the GRIP program. The pin's original arrays X_O, Y_O, and Z_O are calculated using the aforementioned formulae in the program at first before the following statement is used to create a single screw pin:

PIN1(i,j)=SOLCYL/ORIGIN,x0, y0,z0,HEIGHT,Lpin,DIAMTR,Dpin

Where X0=**Pnt**(i,j).X, Y0=**Pnt**(i,j).Y and Z1=**Pnt**(i,j).Z1. The pin creation statement is used together with **Do Loop segments** to generate every screw pin (Figure 4-44) of the tooling.

3. Fetch screw pin array pattern file

This process is to import a screw pin array pattern file produced from a geometric model that the tooling is to be adjusted to. By using **Do-Loop**

segments in Figure 4-45, each data is assigned to X_n, Y_n, Z_n arrays.

```
do/loop1:,i,1,ROWpin
   IFTHEN/MODF(i,2)<>0
     do/loop2:,j,1,COLpin-1
              Processing Statements
     loop2:
   ELSE
     do/loop3:,j,1,COLpin
       Processing Statements
     loop3:
   ENDIF
 loop1:
```

Figure 4-45 Do-Loop segments for screw-pin creation

1) Retrieves a screw pin array pattern file; it can be written as:

   FETCH/TXT,2,'driver:\ directory\filename.dat'

   RESET/2

2) Assign data to X_n, Y_n, Z_n arrays:

   READ/2, Pnt(i,j).X, Pnt(i,j).Y, Pnt(i,j).Z,

   X_n(i,j)= Pnt(i,j).X

   Y_n(i,j)= Pnt(i,j).Y

   Z_n(i,j)= Pnt(i,j).Z

4. Screw pin transformation to adjust screw pin from one position to another

   The transformation of each screw pin includes the following steps:

1) Defines an array pattern used to perform a linear transformation of Zt(i,j) distance in Zc. It is expressed as:

$$
\begin{aligned}
MAT1 &= MATRIX\ /TRANSL,0,0,Zt(i,j) \\
&= \begin{bmatrix} 1, & 0, & 0, & 0 \\ 0, & 1, & 0, & 0 \\ 0, & 0, & 1, & Zt(i,j) \end{bmatrix}
\end{aligned}
$$

2) If Zt(i,j) is not equal to zero, create a copy of the original pin in another colour, and move the new pin Zt(i,j) distance in Zc. This is stated as:

```
AJUST1(i,j)=TRANSF/MAT1,PIN1(i,j)
&COLOR(AJUST1(i,j))=&DKRED
```

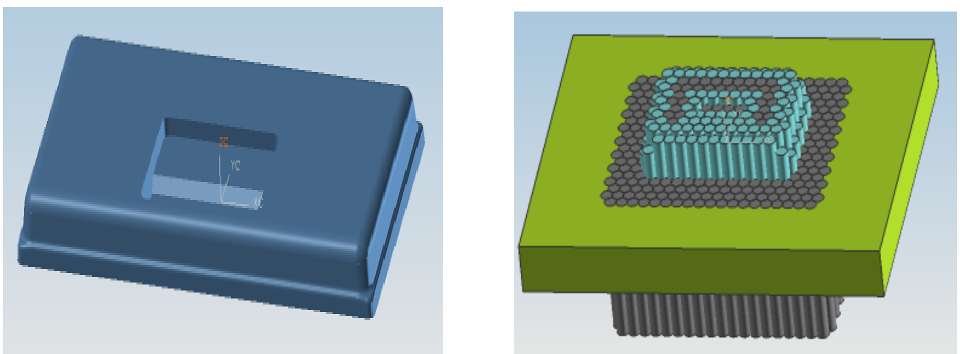
3) Delete the original pins:

```
DELETE/PIN1(i,j)
```

The verification software developed in the GRIP is listed in **Appendix B.5**.

5. Examples

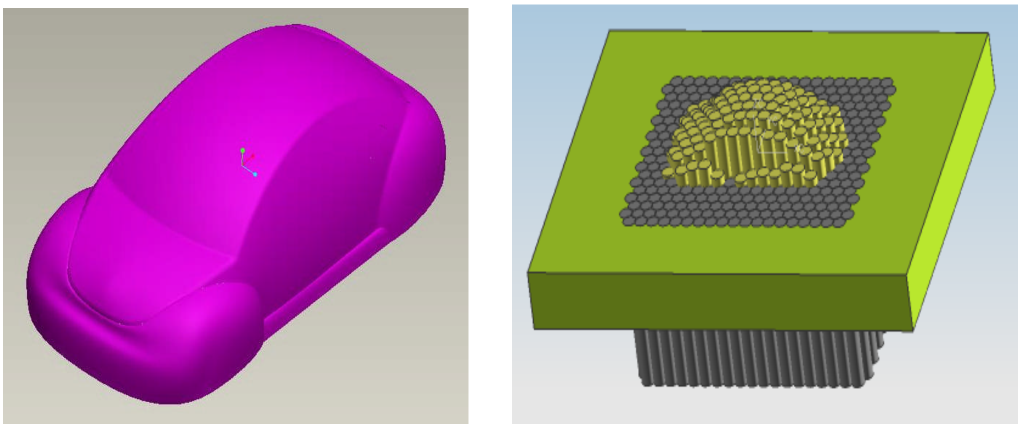
Example 1: Figure 4-46(b) is the screw pin tooling for a rectangular cover model (a). The tooling will be machined for the filler vacuum forming application. It is transformed from the original tooling in Figure 4-44 directly.



(a) Rectangular cover (b) Tooling for rectangular cover

Figure 4-46 Screw pin tooling adjusted to a cover shape

Example 2: Figure 4-47(b) is a screw pin tooling for a beetle car model (a). The tooling will be machined for sacrificial vacuum forming application. It is transformed from the rectangular cover tooling in Figure 4-46 (b) directly.



(a) Beetle car (b) Tooling for beetle car

Figure 4-47 Screw pin tooling readjusted to a car shape

4.8 Summary

The development of support software to enable automatic adjustment of the SPT has been discussed in detail in this chapter. The screw pin tooling shape control methodology has been described and the generation procedure of the digital SPT has been introduced. The methodology has described the mathematics including the design model description, SPT description and adjustment description. The discretization method was employed to obtain point positions of the components. Two types of discretization methods have been illustrated: the 3D CAD model and the 3D physical model. The support software was composed of two packages: the A package for pin adjustment and the B package for simulation. The A package software has been developed with Visual Basic and is composed of four parts: a) the point processor is developed to process the file generated from the Finite Element software (*.int) or the file generated from scanning by the GOM software (*.stl) to obtain component geometry information; b) the screw-pin tooling construction is developed to retrieve or construct the screw-pins array pattern; c) the pin adjustment is employed to select the adjustment type and calculate the amount of adjustment for each individual screw-pin; d) the evaluation and NC code generation are applied to evaluate whether or not the screw-pin array pattern is appropriate for the component and generate NC code. Package B is developed with Graphics Interactive Programming to simulate the SPT adjustment within Unigraphics Solutions' CAD system and verify the results visually.

CHAPTER 5

Experimental Investigation Based on the Integrated Moulding Machine System

5.1 Introduction

The focus of this chapter is to describe the experiments that were conducted on the HAVES test bed which were conducted to measure the screw-pin adjustment performance and evaluate component surface quality as produced by the SPT. Firstly, the tests on screw-pin adjustment performance are described and the repeatability and accuracy of the screw-pin positions are evaluated. Secondly, the SPT is adjusted and used to vacuum form a 600x600x5 mm HIPS; then the SPT is machined according to the design model and employed to produce components using different thermoplastic material and thickness. The defects in surfaces of formed components are measured and compared. Thirdly, a few thermoplastic materials are investigated and the best material for sacrificial application selected. Finally, several filler materials are selected, painted onto the SPT, dried and machined to produce a smooth surface for screw-pin tooling. By examining the machined surfaces, the best filler for covering the screw-pin tooling is selected.

5.2 Experiment schedule

The operation of the HAVES test bed includes two key steps: the SPT was adjusted to a near-net shape of the design mould and vacuum formed to produce the final product, so the adjustment performance of the screw pins and the surface quality of the vacuum formed components could be tested before application. The experiments introduced in this chapter include two serials: screw-pin adjustment performance tests and the SPT vacuum forming tests.

The repeatability and accuracy of the screw-pin positions are evaluated by calculating and comparing average errors and standard deviations of the adjustment to determine the adjustment performance of the screw pins. The roughness average and surface deviation average are measured by TALYSURF CLI 1000 to find the surface quality of components produced by vacuum forming. The SPT vacuum forming experiment is composed of four sub-experiments, each with individual test processes as shown in Figure 5-1:

Test process 1: Adjust the SPT according to the design model, and then do the vacuum forming on the SPT.

Test process 2: Adjust the SPT according to the design model, machine the adjusted SPT to the final shape and then complete the vacuum forming on the SPT.

Test process 3: Adjust the SPT according to the design model, machine the adjusted SPT, cover the surface of the SPT with a sacrificial thermoplastic sheet and machine it to the final shape, and then complete the vacuum forming on the sacrificial cover.

Test process 4: Adjust the SPT according to the design model, machine the adjusted SPT, paint the surface of the SPT with a filler material and machine it to final shape after drying, and then complete the vacuum forming on the machined filler surface.

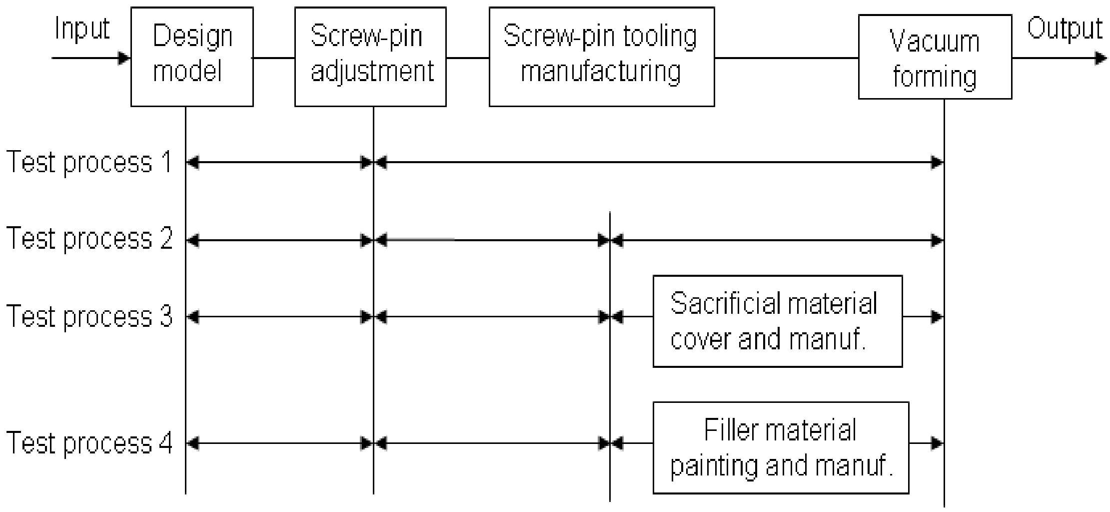


Figure 5-1 Evolution schematic of SPT vacuum forming experiments

5.3 Screw-pin positioning performance

5.3.1 Objective

The objective of this test was to determine the positioning performance of the screw-pin tooling in the HAVES test bed. The positioning performances to be assessed include position repeatability and accuracy.

5.3.2 Evaluation parameters

The repeatability of the screw pins measures how well a pin returns to the same position by using the same adjusting parameters; it calculates the dispersion width of the average value. The accuracy of the screw pins measures how well the pin reaches its target positions; it compares the difference between the target position and the real position.

The sample average value ($\bar{x}$) and sample standard deviation (S) were two parameters used to evaluate repeatability and accuracy, and they can be expressed as follows:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_N}{N} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (5\text{-}1)$$

$$S_{dev} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad (5\text{-}2)$$

Where $\bar{x}$ is the arithmetic mean of the samples x_i ; $\{x_1, x_2, \cdots, x_N\}$ is the samples; $i \in [1, N]$; N is the sample size and S_{dev} is sample standard deviation.

5.3.3 Test set up and procedure

As shown in Figure 5-2, the tests were performed by using the pin driving tool to adjust screw-pins of the tooling in the HAVES. A Mitutoyo digital height gauge with $\pm 0.01mm$ accuracy and 1000mm measurement range (model 570-113) was used to measure screw-pin positions and a datum block was treated as reference. To secure all the screw-pins in home positions, a flat surface milling was applied to manufacture the screw-pin tooling. The screw-pins were adjusted from the home position and four adjustment distances were tested: 50mm, 100mm, 150mm and 200mm; three data sets were collected with 5 adjustment cycles in each set for each of the four distances. As for vertical adjusting movement in the XZ or YZ plane, the approaching feedrate, engagement feedrate, driving feedrate and retract feedrate were set at 3000mm/min, 100mm/min, 5000 degree/min and 3000mm/min respectively. The feedrate of the tool head in the XY plane was set as 10000mm/min.

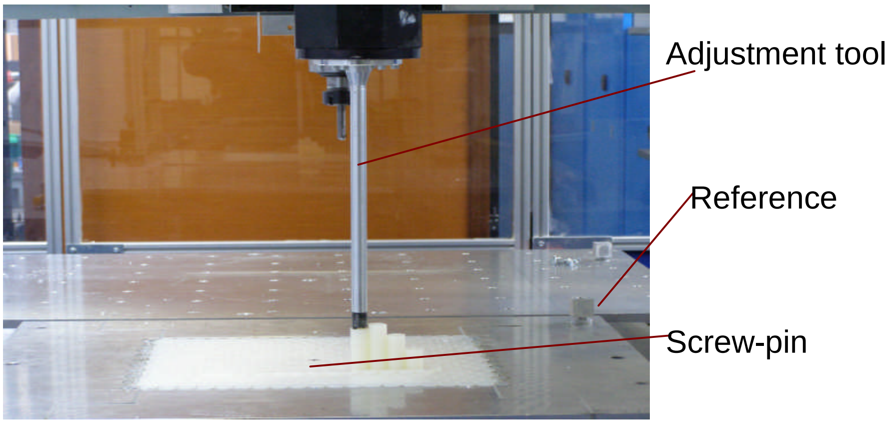


Figure 5-2 Screw-pin adjustment test

1. Repeatability test procedure

As for each repeatability test serial, an initial adjustment was applied to establish a reference position and then five cycles were performed repeatedly according to the following steps:

1) The adjustment tool was moved in the retract plane from its home position to sit on top of the screw-pin for adjustment;
2) The adjustment tool approached, engaged and adjusted the screw-pin to a certain position;
3) The adjustment tool was moved rapidly back to the retract plane on top of the screw pin;
4) The position of the screw-pin was recorded and then the screw-pin was moved back to the home position;
5) Step 2, 3 and 4 were repeated five times, and recorded every screw-pin position;
6) The adjustment tool was moved to its home position.

2. Accuracy test procedure

For each accuracy test serial, the screw-pins were adjusted according to the following steps:

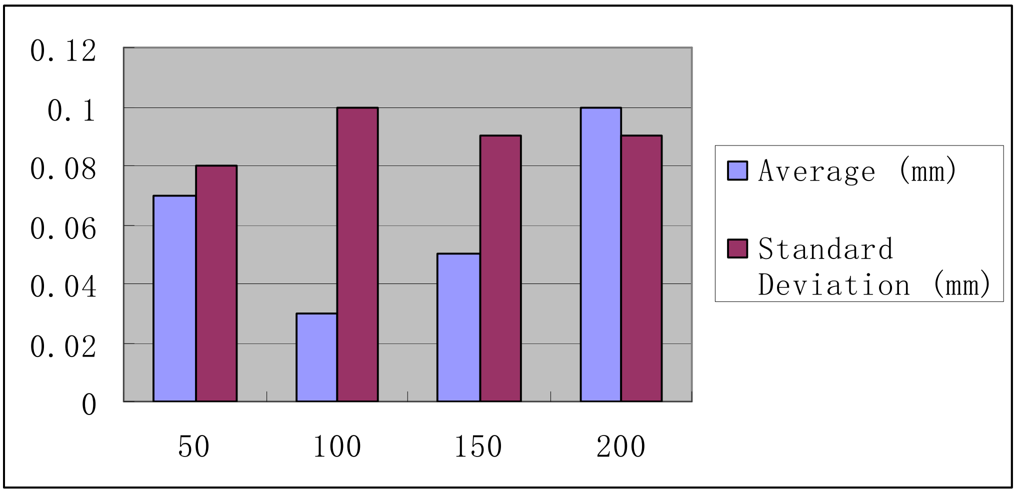
1) The adjustment tool was moved in the retract plane from its home position to sit on top of the first screw-pin to be adjusted;
2) The adjustment tool approached, engaged and adjusted the screw-pin to a certain position;
3) The adjustment tool was moved rapidly back to the retract plane and went to next pin top in the retract plane;
4) Step 2 and 3 were repeated until the adjustments of all the five screw-pins were finished;
5) The adjustment tool was moved to its home position and the positions of all five screw-pins were recorded.

5.3.4 Test results and analysis

1. Repeatability

All test data were recorded in Appendix C.1 and further expressed as a average error from the initial position in each serial. The maximum deviation measured over 60 samples was 0.30mm. The test results are summarized in Table 5-1.

The minimum average error was 0.03mm with a standard deviation of 0.10mm in 100mm adjustment and the maximum average error was 0.10mm with a standard deviation of 0.09mm in 200mm adjustment.



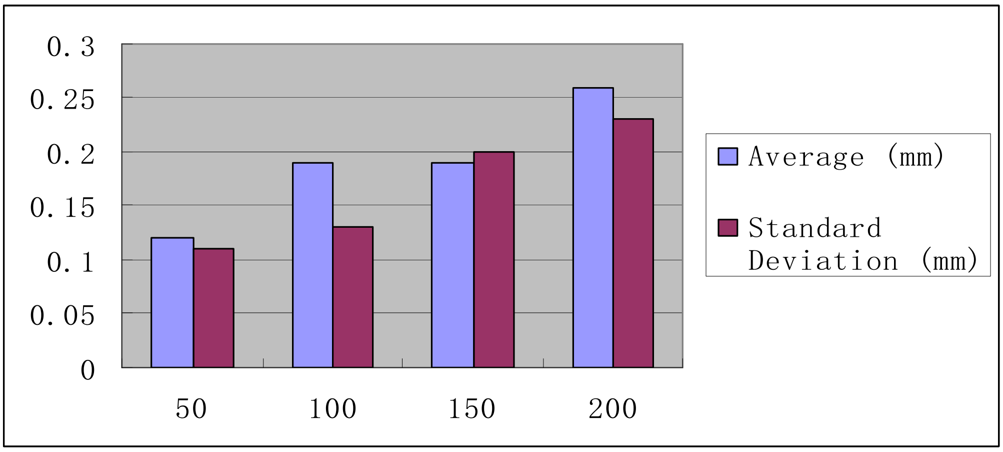
Adjustment Distance (mm)	Average (mm)	Standard Deviation (mm)
50	0.07	0.08
100	0.03	0.10
150	0.05	0.09
200	0.10	0.09

Table 5-1 Screw-pin adjustment repeatability deviation summary

2. Accuracy

All test data was recorded in Appendix C.2 and further expressed as a average error from the target position in each serial. The maximum deviation measured over 60 samples was 0.46mm. The test results were summarized in Table 5-2.

The minimum average error was 0.12mm with a standard deviation of 0.11mm in 50mm adjustment and the maximum average error was 0.26mm with a standard deviation of 0.23mm in 200mm adjustment.



Adjustment Distance (mm)	Average (mm)	Standard Deviation (mm)
50	0.12	0.11
100	0.19	0.13
150	0.19	0.20
200	0.26	0.23

Table 5-2 Screw-pin adjustment accuracy deviation summary

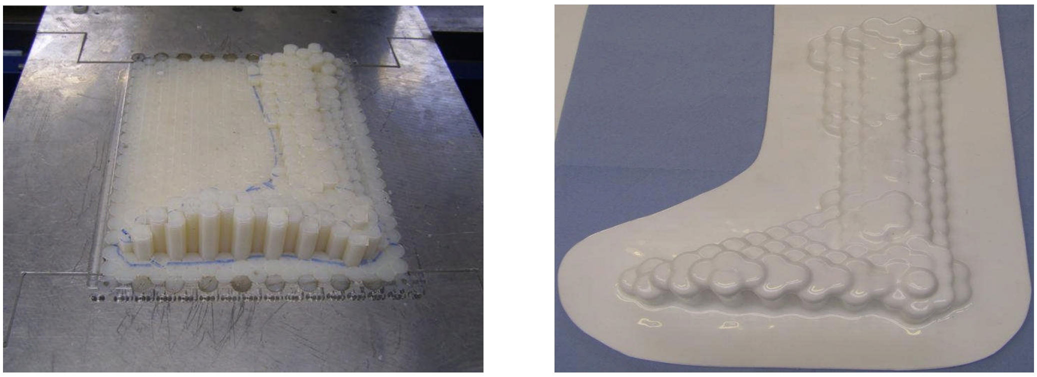
5.4 Screw-pin tooling test

5.4.1 Objective

The objective of this experiment was to provide an initial evaluation of the SPT by checking surface quality of plastic components formed on it and highlighting the further development requirements for the tooling.

5.4.2 Experiment set up and procedure

This experiment was performed within the HAVES test bed. The screw-pin tooling with 19 rows and 20 columns M20x300mm screw-pins discussed in Chapter 4 was used in the test. The screw-pin tooling was adjusted to a leg shape as shown in Figure 5-3 (a) according to the developed tooling shape control methodology, and then a component was formed based on the screw-pin tooling by using a HIPS plastic sheet. The parameters used in the vacuum forming process are listed in Table 5-3. Once the formed component was removed from the machine, the excess material was trimmed to produce the final part.



(a) Leg shape screw-pin tooling (b) Vacuum formed leg

Figure 5-3 Screw-pin tooling and application

Table 5-3 Vacuum forming parameters for leg

Material	Size (mm)	Heater set temp. (°C)	Heating time (seconds)	Vacuum pressure(" Hg)
HIPS	600x600x5	350	180	25

5.4.3 Experiment summary

As shown in Figure 5-3 (b), the component formed by the screw-pin tooling had a very rough surface. The teeth of the screw pins were imprinted on the side surfaces, the engagement gaps among screw pins produced many dimples on the top surfaces and the discrete top surface of the screw pins formed many stairs on the component appearance.

5.5 Machined screw-pin tooling test

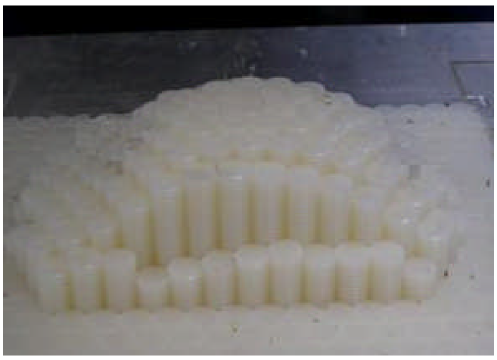
5.5.1 Objective

The objective of this experiment is to provide a performance evaluation of the machined SPT by measuring surface quality of plastic components formed on it and highlighting the further developmental requirements for the tooling.

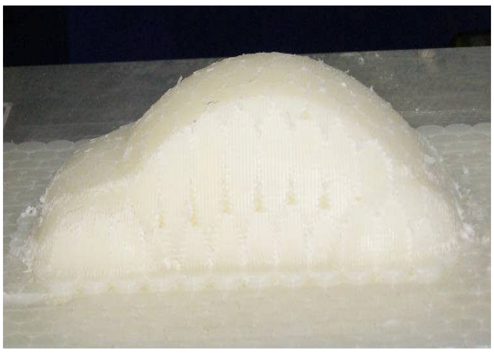
5.5.2 Test set up and procedure

1. Test set up

This experiment was performed within the HAVES test bed. The screw-pin tooling included 19 rows and 20 columns and the M20x300mm screw-pins discussed in Chapter 4 was used in the test. The SPT was adjusted to a beetle car shape in the maximum position for each screw pin as shown in Figure 5-4 (a), and then the stairs of the screw-pin were machined by the CNC according to the CAD model; finally, components were vacuum formed based on the screw-pin tooling by using different thermoplastic sheets.



(a) Before machining



(b) After machining

Figure 5-4 Screw-pin tooling for test

The measurement set up is shown in Figure 5-5, in which a precision 3D surface profiler-TALYSURF CLI 1000 was used to scan 3D surfaces of the workpiece. Analysis software, Mountains® surface, was applied to analyse measurement results.

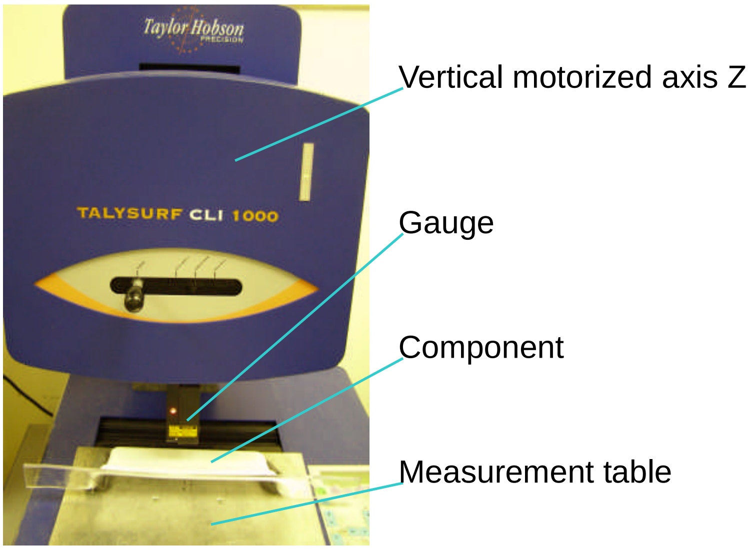


Figure 5-5 Surface measurement

2. Test procedure

The vacuum forming experiments were carried out on the machined SPT of the HAVES test bed before producing the measurements. The following experiments were to be performed:

1) Surface appearance comparison;

2) Front-top surface measurement of HIPS components;

3) Roughness measurement of 5mm thick thermoplastic components;

4) Front surface measurement of 5mm thick thermoplastic components;

5) Back surface measurement of 5mm thick thermoplastic components.

The constant factors of the experiments such as tooling temperature, tooling material, cooling method, etc. are included in table 5-4.

Table 5-4 Constant factors of experiments

Factor	Level	Units
Tooling temperature	24	°C
Tooling material	Nylon	-
Cooling method	Air cooling	-
Sheet feeding speed	400	mm/s
Plug	No	-
Heater style	Top heating, single side	-

For different thermoplastic materials and sheet thickness, their heating time and heating temperature are recommended in the table 5-5 (Formech, 2006).

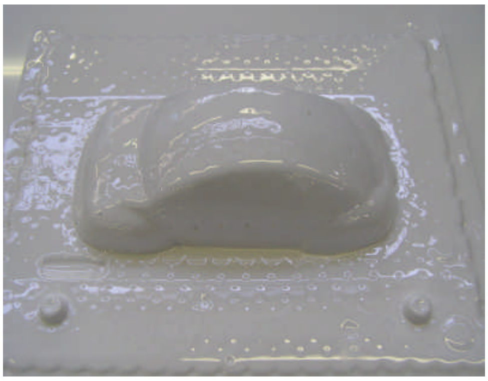
Table 5-5 Thermoplastic forming temperature and heating time

Thermoplastic	**Thickness (mm)**	**Forming temperature (°C)**	**Heat time (Seconds)**
HIPS	1	170	30
HIPS	3	170	90
HIPS	5	170	150
HIPS	6	170	180
ABS	5	180	200
PC	5	200	300
PMMA	5	190	150

5.5.3 Evaluation characteristic

Evaluation is required to identify defects as well as confirm that the surface is generally acceptable. Averaging parameters (e.g R_a) for confirmation of general surface quality and the use of peak parameters (e.g. R_t , R_v) for the identification of potential defects was used. R_a (roughness average) is the arithmetic average value of the absolute departure of the profile from the reference line throughout the sampling length. It is the most commonly used parameter in surface texture analysis. The higher the value the rougher the finish. R_t is the vertical height between the highest and lowest points of the profile within the evaluation length. S_a is the average absolute deviation of the surface. S_v (lowest valley) is largest valley depth within the definition area (Taylor Hobson Limited, 2003).

The components are measured in both front and back surface as shown in Figure 5-6.



(a) Front view

(b) Back view

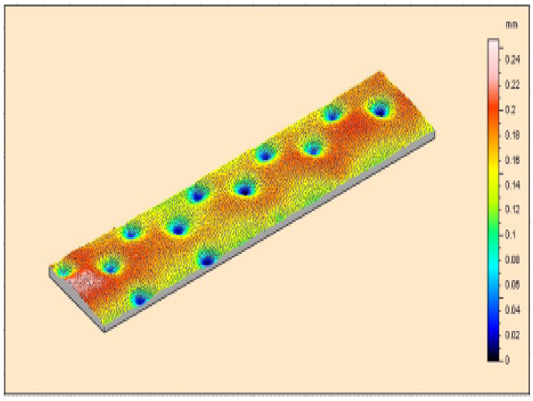
Figure 5-6 Vacuum formed thermoplastic component

5.5.4 Experiment results

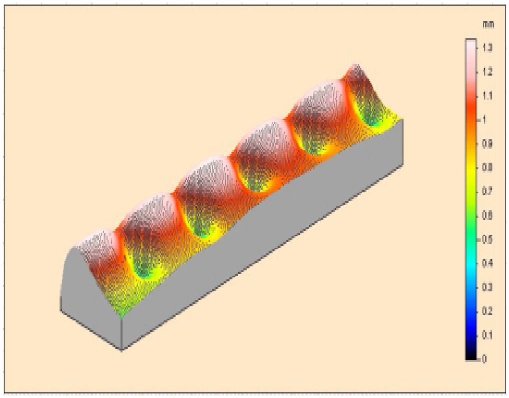
The experiment results are reported in Appendix C.3 and illustrated in the following sections:

1. Surface appearance comparison

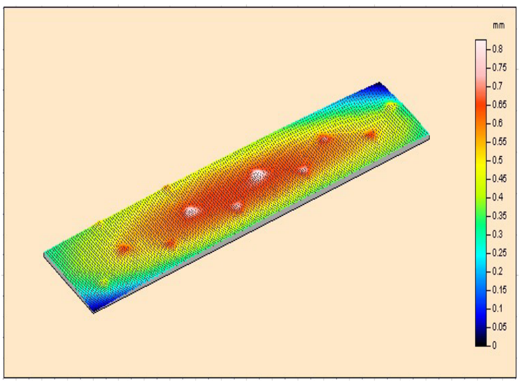
Figure 5-7 shows every surface appearance of a 3mm HIPS component formed on the machined SPT at 22Hg. It can be observed that every front surface has dimples and every back surface has peaks accordingly. They are produced by the gaps among screw pins. The average dimple depth in the front-top surface is about 0.18mm and in the front-side surface about 1.0mm; the average peak height in the back-top surface is about 0.7mm and in the back-side surface about 1.5mm.



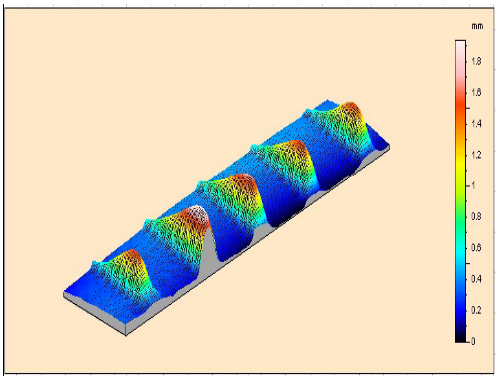
(a) Front-top surface



(b) Front-side surface



(c) Back-top surface



(d) Back-side surface

Figure 5-7 Measurement of component formed on the SPT

2. Front-top surface measurement of HIPS components

Figure 5-8 shows the results of the surface measurement obtained with different thermoplastic sheet thickness combined with several vacuum forming pressures. For the same thermoplastic thickness, it can be observed that the higher the vacuum forming pressure, the bigger the S_a and S_v values. For the same vacuum forming pressure, the thicker the thermoplastic sheet, the smaller the S_a and S_v values. A 6mm HIPS component formed at 20"Hg, the S_a and S_v of its front-top surface is 0.04mm and 0.1mm respectively.

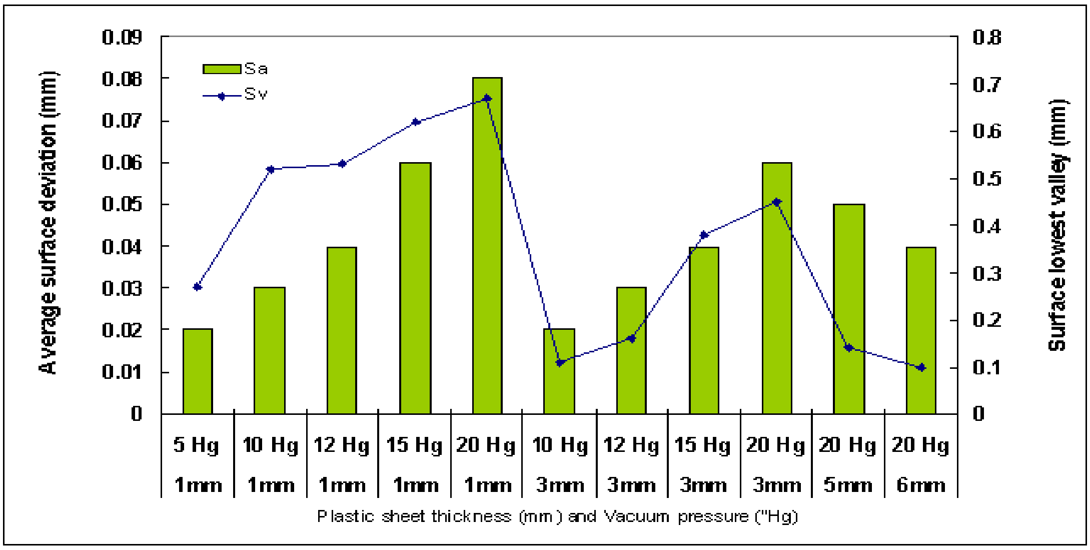


Figure 5-8 Front-top surface measurements of HIPS components

3. Roughness measurement of 5mm thick thermoplastic components

The measurement results of surface roughness obtained with an out-top surface of ABS, HIPS, PC and PMMA formed at 25"Hg are listed in Figure 5-9. Roughness averages R_a and maximum depth R_v obtained with HIPS are the smallest values with 0.35 μm and 2.5 μm respectively; those obtained with PMMA are the biggest values with 0.9 μm and 4.5 μm respectively; those obtained with ABS are 0.55 μm and 3 μm respectively; those obtained with PC are 0.6 μm and 3.0 μm respectively.

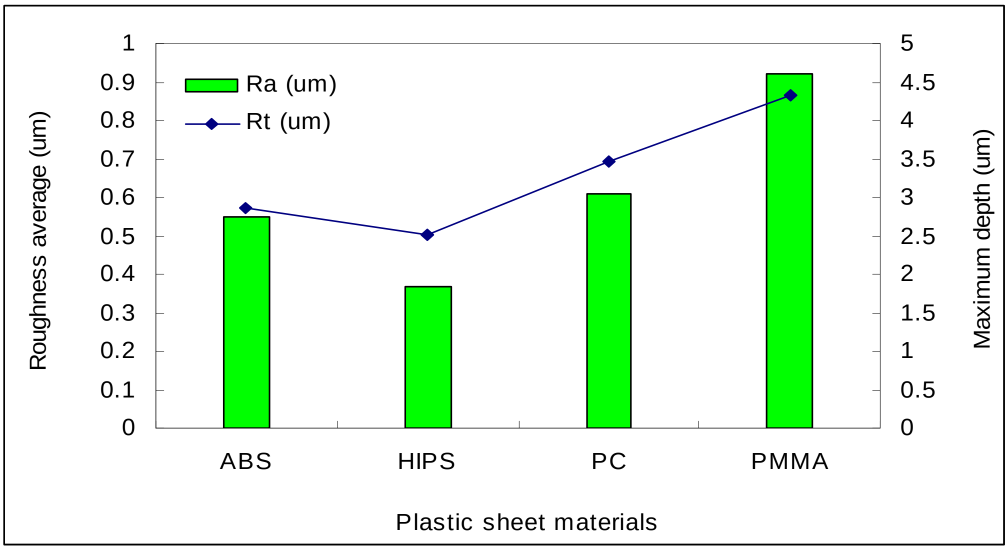


Figure 5-9 Roughness measurement of 5mm formed components

4. Front surface measurement of 5mm thick thermoplastic components

Figure 5-10 shows the results of front surface measurement obtained with different thermoplastic materials at 5mm thickness formed at 25Hg. For each thermoplastic material, its average surface deviation S_a and surface lowest valley S_v of the side surface is always bigger than that of the top surface. Front-top surface of PC thermoplastic has the smallest value of S_a and S_v with 0.02mm and 0.05mm respectively among all the compared front-top surfaces. The front-side surface of PC thermoplastic has the smallest value of S_a and S_v with 0.05mm and 0.23mm respectively among all the compared front-side surfaces.

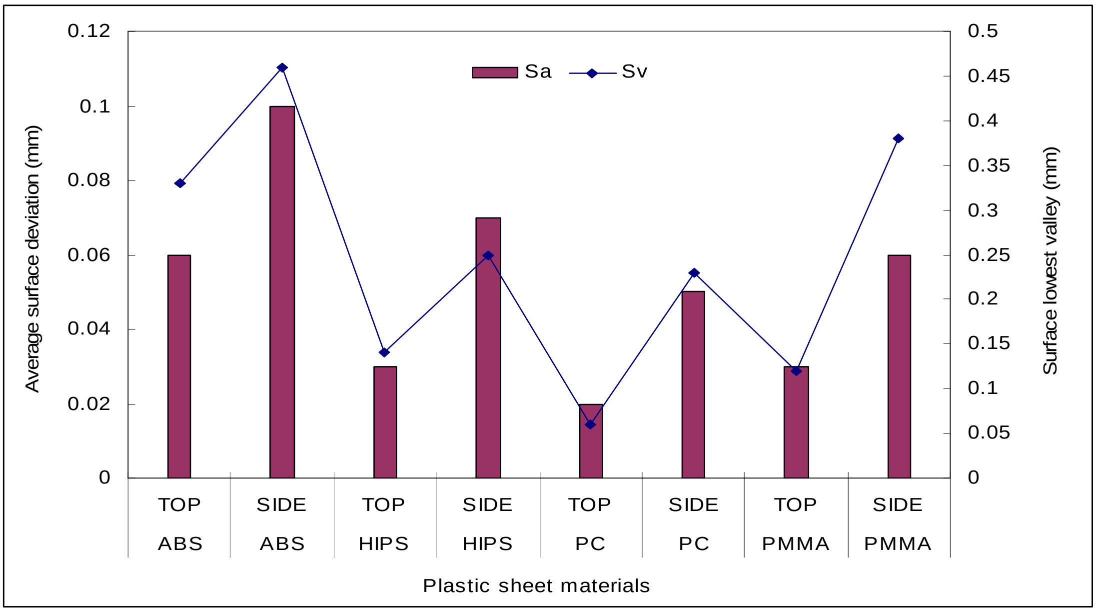


Figure 5-10 Front surface measurements of 5mm components

5. Back surface measurement of 5mm thick thermoplastic components

The measurement results of the back surface obtained with ABS, HIPS, PC and PMMA thermoplastic sheets at 5mm thickness and 25"Hg are listed in Figure 5-11. For each thermoplastic material, its average surface deviation S_a and surface lowest valley S_v of the side surface is always bigger than that of the top surface. The back-top surface of HIPS thermoplastic has the smallest value of S_a with 0.1mm and the back-top surface of the PC thermoplastic has the smallest value of S_v with 0.3mm among all of the compared back-top surfaces. The back-side surface of HIPS thermoplastic has the smallest value of S_a with 0.18mm and the back-side surface of the PC thermoplastic has the smallest value of S_v with 0.43mm among all the compared back-side surfaces.

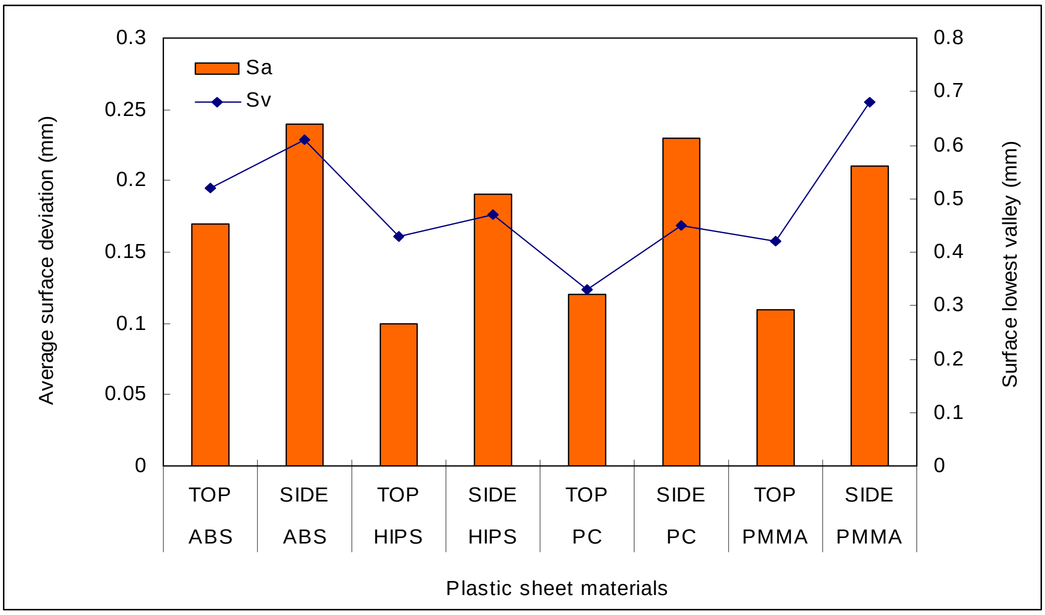


Figure 5-11 Back surface measurements of 5mm components

5.5.5 Experiment summary

From Figure 5-7 to Figure 5-11, it can be seen that there are some visible dimples on the surfaces of components produced on the machined screw-pin tooling whatever its material or thickness. Such components can be used to verify the concept design, but it may not be suitable to act as the final product. Further surface treatment should be given to produce good quality components.

5.6 Sacrificial material selection

5.6.1 Objective

The objective of this experiment is to find the appropriate thermoplastic sheet material that is suitable to act as sacrificial cover on top of the SPT.

5.6.2 Select sacrificial materials

1. Selection method

The Analytic Hierarchy Process (AHP) is employed to help make the selection of the sacrificial materials as shown in Figure 5-12. The AHP is a Multi Criteria decision making method developed in the 1970s by Professor Thomas L. Saaty (Dyer, 1990). The procedure for using the AHP can be summarized as:

1) Arranging the problem as a hierarchy order.
2) Assigning priorities among the elements of the hierarchy.
3) Synthesizing the judgments to determine priorities for the hierarchy.
4) Coming to a final decision based on the results.

2. Design of the decision hierarchy

As shown in Figure 5-12, the designed hierarchy contains the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives. The goal of the hierarchy is to select the top four thermoplastic to be used as the sacrificial cover. The following thermoplastic materials are selected as alternatives: ABS, PETG, PC, PS, PP, PE, PVC, and PMMA. The criteria for evaluating the alternatives include: 1) Continuous service temperature (ST); 2) Hard and rigid property (HR); 3) Cost (COST); 4) Machined surface quality (SQ); 5) Machinability (MB).

3. Assign priorities

The priorities among elements of the hierarchy are established by making a series of judgments based on pairwise comparisons of the elements. The pairwise comparison is the process of comparing the elements in pairs against a given criterion. The Criteria will be compared according to table 5-6, with respect to the goal.

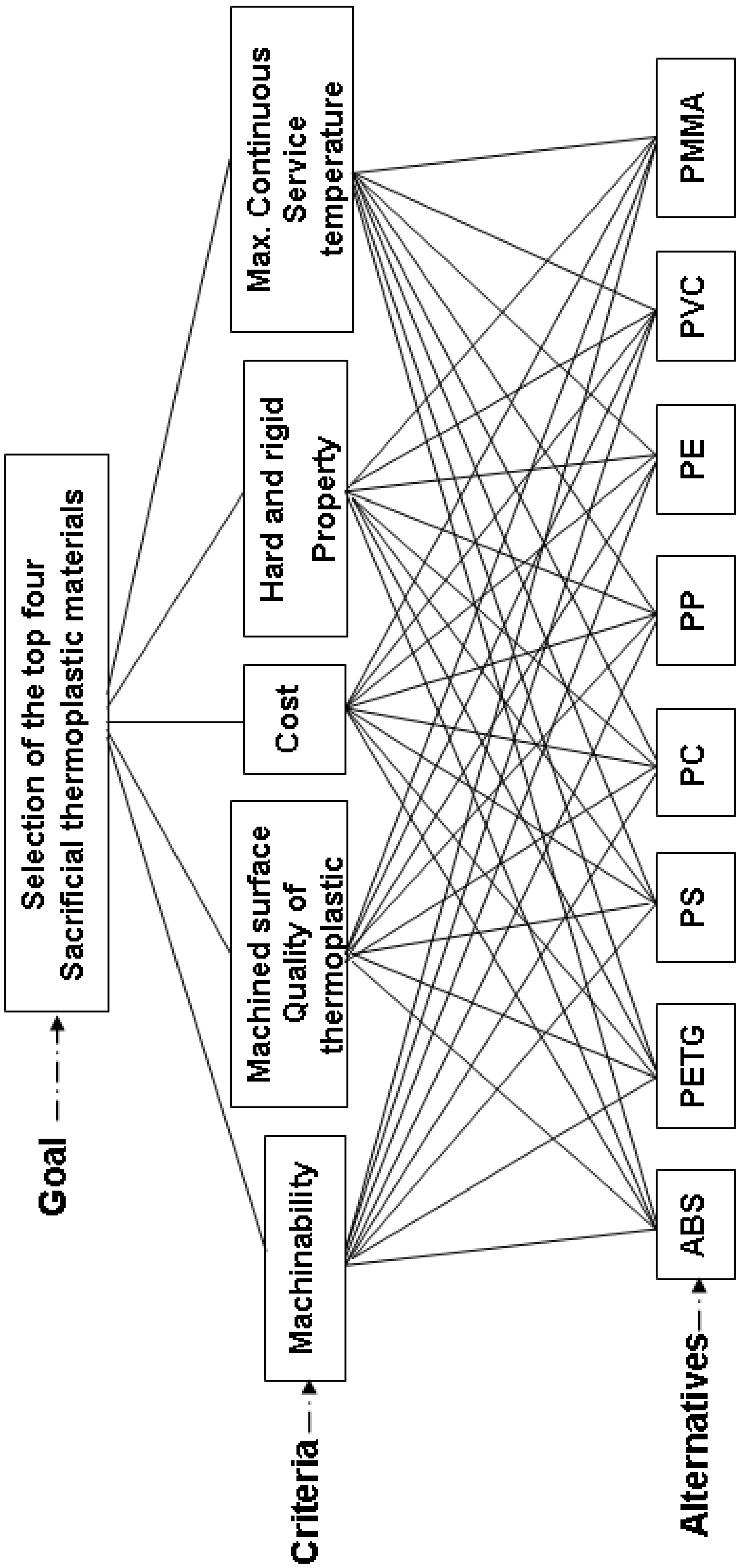


Figure 5-12 Sacrificial materials multi-objective decision-making

Table 5-6 Scale of relative importance for pairwise comparisons

Intensity of importance	Definition	Introduction
1	Equal importance	Two elements are equally important
3	Moderate importance	One element is slightly more important than the other
5	Strong importance	One element is favoured strongly over another
7	Very strong importance	One element is favoured very strongly over another
9	Extreme importance	One is absolutely more important
2, 4, 6 and 8	Intermediate values of one criterion over the other	

a) Criteria prioritizing

To simplify the calculation of the pair-wise comparison, it is hypothesized that the priorities within criteria levels are all equal, so the weights of criteria are all 20% (100%/5=20%).

b) Pair-wise for candidate sacrificial materials

By convention, the comparison of strength is always an activity appearing in the column on the left against an activity appearing in the row on top. The pair-wise comparisons for candidate sacrificial materials form an 8x8 matrix as shown in Table 5-7.

Table 5-8 normalizes the matrix above by dividing each value by the column sum before computing the average value for each row.

Table 5-7 Pair-wise comparison matrix for sacrificial materials

	ABS	PETG	PC	PS	PP	PE	PVC	PMMA
ABS	**1**	3	1/3	1/3	5	5	3	3
PETG	1/3	**1**	1/3	1/5	2	3	3	1/3
PC	3	3	**1**	1/3	3	5	5	2
PS	3	5	3	**1**	5	5	4	2
PP	1/5	1/2	1/3	1/5	**1**	1/2	1/2	1/5
PE	1/5	1/3	1/5	1/5	2	**1**	1/2	1/4
PVC	1/3	1/3	1/5	1/4	2	2	**1**	1/3
PMMA	1/3	3	1/2	1/2	5	4	3	**1**
Column Sum	8.40	16.166	5.90	3.017	25.00	25.5	20.0	9.117

Table 5-8 Normalization of the pair-wise comparison matrix

	ABS	PETG	PC	PS	PP	PE	PVC	PMMA	Average
ABS	0.119	0.186	0.056	0.110	0.2	0.196	0.15	0.329	0.241
PETG	0.04	0.062	0.056	0.066	0.08	0.118	0.15	0.037	0.076
PC	0.357	0.186	0.169	0.110	0.12	0.196	0.25	0.219	0.201
PS	0.357	0.310	0.508	0.331	0.2	0.196	0.20	0.219	0.290
PP	0.024	0.031	0.056	0.066	0.04	0.020	0.025	0.022	0.036
PE	0.024	0.021	0.034	0.066	0.08	0.039	0.025	0.027	0.040
PVC	0.04	0.021	0.034	0.083	0.08	0.078	0.05	0.037	0.053
PMMA	0.04	0.186	0.085	0.166	0.2	0.157	0.15	0.110	0.137

c) Final results

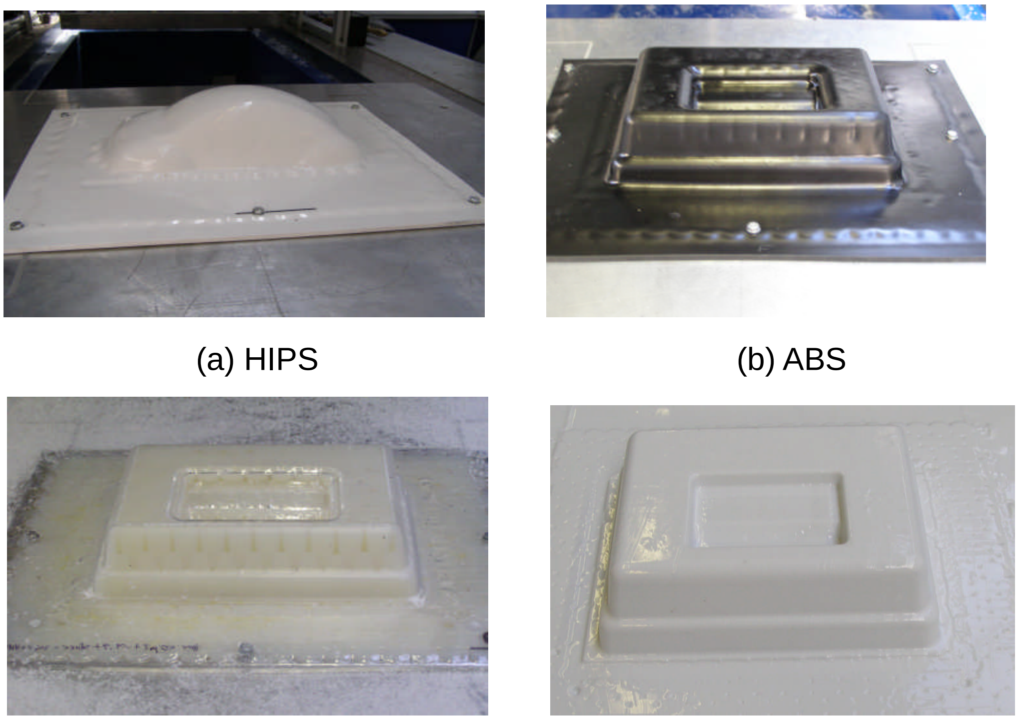
Looking at the average value of each row, the top four weights of the criteria are 29% on PS, 24.1% on ABS, 20.1% on PC and 13.7% on PMMA. So PS, ABS, PC and PMMA are selected for the manufacturing test.

5.6.3 Sacrificial materials manufacturing test

The test procedure of the sacrificial materials is as follows:

1. Vacuum formed sacrificial materials

According to the AHP method, four thermoplastic materials are selected to make the manufacturing test (as shown in Figure 5-13): HIPS, ABS, PC, PMMA. Each material is vacuum formed by using its recommended forming parameters by Formech Ltd.



(a) HIPS (b) ABS

(c) PC (d) PMMA

Figure 5-13 Selection of sacrificial materials for test

ABS, PC and PMMA are all hygroscopic materials, and require pre-drying before vacuum forming. For example, a 4mm PC sheet needs to dry for 10 hours at 90° C drying temperature. If they are not dried for long enough, many bubbles are created (as shown in Figure 5-14) during the vacuum forming and cause waste. It results in much wasted time and energy consumption. By contrast, HIPS is a non hygroscopic material, which can be directly used for vacuum forming.

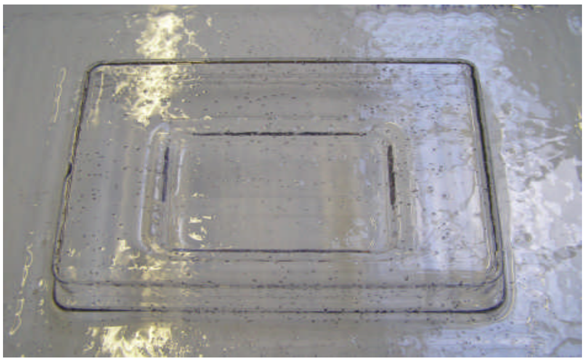


Figure 5-14 Vacuum formed component with bubbles

2. Machine the vacuum formed sacrificial material according to the design mould and then measure the machined surface. The measurement results in machined surfaces of sacrificial materials which are listed in Figure 5-15. All four thermoplastic materials have a similar average surface deviation (0.01mm), but HIPS and PMMA have a smaller surface lowest valley (0.02mm) compared to that of ABS and PC (0.25mm).

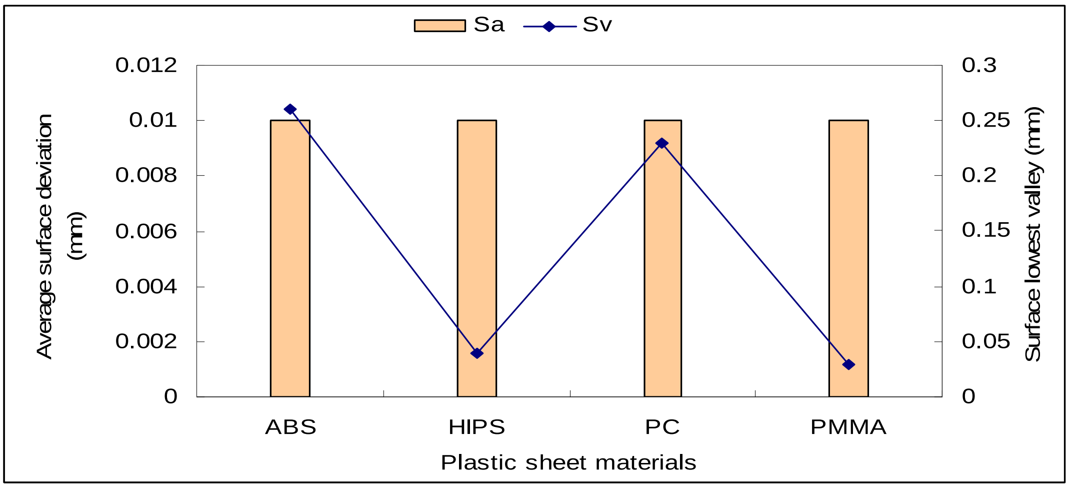


Figure 5-15 Sacrificial surface measurement

Based on the analysis of vacuum forming test and manufacturing test, HIPS material is selected as the best sacrificial material. By employing HIPS, good quality final products can be produced from screw-pin tooling.

5.7 Filler material selection

5.7.1 Objective

The objective of this experiment is to explore the suitable fillers that could be painted and machined on the top of the SPT, and then used to form good quality plastic components.

5.7.2 Selection of filler materials

The select criteria of the filler materials include: 1) short setting time (less than 20 minutes); 2) High softening temperature; 3) good machinability. The candidate filler materials are listed in table 5-9

Table 5-9 Filler materials and selection standards

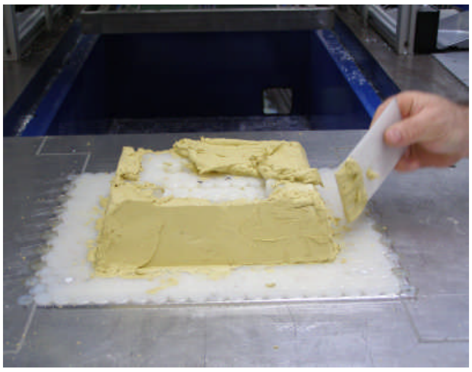
Materials	Functions	Setting Time	Softening Temp.	Machinability
1	Chemical Metal Repair Paste	10 mins	120	Yes
2	Ronseal High Performance Wood Filler - Natural	20 mins	130	Yes
3	Repair Putty	20 mins	120	Yes
4	Decorators' gap filler	2 hours	130	Yes
5	Unibond no more nails super strength interior	3 hours	125	Yes
6	Multi-purpose wood filler	4 hours	110	Yes
7	Unibond tile on walls	4 hours	120	Yes
8	All purpose interior filler	1.5 hours	115	Yes

By comparing the candidate filler materials, the chemical metal repair paste and the Ronseal high performance wood filler are selected to complete the manufacturing test.

5.7.3 Filler materials test

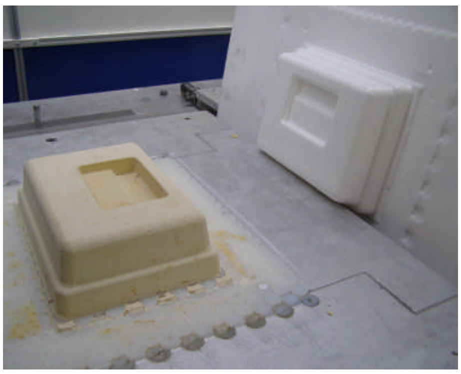
As shown in Figure 5-16, the application filler includes four steps:

1) Painting the filler material on top of the adjusted screw-pin tooling;
2) Manufacturing the filler material according to the design mould;
3) Vacuum forming components based on the manufactured screw-pin tooling with filler;
4) After vacuum forming, the filler is taken off from the top of the screw-pin tooling.



(a) Filler painting

(b) Filler machining

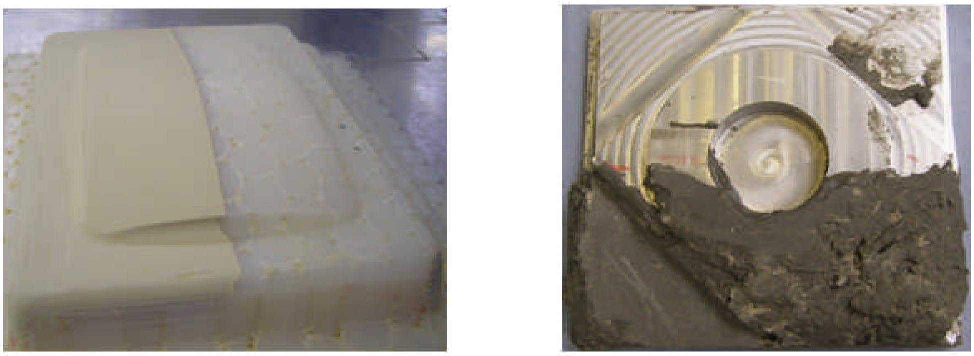


(c) Filler tooling and formed component

(d) Filler removing

Figure 5-16 Test steps with filler

By comparing the machined painting surfaces of the chemical metal repair paste and the Ronseal high performance wood filler (as shown in Figure 5-17), it is found that the Ronseal high performance wood filler has better surface quality, is more easily removed and is therefore selected as the best filler.



(a) Ronseal high performance wood filler   (b) Chemical metal repair paste

Figure 5-17 Comparison of machined painting surfaces

5.7.4 Surface comparison

Figure 5-17 (a) also compares the machined surfaces of SPT with and without Ronseal high performance wood filler; Figure 5-18 compares the surface quality of a vacuum formed component on the SPT in Figure 5-17 (a).

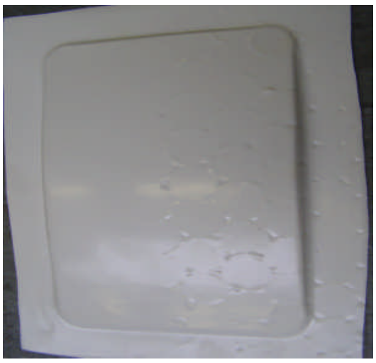


Figure 5-18 Filler comparison test

5.8 Summary

In this chapter, two series of experiments are performed on the HAVES test bed: screw-pin adjustment performance tests and the SPT vacuum forming tests. In each experiment, its objective, equipment, procedure, evaluation characteristic and summary are introduced. In terms of screw pin adjustment performance experiments, the repeatability and accuracy of the screw pin positions are evaluated by calculating and comparing average errors and standard deviations of the adjustment. In terms for vacuum forming experiments on the SPT, four different test processes are employed and the roughness average and surface deviation average selected as evaluation characteristics. The components directly formed by the SPT have a very rough surface. The teeth of the screw pins are imprinted on the side surfaces; the engagement gaps among screw pins produce many dimples on the top surfaces and the discrete top surfaces of the screw pins form many stairs on the component appearance. There are also some visible dimples on the surfaces of components produced on the machined SPT. The sacrificial cover method and filler cover method are investigated to improve the surface quality of vacuum formed components. The HIPS thermoplastic sheet is selected as the best sacrificial material among all the candidates; Ronseal High Performance Wood Filler is chosen as the best filler material among all the potential filler materials. By employing the HIPS thermoplastic sheet or high performance wood filler, components produced from the screw-pin tooling can provide the same surface quality as those produced from the solid tooling. Surface measurement using the Talysurf CLI 1000 proved to be an adequate quantitative evaluation for different types of components produced from the SPT or solid tooling.

CHAPTER 6

ECONOMIC MODEL FOR HAVES TEST BED

6.1 Introduction

The purpose of this chapter is to provide an economic evaluation for the HAVES test bed. Firstly, a manufacturing cost model for a reconfigurable pin tooling system is created, and then a comparison of the tooling construction costs between four different types of pin tooling is executed. Secondly, an application cost model is built for the HAVES test bed. Further comparison between application cost by the HAVES test bed and traditional tooling system is performed. Finally, breakeven analysis is implemented based on the created economic models.

6.2 Manufacturing cost model

The manufacturing cost is a major performance criterion for the successful promotion of the reconfigurable screw-pin tooling system. The manufacturing cost model is to be used as reference in order to calculate the capital investment in machinery fabrication. Just like the construction of the HAVES test bed formed by the five modules, the total cost C_t of the manufacturing cost model consists of the following five cost elements: pins cost C_{pins}, frames cost C_{frame}, control system cost $C_{control}$, hardware cost $C_{hardware}$ and other cost C_{others}; it can be expressed as follows:

$$C_t = C_{pins} + C_{frame} + C_{control} + C_{hardware} + C_{others} \qquad (6\text{-}1)$$

It is assumed that the cost data for each element includes all costs for plant and production, costs for administration, and costs for the necessary overheads. The cost elements are described in the following sections.

6.2.1 Pins cost C_{pins}

For the integrated screw-pin tooling system, the most important components are the pins in the reconfigurable array pattern. The pin numbers N_{pins} of the tooling can be calculated as:

$$N_{pins} = f(r, c, em) \qquad (6\text{-}2)$$

Where r is the number of rows; c is the number of columns; em is the engagement method (rectangular or triangular pattern) and f is the pin number calculation function. Price for a single pin C_{1-pin} is written as:

$$C_{1-pin} = g(N_{pins}, mat, cmx) \qquad (6\text{-}3)$$

Where mat represents the pin material (aluminium, steel, nylon, etc.); cmx represents the complexity of the pin and g represents the price compute function for a single pin. Therefore, the cost of all the pins C_{pins} can be expressed as:

$$C_{pins} = N_{pins} \cdot C_{1-pin} \tag{6-4}$$

6.2.2 Frame cost C_{frame}

The die frame is also called the pin container; it is used to clamp the pins of the tooling. The frame cost consists of the frame material cost C_{fm}, related manufacturing costs C_{fmanu} and the assembly cost C_{fa}:

$$C_{frame} = C_{fm} + C_{fmanu} + C_{fa} \tag{6-5}$$

6.2.3 Control cost $C_{control}$

The control cost includes two parts: one is the cost of the Numerical Control Device package C_{cnc} and the other is the service cost for wiring the machine for CNC control C_{ws}:

$$C_{control} = C_{cnc} + C_{ws} \tag{6-6}$$

6.2.4 Hardware cost $C_{hardware}$

The cost of the hardware is the sum of the machine bed C_{bed}, drive motors C_{motors}, encoders C_{encs}, leadscrew actuators C_{lsa} and other related parts $C_{h-parts}$:

$$C_{hardware} = C_{bed} + C_{motors} + C_{encs} + C_{lsa} + C_{h-parts} \tag{6-7}$$

6.2.5 Other cost C_{other}

To ensure safe and smooth running of the tooling system, devices or components such as safety equipment C_{sf} and personal computer C_{pc}, are necessary. This type of cost can be expressed as:

$$C_{other} = C_{sf} + C_{pc} \qquad (6\text{-}8)$$

6.3 Manufacturing cost comparison

Im, Walczyk, et al. (2000) estimated and compared manufacturing costs for the sequential set-up pin tooling (SSU, Appendix D.1) developed by the Massachusetts Institute of Technology, hydraulically actuated pin tooling (HA, Appendix D.2) developed by Rensselaer Polytechnic Institute and shaft-driven leadscrew pin tooling (SDL, Appendix D.3) developed by Northrop Grumman for developing a production-scale version, 1.2mx1.8m discrete die concept. The method used to estimate costs involves extrapolating the purchased components, machining and assembly costs associated with the design prototype to a production-scale version. The expected total costs of the manufacturing of each concept (see Appendix D-1, 2, 3) are reclassified according to the manufacturing cost model developed in section 6.2.

The same cost estimates for the screw-pin tooling (SPT) for developing the 1.2mx1.8m discrete die concept are based on the finished HAVES test bed. The concept of "economies of scale" (for example, decrease in product costs due to increased purse number) is used in the cost estimation. The estimated manufacturing cost of the SPT is shown in Appendix D.4. Table 6-1 lists the manufacturing cost comparison of the four pin tooling concepts: SPT, SSU, HA and SDL.

Table 6-1 Manufacturing cost comparison

	SPT	SSU	HA	SDL
C_{pins}	$14,333	$259,000	$107,000	$259,000
C_{frame}	$1,725	$57,650	$30,000	$57,650
$C_{control}$	$43,202	$14,200	$21,000	$40,000
$C_{hardware}$	$94,200	$77,000	$247,783	$484,014
C_{others}	$4,500	$73,700	$14,000	$34,700
C_t	$157,960	$481,550	$419,783	$875,864

Figure 6-1 shows the importance of cost categories for the different pin tooling concepts. The pin setting hardware cost, with 60%, 60% and 54% of the total cost in the SPT, HA and SDL respectively, appears to be the main cost issue for each mould concept. The pins cost, with 54% of the total cost, is the main economical issue for the SSU concept.

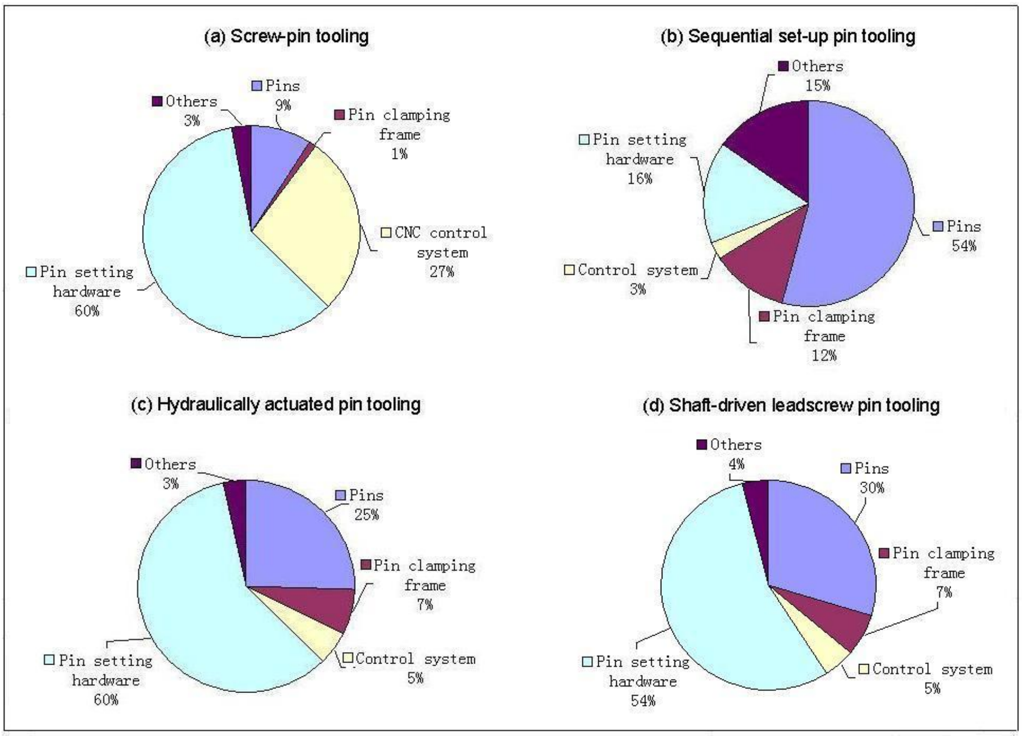


Figure 6-1 Cost categories of mould concepts

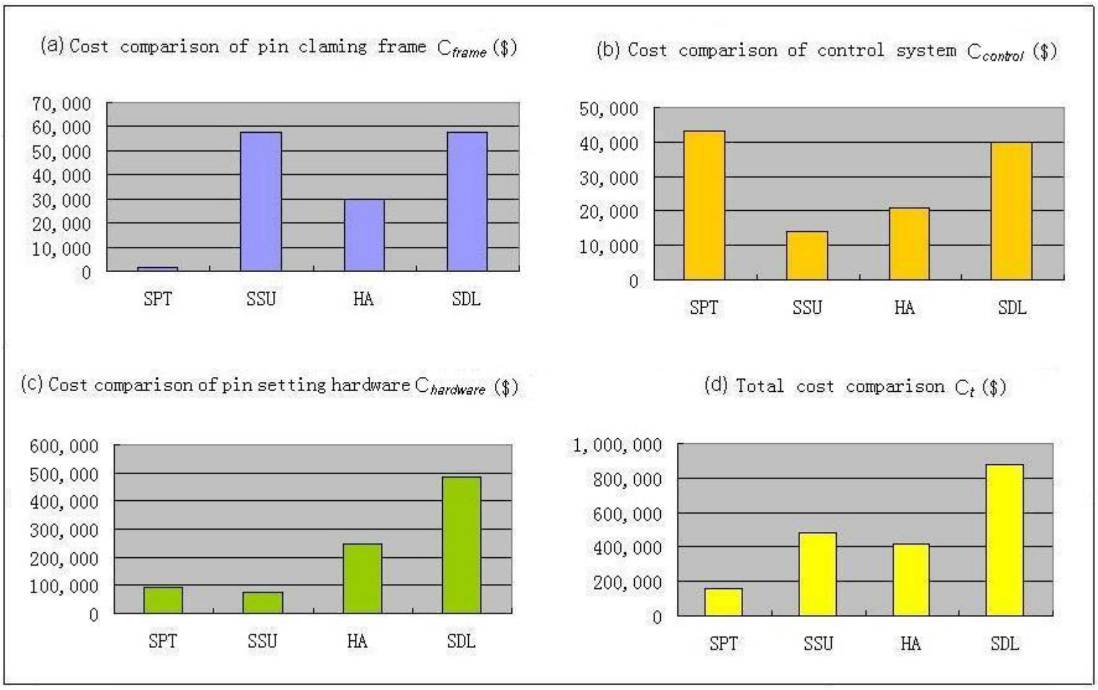
Single pin costs and total pin costs of the different pin mould concepts are given in Table 6-2. The screw-pin of the SPT concept has the lowest pin cost. There are significant price differences between the screw-pin of the SPT concept, at $2.25 each and the hollow die pin with a threaded nut of the SSU and SDL concepts, at $96.35 each. The price differences are almost 1 to 43 times. The price of the hollow pin used in the HA mould concept, at $30.96 each, is also about 13 times higher than the price of the screw-pin. The extensive cost difference is because the pins used by the SPT mould concept are simple and standard while the pins used by the SSU, HA and SDL mould concept are of a special design and are complex. Therefore, the SPT has the lowest total pin cost at $14,333 and the SSU and SDL have the highest total pin cost at $259,000.

Table 6-2 Cost comparison of pin concepts

Tooling types	Cost for single pin ($)	Cost for total pins ($)
SPT	2.25	14,333
SSU	96.35	259,000
HA	30.96	107,000
SDL	96.35	259,000

Figure 6-2 describes cost comparisons of the four different pin mould concepts which include pin clamping frame comparison, control system comparison, pin setting hardware comparison and total cost comparison. The SPT mould concept has the lowest costs in the pin clamping frame, pin setting hardware and total cost among four different mould concepts which are $1,725, $94,200 and $157,960 respectively. However, the SPT mould concept has the highest control system cost at $43,202. This is because the control system for the SPT system is not only used to control the movement of the pins, but to also control the system and acts as a CNC machine to the milling pins' surface. The SDL mould concept has the highest cost in pin clamping frame, pin setting hardware and total cost which are $57,650, $484,014 and $875,864 respectively; it has the second highest cost at $40,000 in control system construction. The SDL mould concept uses the most complex mechanical and electronic systems.

Figure 6-2 Cost comparison of mould concepts



6.4 Application cost model

6.4.1 Cost analysis

The purpose of the application cost model is to help analyse the mould manufacturing cost utilising the screw-pin tooling system and setting the moulding selling price. In the proposed model, the application cost C_{app} is divided into two categories: direct costs C_{dir} and indirect costs C_{indir} as shown in Table 6-3. Only material consumption M_c in the mould manufacturing is considered to be a direct cost. So the direct cost is equal to all the material costs $Cost(M_c)$ arising during the mould manufacturing process. The indirect costs include production labour, machining consumables, machine costs and administration overheads; they are allocated to each individual process by the time T_{tech} in which the technician takes to build them $Cost(T_{tech})$. Therefore:

$$C_{app} = C_{dir} + C_{indir} \tag{6-9}$$

$$C_{app} = Cost(M_c) + Cost(T_{tech}) \tag{6-10}$$

The consumption materials M_c and the used technician time T_{tech} in screw-pin tooling application are discussed in the following sections.

Table 6-3 Costs associated with the screw-pin tooling application

Cost Elements		Detail Descriptions
Direct cost	Materials	For sacrificial method: ✧ Sacrificial plastic sheets; ✧ Screw pins; ✧ Production plastic sheets. For wood filler method: ✧ Wood filler; ✧ Production plastic sheets.
Indirect cost	Production labour	✧ Technician salary; ✧ Employer contributions, etc.
	Machining consumables	✧ Energy consumption; ✧ Floor space rent; ✧ Tooling for machining; ✧ Overalls, masks, paper towels; ✧ Wastage etc.
	Machine costs	✧ Software and hardware upgrades; ✧ Repair & maintenance machine; ✧ Machine depreciation, etc.
	Administration overhead	✧ Hardware purchase and update; ✧ Software purchase and update; ✧ Office consumables; ✧ Administrative staff; ✧ Office space, etc.

6.4.2 Material calculation

1) Sacrificial method: the materials used in the sacrificial method include the sacrificial plastic sheet material M_s, the machined screw pins material M_{pin} and the product plastic sheet M_{pps}.

$$M_c = M_s + M_{pin} + M_{pps} \tag{6-11}$$

2) Wood filler method: the materials consumed in the wood filler method consist of the wood filler material M_{wf} and the product plastic sheet M_{pps}.

$$M_c = M_{wf} + M_{pps} \tag{6-12}$$

6.4.3 Time calculation

1) Time to sacrificial method

The total technician time T_{tech} is the sum of the time associated with five different processes employed in the sacrificial method. The five different times are CNC programming time T_{p-cnc}, screw-pin tooling shape set up time T_{setup}, screw-pin machining time T_{mp}, Sacrificial machining time T_{ms} and vacuum forming time T_v. It is written as:

$$T_{tech} = T_{p-cnc} + T_{setup} + T_{mp} + T_{ms} + T_v \tag{6-13}$$

2) Time to wood filler method

There are four different times to calculate: the CNC programming time T_{p-cnc}, the screw-pin tooling shape set up time T_{setup}, the wood filler set up time T_{wf}

and the wood filler surface machining time T_{mf}. It is expressed as:

$$T_{tech} = T_{setup} + T_{wf} + T_{mf} + T_{p-cnc} + T_v \tag{6-14}$$

3) Screw-pin tooling shape set up time

CNC based screw pin tooling shape setup time T_{setup} is calculated by the sum of each pin positioning time t_{pins}, X and Y axis motion time t_{xy} and the time needed to engage and disengage the adjustment tool t_{eng} with the screw pins.

$$T_{setup} = t_{pins} + t_{xy} + t_{eng} \tag{6-15}$$

The pin positioning time t_{pins} is a function of the total length of the pin movement needed to transform the tooling from its current shape to a new shape. The pin move distance of the screw-pin tooling is expressed as:

$$\Delta h(i,j) = h_{new}(i,j) - h_{current}(i,j) \tag{6-16}$$

Where i, j represents the number of the row and volume of the screw-pin tooling respectively; $\Delta h(i,j)$ represents the pin height change matrix; $h_{current}(i,j)$ represents the current die shape and $h_{new}(i,j)$ represents the new die shape. Therefore,

$$t_{pins} = \frac{\sum \left[\left| \Delta h(i,j) \right| \right]}{F_{adj}} \tag{6-17}$$

Where F_{adj} is the screw-pin adjustment feed rate.

X and Y axis motion time for setup is calculated by using:

$$t_{xy} = \frac{L_x}{F_x} + \frac{L_y}{F_y} \tag{6-18}$$

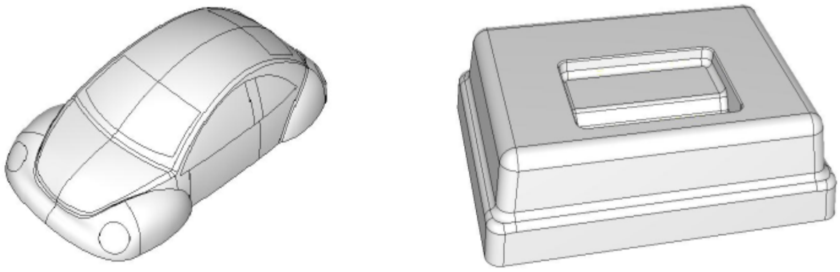
Where L_x is the move length for the X axis; L_y is the move length for the Y axis; F_x is the feed rate in the X axis and F_y is the feed rate in the Y axis.

$$t_{eng} = \frac{L_{eng}}{F_{eng}} + \frac{L_{dis-eng}}{F_{dis-eng}} \tag{6-19}$$

Where L_{eng} is the engagement distance; $L_{dis-eng}$ is the disengagement distance; F_{eng} is the engagement feed rate and $F_{dis-eng}$ is the disengagement feed rate.

6.5 Application cost comparison

The new cost model is used to calculate the mould manufacturing costs based on the screw-pin tooling in both the wood filler method and sacrificial method. Two moulds for component, as shown in Figure 6-3, are selected for manufacturing cost calculation; one is a complex beetle car mould and the other is a regular rectangular cover mould. The envelope dimensions of the beetle car mould are about 253mm in length, 125mm in width and 70mm in height; the envelope dimensions of the rectangular cover mould are about 230mm in length, 168mm in width and 62mm in height. It is assumed that the material used by the moulds is the white-coloured Nylon 6 and the production volume is a one off for both moulds. Quotation prices from companies are also obtained to compare the calculated manufacturing costs of the selected moulds.



(a) Beetle car (b) Rectangular cover

Figure 6-3 Examples for cost comparison

6.5.1 Mould manufacturing cost analysis of SPT

Table 6-4 lists consumed materials and used technician time during the construction of the beetle car mould and the rectangular cover mould based on the screw pin tooling with the wood filler method. 1375g of wood filler material is consumed and 435min is spent on beetle car mould manufacturing; 1450g wood filler material is consumed and 495min is spent on rectangular cover mould manufacturing.

Table 6-4 Mould manufacturing cost with wood filler

Process	Variable	Beetle car	Rectangular cover
Technician cost per hour (￡/h)	C_{tech}	25.00	25.00
Wood filler material price (￡/550g)	C_{mat}	7.99	7.99
a. Technician time calculation			
Screw pin adjustment (min)	T_{setup}	180	195
Wood filler set up (min)	T_f	60	70
Surface machining (min)	T_{f-mach}	75	80
CNC programming (min)	T_{p-cnc}	120	150
Total time (min)	T_c	435	495
b. Material calculation			
Mass of wood filler (g)	M_{wf}	1375	1450
c. Total cost			
Total cost (￡)	$Cost_{PART}$	202	228

Table 6-5 lists consumed materials and the used technician time during the construction of the beetle car mould and rectangular cover mould based on the screw pin tooling with the sacrificial method. One 600x600x5mm HIPS plastic sheet and about 40 unit screw-pins are consumed and 455min is spent on beetle car mould manufacturing; One 600x600x5mm HIPS plastic sheet and about 46 unit screw-pins are consumed and 525min is spent on rectangular cover mould manufacturing.

Table 6-5 Mould manufacturing costs with the sacrificial method

Process	Variable	Beetle car	Rectangular cover
Technician cost per hour (£/h)	C_{tech}	25.00	25.00
Screw-pin (M20xL300) cost (£/unit)	C_{1-pin}	1.45	1.45
a. Technician time calculation			
Screw pin adjustment (min)	T_{setup}	200	220
Screw pin machining (min)	T_{m-pin}	30	45
Sacrificial vacuum forming (min)	T_{s-vac}	30	30
Sacrificial machining (min)	T_{s-mach}	75	80
CNC programming (min)	T_{p-cnc}	120	150
Total time (min)	T_c	455	525
b. Material calculation			
Sacrificial plastic sheet price (HIPS,600x600mm, £/sheet)	M_s	8.82	8.82
Machined screw pin material (unit)	M_{pin}	40	46
c. Total cost			
Total cost (£)	$Cost_{PART}$	257	295

Figure 6-4 shows time models for the beetle car mould and the rectangular mould manufacture by using the wood filler method and sacrificial method. The highest percentage of manufacturing time in each pie chart is taken up by the screw-pin adjustment process with 41% in pie chart (a), 40% in pie chart (b), 44% in pie chart (c) and 41% in pie chart (d). The CNC programming time accounts for the second highest percentage of manufacturing time in all four pie charts. As for beetle car moulds, the machining time percentage of the sacrificial method which includes sacrificial machining time percentage 16% and screw-pin machining time percentage 7% is a little higher than the machining time percentage of the wood filler method at 17%. As for rectangular cover moulds, the machining time percentage of the sacrificial method which includes the sacrificial machining time percentage at 15% and the screw-pin machining time percentage at 9% is a little higher than the machining time percentage in the wood filler method which stands at 16%.

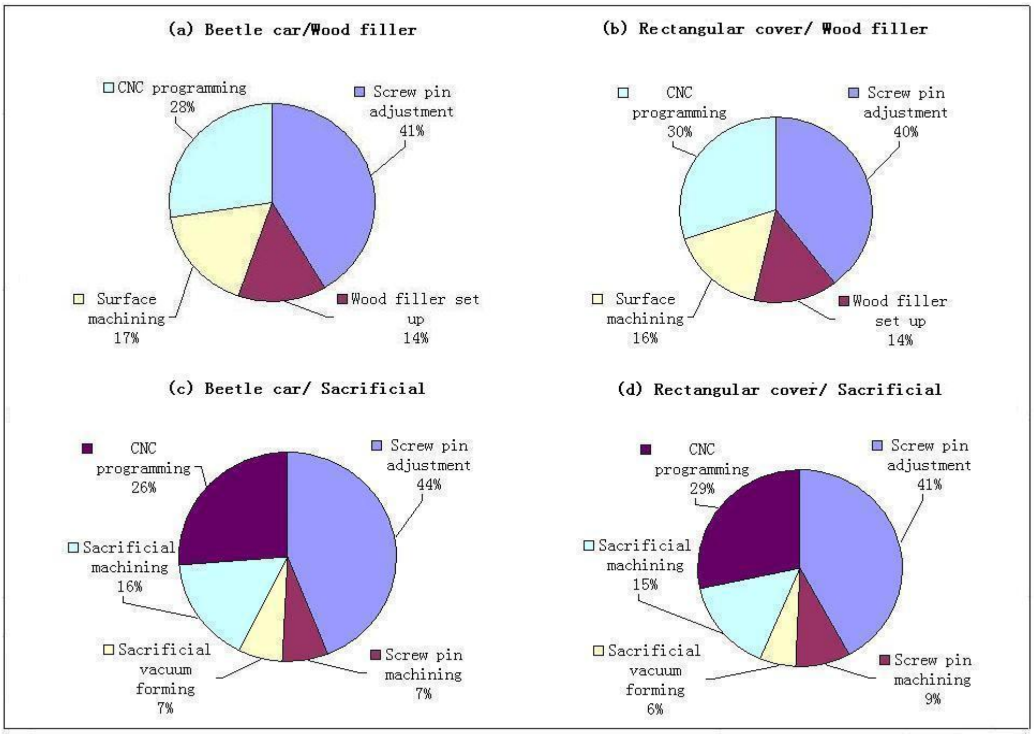


Figure 6-4 Time categories for the SPT mould manufacture

6.5.2 Mould manufacturing cost comparison

Manufacturing costs for the beetle car mould and the rectangular cover mould that are produced with the wood filler or sacrificial method are provided in Table 6-6. At the same time, quotation prices for the two moulds from the First cut ltd (Appendix D.5), Ansini ltd. and Robinson P.E. ltd are also given in the same table. All quotation prices are inclusive of delivery and exclude VAT. Manufacturing costs of moulds produced with the wood filler method are lower than manufacturing costs of the moulds produced with the sacrificial method. The lowest quotation price for the beetle car mould is ￡320 from Ansini Ltd. and the lowest quotation price for the rectangular cover is ￡358 from First Cut Ltd. The manufacturing costs of the beetle car mould and the rectangular cover mould with wood filler are ￡202 and ￡228 respectively; the selling prices for the moulds can be defined as being between the maximum manufacturing costs and the minimum quotation prices. The highest quotation prices are ￡960 for the beetle car mould and ￡1084 for the rectangular cover mould from Robinson P.E. Ltd, with these quotes being nearly two times higher than the lowest quotation prices.

Table 6-6 Cost comparison of moulds

Mould	**Manufacturing Cost (￡)**		**Quotation Price (￡)**		
	Wood filler	Sacrificial	First Cut Ltd.	Ansini Ltd.	Robinson P.E. Ltd.
Beetle car	202	257	324	320	960
Rectangular cover	228	295	358	372	1083

6.6 Breakeven analysis of the screw-pin tooling

6.6.1 Introduction

Breakeven analysis is a widely used technique that helps determine at what point a product or service can be expected to become profitable. It can be employed together with economic evaluations to develop a pricing strategy for the business. The breakeven point is calculated based on the fixed costs, variable costs, and selling price of the product or service being analyzed. If the product can be sold above the breakeven point, then the firm will make a profit; if it is below this point, they make a loss.

6.6.2 Variables for breakeven analysis

Table 6-7 shows the variables to consider when conducting breakeven analyses. The relationship of the variables can be expressed as equations from (6-20) to (6-25).

$$C_{t-\mathrm{var}\,i} = N_s \times C_{u-\mathrm{var}\,i} \tag{6-20}$$

$$C_{total} = C_{fix} + C_{t-\mathrm{var}\,i} \tag{6-21}$$

$$R_{total} = N_s \times P_{unit} \tag{6-22}$$

$$P_m = R_{total} - C_{total} \tag{6-23}$$

$$N_{be} = C_{fix} \big/ (P_{unit} - C_{u-\mathrm{var}\,i}) \tag{6-24}$$

$$T_{be} = T_c \times N_{be} \big/ H_y \times 60 \tag{6-25}$$

Table 6-7 Variables for breakeven analysis

Variable Name	**Notation**	**Definition** [Johal, S., et al, 2008]
Fixed Cost (£)	C_{fix}	The sum of all costs required to produce the first unit of a product
Variable Unit Cost (£)	$C_{u-\mathrm{var}\,i}$	Costs that vary directly with the production of one additional unit
Expected Unit Sales (£)	N_s	The number of product units projected to be sold over a specific period of time
Unit Price (£)	P_{unit}	The amount of money charged to the customer for each unit of a product
Total Variable Cost (£)	$C_{t-\mathrm{var}\,i}$	The product of expected unit sales and variable unit cost
Total Cost (£)	C_{total}	The sum of the fixed cost and total variable cost
Total Revenue (£)	R_{total}	The product of expected unit sales and unit price
Profit (or Loss) (£)	P_m	The monetary gain (or loss) resulting from revenue after subtracting all associated costs
Working Hours Per Year (hour)	H_y	Hours per year that the machine is in operational condition
Break Even Number (unit)	N_{be}	Number of units that must be sold in order to produce a profit of zero
Break Even Time (year)	T_{be}	Time required to produce a profit of zero
Mould Manufacturing Time (min)	T_c	Time required to produce a mould for its accordingly component

6.6.3 Breakeven analysis case study for screw-pin tooling

1. Screw-pin tooling with wood filler

The beetle car tooling produced by the screw-pin tooling with wood filler in section 6.5 is employed as the first example. The British Pound is used as the monetary unit of breakeven analysis with the exchange rate for the US Dollars to the British Pounds being 0.62 (as of 7th, July 2009).

In this example, the construction cost of the reconfigurable screw-pin tooling machine can be selected as the fixed cost C_{fix} for making the beetle car mould. This equates to a number of £97,935. The manufacturing cost of the beetle car mould can be chosen as the variable unit cost $C_{u-\mathrm{var}\,i}$ and is at £202. The selling price P_{unit} for the beetle car tooling is set below that of First Cut Ltd and £302 is selected. Therefore:

$$N_{be} = 97935/(302-202) = 979$$

Figure 6-5 is a breakeven analysis chart for the beetle car tooling. As shown in Figure 6-5, the total cost curve shows the total cost associated with each possible level of output. The fixed cost curve shows the costs that do not vary with output level, and the total revenue line shows the total amount of revenue received at each output level. The breakeven point is the intersection point between the total cost curve and the total revenue curve. The breakeven quantity at the selling price can be read off the horizontal axis and the break even price at each selling price can be read off the vertical axis.

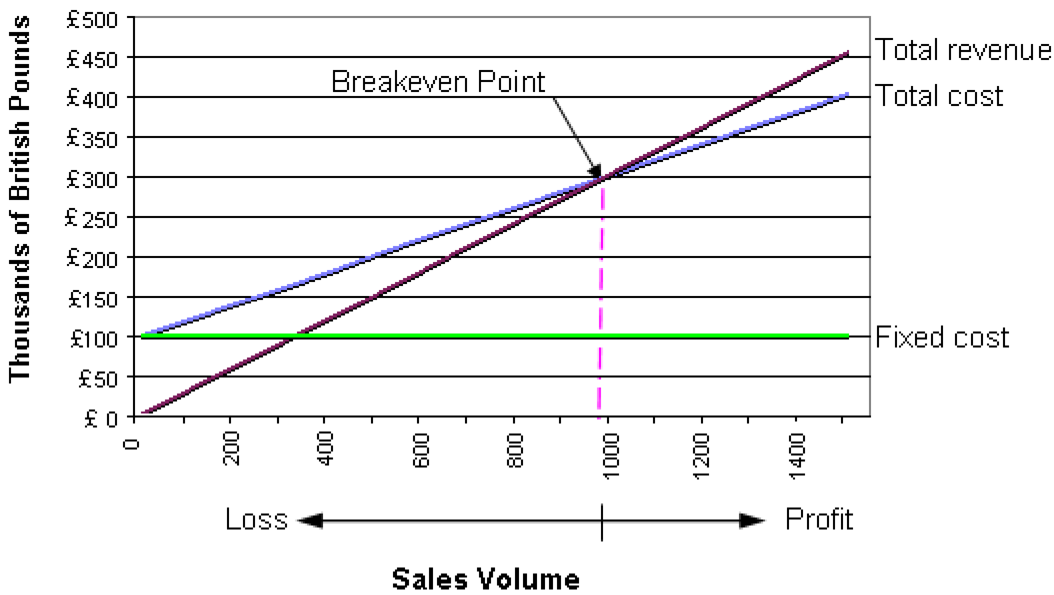


Figure 6-5 Breakeven analysis

Different selling prices have different breakeven point values. To get an optimized pricing strategy for the business, it is necessary to try different selling prices for the beetle car mould. It is assumed that the amount of the expected unit sales N_{vol} is 2000 and the machine is at work 90% of the time a year. Table 6-8 shows four different selling prices and their corresponding breakeven points, the total cost, total revenue, total variable cost and profit for the beetle car mould.

Table 6-8 Breakeven analysis for wood filler

N_{vol} (unit)	2000			
C_{fix} (£)	97,935			
H_y (hour)	365x24x90%=7884			
T_c (min)	435			
$C_{u-\mathrm{var}\,i}$ (£)	202			
P_{unit} (£)	322	310	302	279
R_{total} (£)	644,800	620,000	603,880	558,000
C_{total} (£)	503,415	503,415	503,415	503,415
$C_{t-\mathrm{var}\,i}$ (£)	405,480	405,480	405,480	405,480
P_m (£)	141,385	116,585	100,465	54,585
N_{be} (unit)	818	913	987	1284
T_{be} (year)	0.75	0.84	0.91	1.18

As can be seen in Table 6-8, the higher the selling price of the beetle car mould, the lower the value of the breakeven point, the higher the total revenue and profit , the total cost and total variable cost remain the same.

2. Screw-pin tooling with the sacrificial method

The beetle car mould produced by the screw-pin tooling with the sacrificial method in section 6.5 is used as the second example. Similar to the first example, the fixed cost C_{fix} of making the beetle car mould by using the sacrificial method is equal to the construction cost of the reconfigurable screw-pin tooling machine which is £97,935; the variable unit cost $C_{u-\mathrm{var}\,i}$ is equal to the manufacturing cost of the beetle car mould with the sacrificial method and is £257. Four different selling prices are selected for breakeven point analysis. It is assumed that the amount of the expected unit sales N_{vol} is 2000 and the machine is at work 90% of the time a year. The calculation results are listed in Table 6-9.

Table 6-9 Breakeven analysis for sacrificial method

N_{vol} (unit)	2000			
C_{fix} (£)	97,935			
H_y (hour)	365x24x90%=7884			
T_c (min)	455			
$C_{u-\mathrm{var}\,i}$ (£)	257			
P_{unit} (£)	322	310	302	279
R_{total} (£)	644,800	620,000	603,880	558,000
C_{total} (£)	613,775	613,775	613,775	613,775
$C_{t-\mathrm{var}\,i}$ (£)	515,840	515,840	515,840	515,840
P_m (£)	31,025	6,225	-9,895	-55,775
N_{be} (unit)	1518	1880	2224	4645
T_{be} (year)	1.46	1.81	2.14	4.47

As shown in table 6-9, the selected selling prices £279 and £302 for the beetle car mould have high breakeven point values and cannot produce a profit for the company at 2000 products; the breakeven point value of the selected selling price of £322 and £310 is less than 2000 and can make a small profit for the company. By comparing table 6-8 and table 6-9, it can be seen that the wood filler method has a better economic value than the sacrificial method.

6.7 Summary

A construction cost model and an application cost model have been developed for the reconfigurable pin tooling system. Based on the created construction cost model, the building cost of the HAVES test bed has been investigated and compared to that of the SSU, HA and SDL mould concepts. It is confirmed by the investigation that the HAVES test bed has a very good economical construction advantage over the other discrete tooling concepts. Based on the manufacturing process analysis of the beetle car moulds and rectangular cover moulds with the SPT wood filler method and the SPT sacrificial method, the application costs of the HAVES test bed have been collected and compared to the given quotation prices from different companies. The SPT with wood filler method has proved to be a better approach than the SPT with sacrificial method. Break-even analysis has been performed by setting several selling prices for the moulds to be produced, and the SPT with the wood filler method has a lower break-even value than the sacrificial method when manufacturing the same mould.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Introduction

This thesis work was motivated by the newly arising requirements in the highly competitive modern manufacturing industry to reduce the cost and lead time of tooling (mould and die) development. Traditional mould and die is dedicated and expensive, and not suitable for the current dynamic and rapid customization market. The main aim of this research was to build a Hybrid Vacuum Forming system based on the SPT as the test bed to understand the processes involved and examine the feasibility of the implementation of this machine in an industrial system. In particular, the objectives of the research reported in this thesis were as follows:

a. To design and build a machine test bed that integrates reconfigurable tooling with CNC and vacuum forming machines.
b. To develop a tooling shape control methodology for the SPT to adjust the screw pins from one position to another by using digital CAD as input.
c. To test and validate the developed HAVES and its associated support software.
d. To investigate the economic feasibility of the developed HAVES in producing plastic parts.

The HAVES test bed was designed and constructed in a full scale and systematic manner. The entire procedure of system development for the HAVES included four parts: hardware development, software development, experiments and economic model analysis. This chapter summarises the main contributions of this research and presents the conclusions that can be drawn from it while also recommending some actions for future work.

7.2 Contributions

The main contributions of this research may be summarised as follows:

1) Mathematical description of the SPT adjustment process. The description treats the adjustment of screw-pins according to component geometry as a mapping process from component surface model to screw pin array pattern and includes three components: surface and point cloud model description, screw pin tooling description, adjustment description.

2) Architecture development of the test bed by incorporating the SPT into a machine system. The concept of reconfigurable SPT is illustrated by, but not limited to, a hybrid vacuum forming machine.

3) Design and construction of the HAVES test bed on an industrial scale based on the SPT. The requirements of the HAVES test bed were analysed first before a generalized procedure for design of the HAVES test bed was outlined. This was followed by the development of the detailed design of the key components of the system including the CNC controller, the drive motors, the encoders, the milling and screw adjustment head, the SPT, the vacuum forming, etc. Finally, the calibrations of machine axes and the heater for the vacuum forming system were implemented. The HAVES test bed is composed of five modules: the SPT, the CNC control, the dual tool head, the vacuum forming and component evaluation. The integration of the HAVES test bed is demonstrated through a gantry machine, which could be retrofitted from an old CNC machine or constructed from a new one. The SPT is composed of an array pattern of interlocking screw-pins. To realise the reconfigurability of the tooling, the dual-tool head screw-pin adjustment tool and the milling cutter were developed. The constructed vacuum forming system includes a RAYMAX® 1120 radiant heater, a GAST® rotary vane vacuum pump, two Norgren roundline lift cylinder and a clamp and support frame. A GOM ATOS II-400 digitizing system is selected to inspect the vacuum formed components.

4) Development of a software package named SCAG to support the HAVES test bed, aimed at generating CNC program automatically for the SPT adjustment for 3D surface CAD model or 3D physical model; development of demo software called SPT-Demo to simulate screw pin adjustment of the SPT. The SCAG was developed using Virtual Basic and has a graphical user interface. It requires only an .inp file from FEA software (e.g. ABAQUS) for a complete description of the tool shape. The software package includes four functions: component discretisation, parametric expression of screw pin array pattern, mapping from components to screw

pin array pattern; and generation of CNC program. The SPT-Demo was developed using Unigraphics/GRIP; it is used to generate 3D screw-pin geometry within a Unigraphics/CAD module, so that the user can assess whether or not the position of the screw pin can represent the component geometry.

5) Experiments were performed to test the accuracy and repeatability performance of the screw pins adjustment of the HAVES test bed. The shape adjustment of the SPT, with screw pins in a close-packed arrangement, was demonstrated using a 20x21 discrete tool. The positioning accuracy and repeatability of screw pins were measured by using a Mitutoyo digital height gauge.

6) Identification of the methods for surface quality improvement of the SPT. The gaps among the screw-pins may inevitably be passed on to the vacuum formed components, which appear as dimples on them, which may be a problem for quality sensitive applications. Two options, sacrificial and filler, were employed to eliminate the dimples on the vacuum formed components. Several selected sacrificial and filler materials were evaluated and tested to determine the best one for application to achieve a surface quality similar to that of traditional dedicated moulds. The screw-pins are firstly adjusted by the CNC control to pre-determined positions to represent the geometry of proposed component. A sacrificial, a plastic sheet that is much thicker than the thickness of the vacuum formed component, is firstly vacuum formed. Further machining may be needed on the sacrificial to get rid of stairs among screw-pins and recover the geometry details on the vacuum formed component. Filler is applied on the screw-pin when it is in a liquid form and is left to cool to a solid status in a short time. Milling operation is carried out on the filler rather than on the screw-pins to take off

extra materials from the filler so that the machined filler will have the shape of the geometry of the component to be vacuum formed. Comparison experiments were also performed on parts produced by traditional solid moulds, the SPT with a sacrificial method and the SPT with filler material method.

7) Economic model construction and formulation for the reconfigurable tooling. Economic analyses were conducted and compared to validate the feasibility of the HAVES test bed. Two economic models were developed; one was the construction model of the reconfigurable tooling, and the other was the application model of the reconfigurable tooling. The elements of the construction model included pin costs, pin positioning costs, pin locking costs, pin container costs, etc.; the elements of the application model included time for programming, time for shape adjustment, time for machining, technician cost per hour, etc.

7.3 Conclusions

The conclusions that can be drawn from this research are summarised as follows:

1) The developed HAVES test bed is a compact machine system created by integrating the reconfigurable SPT with CNC machine and vacuum forming machine; It has been implemented and shown to have significant potential at an industrial system.

2) The SPT of the HAVES test bed is composed of a matrix of disposable and self interlocked screw-pins which are adjusted to a near-net shape

position and machined to a final shape which achieves a quality good surface finish of the vacuum formed component. The SPT can be reconfigured and reused to produce many different components. This method overcomes the traditional lead time and cost issues associated with manufacturing components in low volumes; it has the potential to replace current dedicated moulds.

3) The mathematical description of the SPT adjustment process was capable of expressing parametric SPT and extracting the required element positions from a CAD model or reverse engineering file by using the designed algorithm to enable automatic CNC G-code generation.

4) The CNC setup mechanism has been confirmed to be a simple and valuable means for reconfiguring the SPT in the full scale HAVES test bed. Adjustment to the screw pins can be made accurate enough for use in producing the SPT shape for sacrificial or filler material based component vacuum forming;

5) The experiments have revealed that the sacrificial and filler material can be employed to eliminate the dimples on the surface and improve surface accuracy of the vacuum formed components. By utilising CNC machining on a sacrificial plastic sheet cover or painted filler material, the reconfigurable screw-pin tooling is transferred into a solid and continuous mould and can be applied to produce components with complex geometry to the same level of quality as that of traditional dedicated tooling.

6) Based on economic analysis, it was found that the HAVES test bed is justified and has the lowest construction cost compared with sequential set-up tooling, hydraulically actuated pin tooling and shaft-driven leadscrew

tooling.

7) The proposed technology has commercial viability and competitiveness in rapidly producing small-lot customised products. It will benefit industry by providing flexibility and low cost reconfigurable moulding machines to eliminate dedicated moulds for vacuum forming. The economical impact of the developed laboratory prototype (HAVES test bed) is delivered by reducing labour and material cost and storage for the dedicated mould. The ecological impact of the HAVES test bed is delivered by eliminating the need for a dedicated mould, saving material and reducing the cost of material recovery.

7.4 Advantages and potential applications

7.4.1 Advantages

In general, compared to current procedure of vacuum forming component manufacturing, the advantages of utilising the HAVES test bed are:

1) Savings in time on set-up, production and mould materials;
2) Faster product turnaround and reduction of tooling costs;
3) Flexibility improvement of the vacuum forming process and quicker response to market change;
4) Significantly greener technology: lower environmental resource consumption and dramatically reduced waste.

7.4.2 Potential application

There are many potential applications of the reconfigurable moulding machine utilising screw-pins including:

- Vacuum forming for products needing rapid customisation. Applications for products could be made more personal. An example would be a personal face model for an Easter mask.

- Reconfigurable lay up die for composites. Due to its high strength to weight ratio, composites have been widely used in the aerospace industry, which is a typical industry of small batch and large variety, requiring a large number of moulds for moulding composite components. Reconfigurable moulds will have the advantage of reducing lead time and cost associated with storage, inventory, set-up, material handling and de-oxidation as well as the refurbishment of unused moulds.

- Reconfigurable stretch forming of sheet metal. The screw-bins are self-locked and can resist a large amount of loading from presses, which makes them ideal for sheet metal stretch forming.

- Medical casting application. Medical applications of the machine could be orthopaedic prosthesis and orthosis, which are typically globally localised due to the requirement to configure these components for individual (personalised) applications, yet they need to be made at a decent speed and in an economic fashion. Typical applications such as rapid customised prototype, fractured bone casts, artificial limbs, orthosis (all of which are produced almost as personalised prototypes) etc; require a high level of customisation that is not economical with standard methods. Therefore companies and hospitals (nurses) naturally tend to design components to suit these methods of production whenever they are the appropriate and only method.

7.5 FUTURE WORK

A laboratory prototype of the reconfigurable vacuum forming moulding machine that is capable of reusing the mould for many different components has already been constructed. There are a number of aspects that are worth further investigation before this integrated system can be commercialized. A list of further work is planned as follows:

1) New screw pin material tests. The screw pins of the SPT can use different materials such as steel, nylon, aluminium, etc., just like materials used by traditional solid tooling. Only nylon screw pins have been used in this thesis, experiments that use steel and aluminium as screw pin materials are necessary.

2) The SPT temperature control. For different plastic materials, different mould temperatures which vary from about 80°C to 130°C are recommended by Formech International Ltd. (Formech International Ltd., 2002). For large production runs, to ensure consistent product results combined with optimum cycle times, a constant mould temperature should be maintained. To simplify the construction of the system, the SPT was used only at room temperature. Mould temperature control units are thus required to regulate the temperature within the mould ensuring accurate and consistent cooling time for the commercial machine. The concept of SPT with a temperature control unit is shown in Figure 7-1. The Watlow FIREROD ® cartridge heaters can be put into the selected screw pins and heat the whole tooling.

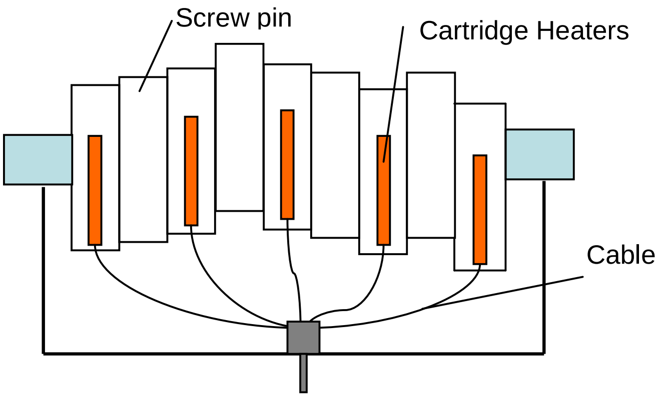


Figure 7-1 The SPT with temperature control unit

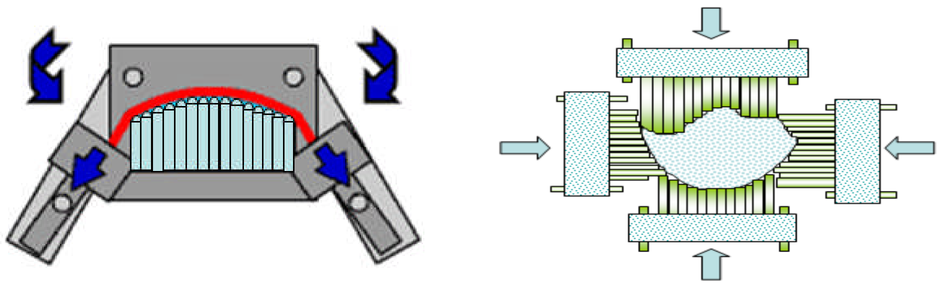
3) Only rudimentary testing has been done to show the role of a filler in wrinkle and dimple suppression. The selected wood filler is a little brittle and may not be suitable for producing middle or large volume products. A comprehensive study should be conducted to find further and better material that suits the requirements to cover the surface of screw pins. Furthermore, rapid and effective methods for filling such materials onto the SPT surface also need to be developed.

4) Component fidelity (dimension accuracy) control. In addition to dimple suppression, component fidelity of the final plastic part is extremely important. There are several elements that need to be considered: shrinkage of the plastic material, the filler material, vacuum forming process parameters, etc. By comparing the design model with the reverse engineering model by scanning, the difference between them can be calculated.

5) Plug assist over the SPT. The plug assist is needed when vacuum forming complicated or deep-draw parts. It is used to prevent webbing in the forming of multiple male moulds which are close together and helps achieve good wall thickness when forming deep cavities. The current

HAVES has no plug assist; it may have some problems when producing complex or deep-draw parts. To integrate the plug assist with the system, it will be mounted on a pneumatic or hydraulic cylinder situated over the forming area of the SPT so as to force the material into a female cavity within the tooling area.

6) New applications exploration. Further applications of the SPT could include composite forming, stamp forming, stretch forming, casting, etc. Among the new applications, the composite forming is most similar to vacuum forming. The HAVES can easily be adopted to produce composite components, which have been increasingly used in the automobile and aerospace industries. By properly retrofitting, as shown in Figure 7-2, the screw pin concept may also be adaptable for stretch forming by employing two separate screw-pin tooling and for casting by using four individual screw-pin toolings.



(a) Stretch-forming (b) Casting

Figure 7-2 New application concepts for the SPT

7) A user-friendly interface has already been developed for automated CNC program generation for screw-pin adjustment. However, generation of CNC program for milling operations based on scanned images is very time-consuming and needs skills in reverse engineering, CAD and CAM; therefore, the development of a user-friendly software is needed to automate these processes.

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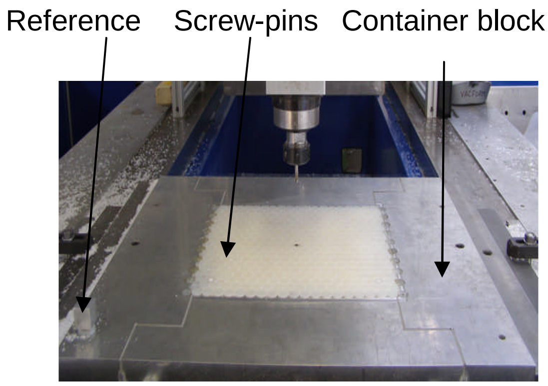
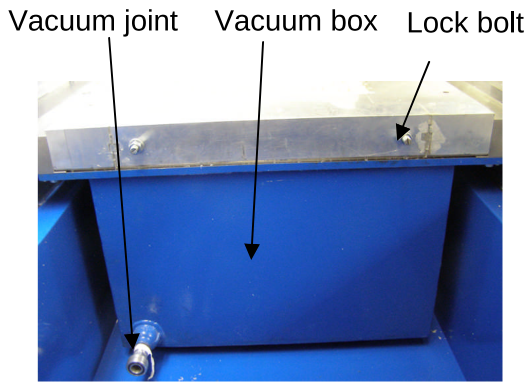
Appendix A

1. Screw-pin tooling prototype



(a) Tooling top view



(b) Tooling front view

2. CNC controls main features comparison

	OSAI 10/510i light	**FAGOR 8055 CNC**	**E.C.S. 2801 CNC**	**NEE AMC B3/6**
Number of axes	6 axes, servo drives	7 axes, servo drives	8 axes, servo drives	6 axes, servo drives
Spindle	1	2	1	1
Gantry axes	Yes	Yes	Yes	Yes
Encoder Input/output	6 I/6 O	8 I/8 O	8 I/8 O	6 I/6 O
Programming languages	ISO	ISO	ISO	ISO
Controller screen	WINMEDIA Colour touch	TFT Colour touch	TFT Colour touch	WinAMC® soft. on PC
Input/output	16 I/ 16 O (digital)	104 I/56 O (PLC)	48/32 I/O (PLC)	Max (PLC) 1024 I/1024 O
CNC price	£7,928	£5,649	£35,000	£8,500
Remark	5 axes +spindle	5 axes +spindle	5 axes +spindle+2 PLC control + installation	5 axes +spindle

3. Quotation of CNC from Fagor Automation U.K. Limited

05:24 25/07/2006 01327300880 FAGOR AUTOMATION UK PAGE 01

FAGOR

Fagor Automation U.K. Limited
2a Brunel Close
Drayton Fields Industrial Estate
Daventry Northamptonshire NN11 5RB
Tel: 01327 300067 Fax: 01327 300880
info@fagorautomation.co.uk
www.fagorautomation.co.uk

FAO: Mr. James Wang
B2 Room, Manufacturing Lab,
The University of Nottingham,
Notts.
NG7 2RD

Date: 8 August 2006

Reference: Q0808-NU-1

Dear Mr. Wang,

Further to our meeting today. Since discussing your requirements, we are pleased to provide a modified quotation for your special purpose machine:

1) CNC 8055 /B - MC comprising of:

11" LCD TFT colour monitor with integrated keyboard and Jog panel.
1 Mb RAM and 4 Mb Flash memory
104I / 56O for the PLC.
"B" model CPU module providing 6 Ms BCT
Ethernet
1 Gb Compact flash memory (Solid State Hard Disk)
Seven axes analog output and position feedback.
10 Meter Cables for Jog and Monitor.
MC (Milling Conversational) software option
DNC (Communications software including PC CD)
Profile Editor
PC customising software for CNC screens

One day on-site commissioning training

Discounted price to Nottingham University: £5649.00

This Numerical Control Device, is strictly subjected to "double use technology" laws (E.U. 1334/2000 regulation) which severely restrict its free re-exportation without the pertinent country's national authorities' consent.

RISK OF LOSS OR DAMAGE SHALL PASS TO THE BUYER WHEN THE GOODS LEAVE THE SELLERS PREMISES.

We look forward to receiving your instructions, meanwhile should you need any further assistance please do not hesitate to contact us.

Yours faithfully,

Leslie Drury
For and on behalf of Fagor Automation UK Ltd.

MONDRAGON CORPORACION COOPERATIVA

Nottingham University
6 axis routing machine with PC Front-end
with interface for analogue drives

QJB_NottsUniv_0001a

Quantity	CODE	DESCRIPTION	PRICE GBP
1	93000659U	10/510i LIGHT CONTROL UNIT - 850 MhZ Processor - 1 Ethernet Interface (RJ45)	
1	93000666R	510 LIGHT 1.8GB USER PROGRAM MEM	
1	93000656D	OS-WIRE 6 AXES BOARD+1AO+2AI	
2	93000577N	OS-WIRE DIGITAL BRIDGE - 3 ENC. CHN	
1	93000558Z	KIT SW MACHINING CENTER	
1	93000494G	KIT SOFTWARE WinNBI	
1	93000495A	WinNBI CUSTOMIZED LAYOUT ENABLE	
1	R536301471	RIO EC OS-WIRE	
3	R536400171	RIO 16I /KE BLOCK Modular I/O block providing: - 16 digital inputs 24Vdc - clips for optional terminal expansion	
2	R536400271	RIO 16O /KE BLOCK Modular I/O block providing: - 16 digital outputs 1A - clips for optional terminal expansion	
1	93000225J	DOC KIT FOR MC (ENG)	
1	97810000T	OS3 FASTWIRE TERM. PLUG	
1	97810201A	OS-WIRE CABLE 2M CAT7	
1	97810101H	OS-WIRE CABLE 1M CAT7	
2	97810031V	OS-WIRE CABLE 0.3M CAT7	
1	93000599U	WINMEDIA KEYBOARD	
1	93000636L	WINMEDIA 1.2 GHz TOUCH SCREEN - 15” TFT colour screen with touch screen	
1	93000596D	512 MBYTE RAM DDR MEMORY	
1	93000597F	CD-ROM DRIVER FOR WINMEDIA	
1	93000598S	FDU DRIVER FOR WINMEDIA	
1	93000602T	WIN XP MULTI-LANG. FOR WINMEDIA	
1 Lot	Software Dev	Application Software - Develop plus and Part program cycles	
		Total cost for 6 axis CNC with WinMedia panel and keyboard	**£ 7,928**

All prices are Ex VAT and Ex Works

Osai UK Ltd. Standard Terms and Conditions apply (Available on request)

Quotation valid for 90 days from date of quotation

Page 1

4. Drive for X axis and Y axis (Y1, Y2)

Manufacturer	SEM
Model number	MT30R4-58
Type	Ferrite brushed DC servo motor
Max. speed	5000 RPM
Max terminal voltage	95V
Continuous stall torque	0.5 NM
Continuous stall current	2.8 A
Current at peak torque	11 A

5. X axis feedback measurement

Manufacturer	Sony Magnescale Inc.
Model	SL110
Type	Linear encoder
Measuring length (mm)	2000
Overall length (mm)	L+103
Accuracy (at 20°C, μm)	± (25 + 5L/ 1000)
Resolution	10 μm
Max. response speed	300 m/ min
Expansion coefficient	(11.1 ± 1) x 10-6/ °C
Operating temperature	-5 °C to 45 °C
Compatible read head	PL20B/ 25

6. Y1, Y2 feedback measurements

Manufacturer	Sony Magnescale Inc.
Model	SL130
Type	Linear encoder
Measuring length (mm)	2500
Overall length (mm)	L+100
Accuracy (at 20°C, μm)	± (25 + 5L/ 1000)
Resolution	10 μm
Max. response speed	300 m/ min
Expansion coefficient	(10.4 ± 1) x 10-6/ °C
Operating temperature	-5 °C to 45 °C
Compatible read head	PL20B/ 25

7. Drive for Z axis

Manufacturer	SEM
Model number	MT22R2-24
Type	Ferrite brushed DC servo motor
Max. speed	5000 RPM
Max terminal voltage	120V
Continuous stall torque	1.2 NM
Continuous stall current	5.2 A
Current at peak torque	35 A

8. Parameters of lead screw actuator used on the Z axis

Total length of lead screw	550 mm
Diameter and pitch of lead screw	15x5 mm
Stroke	250 mm
Mass of the lead screw	1.55 kg/m

9. Drive for C axis

Manufacturer	ECL
Model number	S644-3B/T
Type	DC permanent magnet servo motor
Max. speed	3000 RPM
Max terminal voltage	60V
Continuous stall torque	1.46 NM
Continuous stall current	7.0 A
Current at peak torque	32.5 A

10. Z and C axes feedback measurement

Manufacturer	Hengstler
Model	RS58-O/1024AS.41RB
Type	Rotary encoder
Output Signal	RS-422
Supply Voltage	5V(dc)
Shaft Diameter	6mm
Body Diameter	58mm
Shaft Type	Incremental; Standard
No Load Current	40mA
Pulse Per Revolution	1024
Maximum Revolutions	10000rpm
IP Rating Housing	IP65

11. Pulley pair for Z axis

Both drive pulley and slave pulley are reduced backlash timing pulleys made by HPS Gears Ltd. The pulley material is aluminium and the flange material is steel. The pitch of the pulley is 5mm.

The timing belt of the pulley (Part number: T5/460) has 92 teeth, and its width is 16mm, pitch 5mm and pitch length 460mm.

Pulley	Part Number	Teeth	PCD mm	Flange No.	ΦD mm	Boss Φ mm	Bore Φ mm
Drive pulley	20ABT 5-21	20	31.84	20XL	30.60	20	6
Slave pulley	40ABT 5-15	40	63.69	16H	62.45	40	8

Gear ratio of Z axis: $r_w = \frac{Z_d}{Z_s} = \frac{20}{40} = 1:2$

Z_d -- Teeth number of Z axis drive pulley;

Z_s -- Teeth number of Z axis slave pulley.

12. Pulley pair for C axis

Both drive pulley and slave pulley are reduced backlash timing pulleys made by HPS Gears Ltd. The pulley material is aluminium and the flange material is steel. The pitch of the pulley is 5mm.

Pulley	Part Number	Teeth	PCD mm	Flange No.	ΦD mm	Boss Φ mm	Bore Φ mm
Drive pulley	24ABT 5-15	24	38.19	24XL	36.95	25	6
Slave pulley	72ABT 5-15	72	114.59	28H	113.35	60	10

The timing belt of the pulley (Part number: T5/500) has 100 teeth, and its width is 10mm, pitch 5mm and pitch length 500mm.

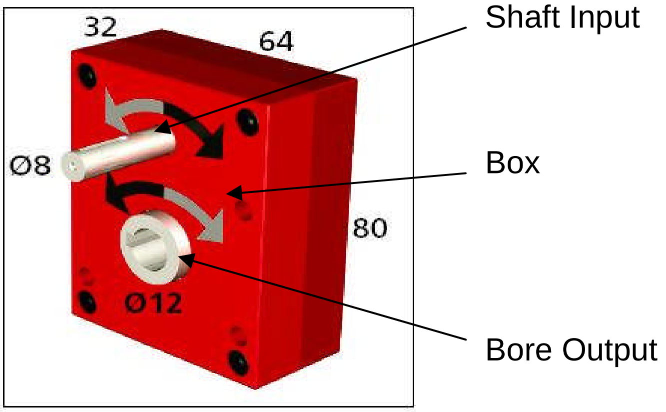
Gear ratio of C axis: $r_c = \frac{C_d}{C_s} \bullet r_g = \frac{24}{72} \times \frac{1}{7} = 1:21$

C_d -- Teeth number of C axis drive pulley;

C_s -- Teeth number of C axis slave pulley.

r_g -- Gear box ratio.

13. Offset spur gear reducer FF15-7 on C axis



The FF15-7's ratio is 1:7, and its max input speed is 2000 Rpm. The relationship between the input speed and the output torque is shown in the table below.

Input Speed (Rpm)	10	50	100	200	500	1000	2000
Output Torque (Nm)	6.10	4.00	3.70	3.20	3.00	2.60	2.20

14. Drive motor for W axis

Manufacturer	SEM
Model number	MT22D2-19
Type	Ferrite brushed DC servo motor
Max. speed	2500 RPM
Max terminal voltage	140V
Continuous stall torque	3.5 NM
Continuous stall current	6.1A
Current at peak torque	37 A

15. Pulley pair for W axis

Both drive pulley and slave pulley are heavy duty timing pulleys made by HPS Gears Ltd. The pulley material is mild steel and the flange material is steel. The pitch of the pulley is 8mm.

The timing belt of the pulley (Part number: HTD8/480) has 60 teeth, and its width is 20mm, pitch 8mm and pitch length 480mm.

Pulley	**Part Number**	**Teeth**	**PCD mm**	**Flange No.**	**ΦD mm**	**Boss Φ mm**	**Bore Φ mm**
Drive pulley	36 HTD8-28	36	91.67	23H	90.30	70	15
Slave pulley	36 HTD8-28	36	91.67	23H	90.30	70	15

Gear ratio of W axis: $r_z = \frac{W_d}{W_s} = \frac{36}{36} = 1:1$

W_d -- Teeth number of W axis drive pulley;

W_s -- Teeth number of W axis slave pulley.

16. Parameters of lead screw actuator used on the W axis

Total length of lead screw	450 mm
Diameter and pitch of lead screw	24x5 mm
Stroke	250 mm
Mass of the lead screw	2.47 kg/m

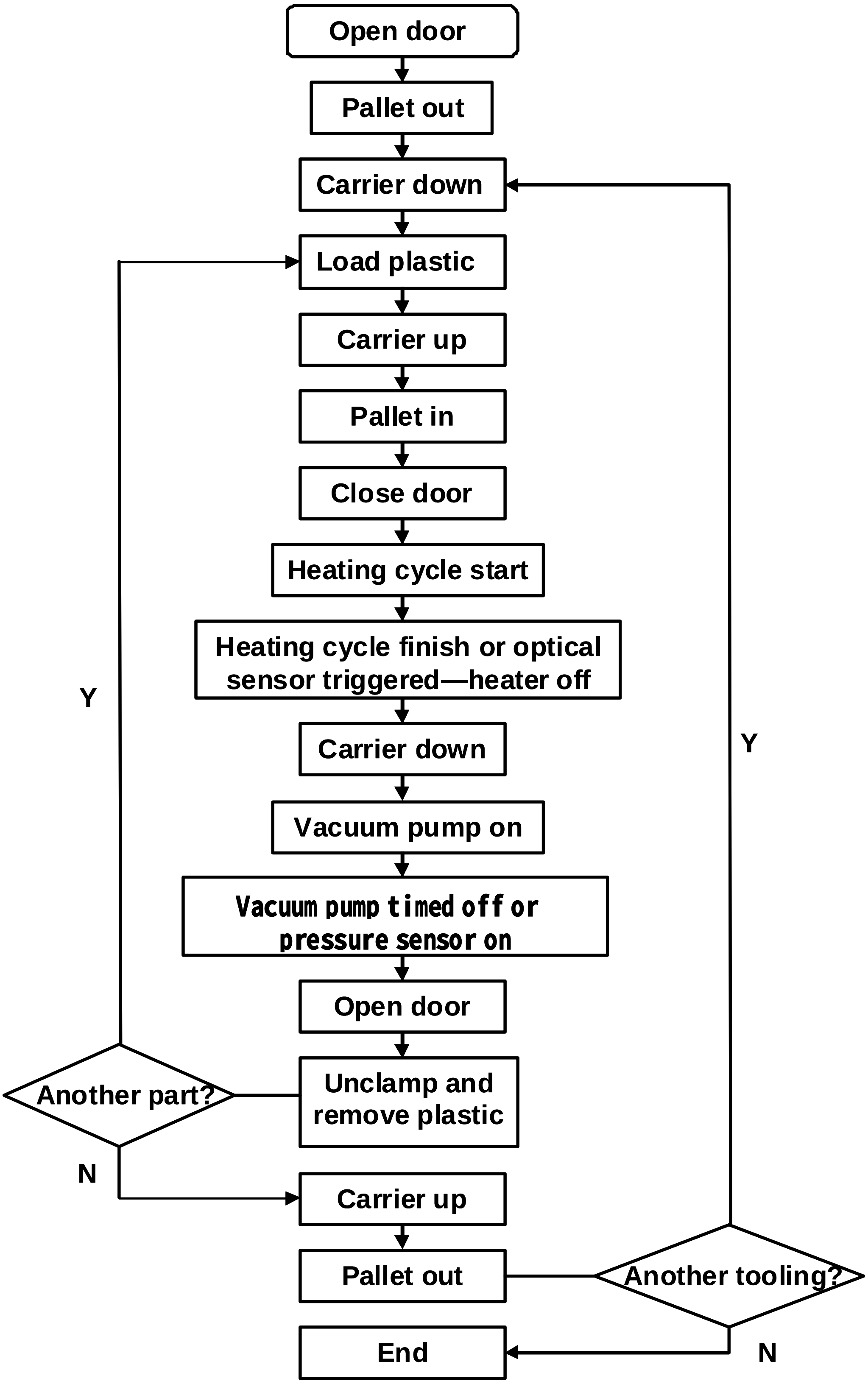
17. W axis measurement feedback

Manufacturer	HEIDENHAIN
Model	ROD 426 B
Type	Rotary encoder
Output Signal	TTL
Supply Voltage	5V(dc)
Shaft Diameter	6mm
Body Diameter	58mm
Shaft Type	Incremental; Standard
No Load Current	150 mA
Pulse Per Revolution	1024
Maximum Revolutions	12000rpm
IP Rating Housing	IP67

18. Router spindle

Manufacturer	SEV		
Model number	AT/MT 1090-140		
Type	Asynchronous 3-phase motor		
Max terminal	380 V		
Hz	300	350	400
Speed (Rpm)	18000	21000	24000
Power (KW)	6.0	6.0	5.5
Current (A)	12.6	12.6	12

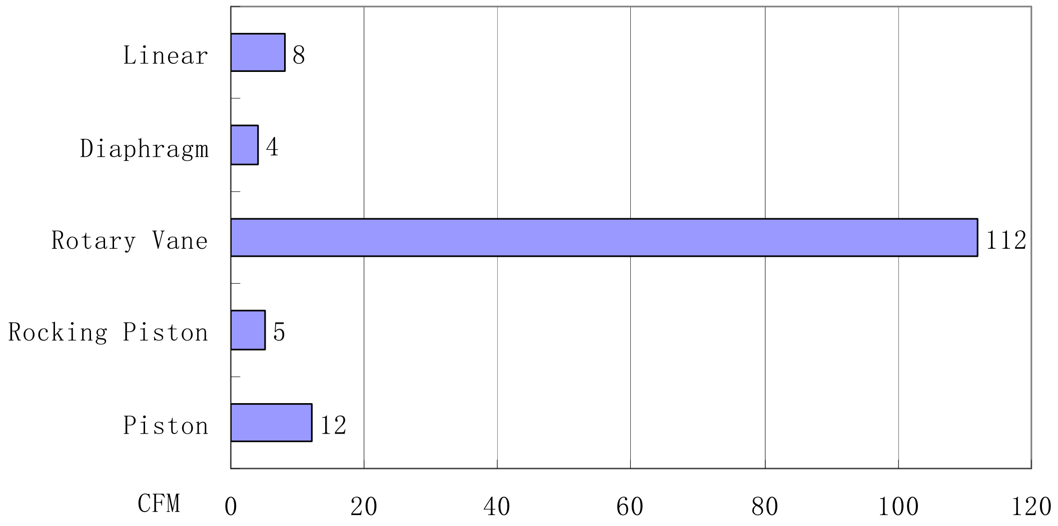
19. Vacuum forming working process



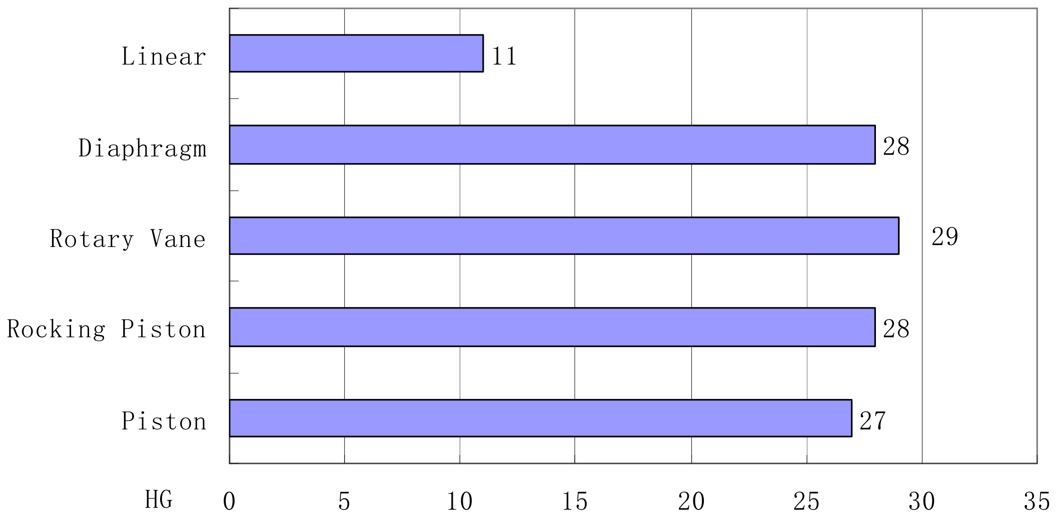
20. Vacuum pump comparison

	Piston	Rocking Piston	Rotary Vane	Diaphragm	Linear
Flow Rates	12	5	112	4	8
Maximum Vacuum	27	18	29	28	11

(a) Air Flow Rates



(b) Maximum Vacuum



21. Time for vacuum forming calculation

A calculation method of pumping speed by constant volume is described as the following equation [Biltoft, Benapfl, and Swain, Vacuum Technology, Las Positas College, 2002, P100]:

$$S_p = 2.3 \times \left[\left(\frac{V}{t_2 - t_1} \right) Log_{10} \left(\frac{P_1}{P_2} \right) \right]$$

We have:

$$t_2 - t_1 = \frac{2.3 \times V \times Log_{10} \left(\frac{P_1}{P_2} \right)}{S_p}$$

Where:

V = volume of air in vacuum box [liters];

t_1 = time at pressure P_1 [seconds];

t_2 = time to reach pressure P_2 from pressure P_1 [seconds];

P_1 = pressure at t_1 [torr];

P_2 = pressure at t_2 [torr];

S_p = pump speed [liters/sec].

To calculate the time required for vacuum forming from standard atmospheric pressure 30"Hg (at the beginning of vacuum forming, t_1=0 and P_1=762 torr) to 20"Hg (508 torr, $P_2 = P_1$ -508=254torr) vacuum, we can set S_p =10CFM (4.72 liters/sec). Then we have:

$$t_2 = \frac{2.3 \times V \times Log_{10} \left(\frac{P_1}{P_2} \right)}{S_p} = \frac{2.3 \times 110 \times Log_{10} \left(\frac{762}{254} \right)}{4.72} = 25.57 \quad \text{sec}$$

22. Cylinder selection

The theoretical thrust (outstroke) or pull (in stroke) of a cylinder is calculated by multiplying the effective area of the piston by the working pressure.

The theoretical pull force (F) is given by

$$F = \frac{\pi(D^2 - d^2)P}{40} N$$

We have:

$$d = \sqrt{D^2 - \frac{F \bullet 40}{\pi \bullet P}} = \sqrt{D^2 - \frac{40 \times 9.8 \times 40}{3.14 \times 6}} = \sqrt{D^2 - 832.27} > 0$$

$$\therefore D > \sqrt{832.27}\, mm = 28.85\, mm$$

Where, D is cylinder bore in millimetres, d is piston rod diameter in millimetres, P is pressure in bar and F is thrust or Pull in Newtons.

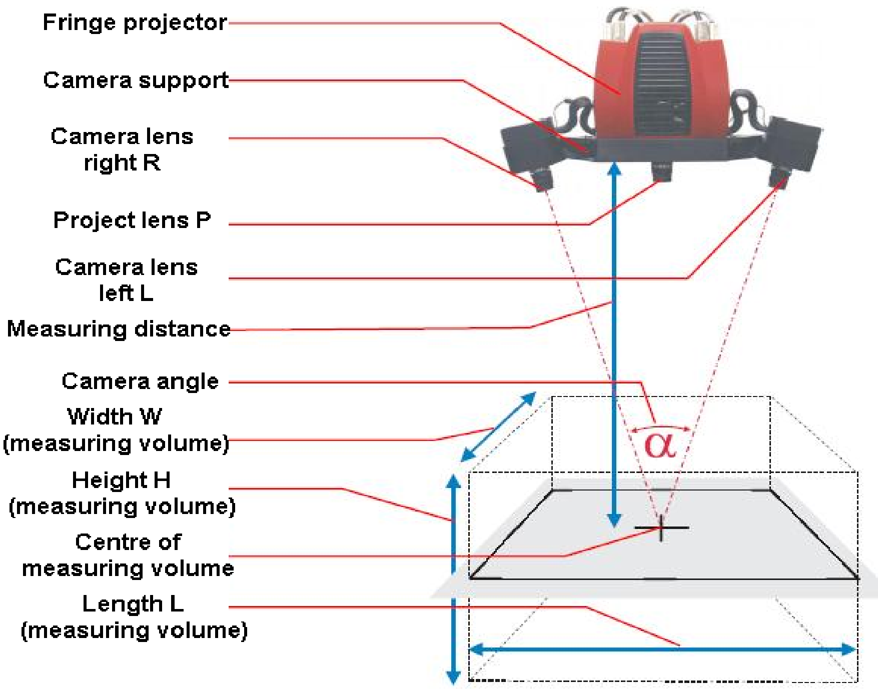
Refer to the manual of Norgren cylinders; the minimum cylinder diameter should beΦ32. Thus a double acting, side port and flat end Norgren roundline cylinder RT/57232MF/500 is selected. Its parameters are listed in table 4-6.

Table Norgren cylinder RT/57232MF/500

Cylinder diameter	Φ32 mm
Piston rod	Φ12 mm
Stroke distance	500 mm
Operation pressure	1 to 10 bar
Thrust force at 6 bar	482 N
Pull force at 6 bar	414 N
Variants	side port and flat end

23. ATOS II 400 system

1) Definition of Terms Referring to the Sensor Unit



2) Application combinations of sensors

Measuring volume (L x W x H in mm³)	Resulting distance of measuring points in mm	Projector Lens	Camera lens	Camera angle (α)	Measuring distance (mm)
1700x1360x1360	1.33	6mm	8mm	14°	1600
1200x960x960	0.94	6mm	8mm	22°	1120
800x640x640	0.62	8mm	12mm		
550x440x440	0.43	8mm	12mm	30°	750
350x280x280	0.27	12mm	17mm		
250x200x200	0.20	17mm	23mm		
175x140x140	0.14	23mm	35mm		
135x108x108	0.11	35mm	50mm		

3) Import CAD file extension in ATOS II 400 system

File Extensions	Description
.asm	Pro/Engineer Assembly file
.stp	STEP
.x_t	Parasolid
.model, .dlv, .exp	CATIA
.igs	IGES
.sat	ACIS Solid Model
.prt	Pro/Engineer Model File
.prt	Pro/Engineer Parts File
.prt	Unigraphics Parts File
.wrl	VRML
.vda	VDA

4) Export file formats in Evaluation Mode of ATOS II 400 system

Export format	3D mesh data	Point cloud	Brief information	File ext.
Export g3d	Yes	No	The ATOS internal data are transferred into the g3d format	.g3d
STL	Yes	No	STL is a format for polygon data and supports colour polygons	.stl
POL	Yes	No	POL is a format for polygon data and can be read by Polyworks software	.pol
IGES	No	Yes	IGES is a CAD interchange format	.iges
VDA/PSET	No	Yes	VDA/SET is a format of the German Association of the Automotive industry. Features are exported as 3D points or as VDA primitives	.vda
ASCII	Yes	Yes	Features are exported as 3D points with additional information in ASCII format	.asc
Reference Points	No	Yes	Point IDs are exported with XYZ coordinates	.ref
Feature PW	No	yes	PW is a format for the Polyworks. The data are exported as 3D points	.pw

24. The purchased components and materials for system construction

Name	Code	Quantity
WATLOW 1120 radiant panel	P2424AX081	1
WATLOW SD temperature controller	SD6C-HCUA-	1
WATLOW SD limit controller	SD6L-HJUA-	1
WATLOW B series DIN-A-MITE	DB30-60C0-0000	1
Semi-conductor fuse 25 amp	17-8025	3
Fuse holder	17-5110	3
Thermocouples to fit RAYMAX 1120 heater with SD6C controller	N10DJFUB096A	2
GAST® rotary vane vacuum pump	1423-1010-G626X	1
Wrought aluminum tooling plate	1210x760x70mm	1
NYLON SCREW POD	M20x300	1500
HSSGT Long SHANK second tap	SHR0850570H	2
Trunking	RS 214-3755	3
Brackets	RS 214-3761	1
Wrought aluminum tooling plat	545x310x8	2
Wrought aluminum tooling plate	15x410x1200	1
Wrought aluminum tooling plate	25x410x1200	1
Steel sheet	2mx1mx1mm	13
Transparent Plastic Sheet	3mx1.5mx5mm	4
Strut profiles-8mm Groove	30x30x2000mm	17
Strut profiles-8mm Groove	30x30x3000mm	12
Pressure switches	PMN250AN1/4PS	2
Clear polycarbonate sheet	2mx1mx5mm	4
Type welded tip thermocouple	621-2158	8
Supersmart ball bushing pillow blocks	LSB-20OPAJ	4
Shaft support rail assembly 600mm long	WU50-020T1ZA	2
Precision rolled ballscrew 20MM * 500	EBB2005-500	1
Linear bearings	LBE30	2
Thomson’s super smart ball bushing bearings and pillow block	SSEPBOM 20DD	4
Norgren Pneumatic Valve	RS 723 438	2
Burkert Two-way Compact Solenoid Valves	RS 306 9973	2

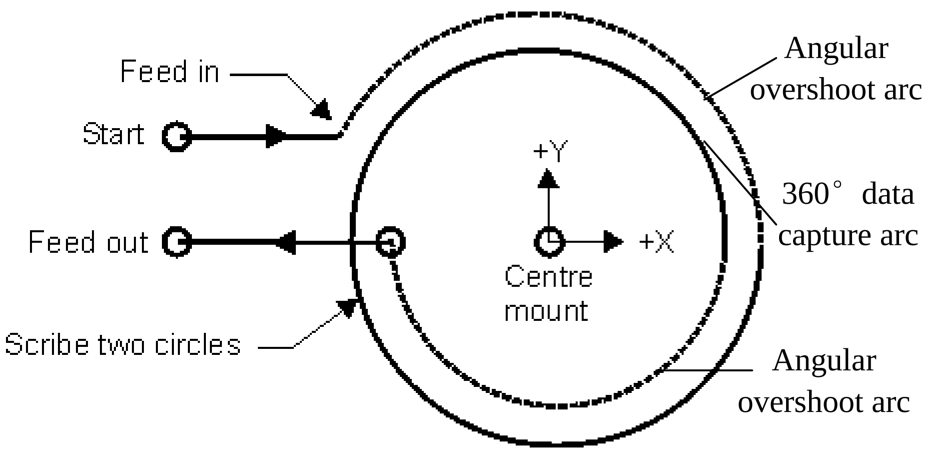
25. Metric part program for Ballbar system

This program moves the Ballbar through two sequential circles in a clockwise direction, as shown below. The reason for scribing two circles rather than one is to allow the machine to attain a constant contouring speed during an angular overshoot arc before data is captured on the data capture arc. Feed in and feed out movements are used to trigger the data capture software.

1) Program

G54;	(apply work offsets)
G90;	(absolute dimensions)
M05;	(spindle off)
G17;	(movements in xy plane)
F3000;	(set federate)
G01 X-151.5 Y0.0 Z0.0;	(move to start point)
M00;	(pause to change software direction)
G01 X-150.0 Y0.0;	(perform feed in)
G02 I150.0 J0.0;	(360 degree CW arc)
G02 I150.0 J0.0;	(360 degree CW arc)
G01 X-151.5 Y0.0;	(perform outfeed)
M30;	(program end)

2) Machine tool path for clockwise 360 degree capture range



26. PICO TC-08 8 Channel Thermocouple Data Logger

Appendix B

1. Point Processor (1)—main programme

```
' This is a Virtual Basic programes for Point Processor

' Author: Zhijian WANG

' Data: May 2008



' Variable Statements


Dim scmatrix_max(100, 100) As screw
Dim scmatrix_min(100, 100) As screw

'Sub function is used to import screw pin tooling information

Private Sub screw_pins_Click()

' Sub function variable statements

Dim pth As String
Dim temp As String
Dim Dpin As Integer
Dim x, y, z, xpos, ypos, zpos As Double
Dim col, row As Integer
Dim point_pos(3) As Integer

' Open path for import file

 pth = "f:\wangzhijian\pinposition.dat"
 Open pth For Input As #1

' Read the file line by line

     Line Input #1, str_ln
```

```
    Line Input #1, str_ln
    Line Input #1, str_ln
    temp = Mid(str_ln, 6, Len(str_ln) - 5)
    'input DPin
    Dpin = CInt(temp)
    Line Input #1, str_ln
    'input Xpin
    temp = Mid(str_ln, 6, Len(str_ln) - 5)
    Xpin = CDbl(temp)
    Line Input #1, str_ln
    'input Ypin
    temp = Mid(str_ln, 6, Len(str_ln) - 5)
    Ypin = CDbl(temp)
    Line Input #1, str_ln
    'input Lpin
    temp = Mid(str_ln, 6, Len(str_ln) - 5)
    Lpin = CInt(temp)
    Line Input #1, str_ln
    'input Rowpin
    temp = Mid(str_ln, 8, Len(str_ln) - 7)
    Rowpin = CInt(temp)
    Line Input #1, str_ln
   'input Rowpin
    temp = Mid(str_ln, 8, Len(str_ln) - 7)
    Colpin = CInt(temp)

    Line Input #1, str_ln
    Line Input #1, str_ln

Do
     j = 0
     Line Input #1, str_ln
     'find the postion of x, y, and z
     For i = 1 To Len(str_ln)
          If Mid(str_ln, i, 1) = "," Then
              point_pos(j) = i
              j = j + 1
           End If
     Next
   'if it is the X,Y,Z position line,
   If point_pos(0) > 0 Then
```

```
'x,y,z position string
 xpos = Trim(Mid(str_ln, 1, point_pos(0) - 1))
 ypos = Trim(Mid(str_ln, point_pos(0) + 1, point_pos(1) -
             point_pos(0)))
 zpos = Trim(Mid(str_ln, point_pos(1) + 1, Len(str_ln) –
            point_pos(1) + 1))
 'x,y,z position in double
  x = CDbl(xpos)
   y = CDbl(ypos)
   z = CDbl(zpos)
   z = 0.000001
  'current screw pin's position: col (i) and row (j) number
  col = screw_position(x, y, Rowpin, Colpin, Xpin,
          Ypin).col_pos
  row = screw_position(x, y, Rowpin, Colpin, Xpin,
           Ypin).row_pos
  'initial matrixs of screw pin tooling
   scmatrix_max(row, col).x = 0.000001
   scmatrix_max(row, col).y = 0.000001
    scmatrix_min(row, col).x = 0.000001
    scmatrix_min(row, col).y = 0.000001
    'store screw pin coordinates in matrixs
    If Abs(x) > 0.000001 Then
         scmatrix_max(row, col).x = x
         scmatrix_min(row, col).x = x
     End If
     If Abs(y) > 0.000001 Then
         scmatrix_max(row, col).y = y
         scmatrix_min(row, col).y = y
     End If
     scmatrix_min(row, col).z = Format(z, "#0.000")
     scmatrix_max(row, col).z = Format(z, "#0.000")

End If

Loop Until EOF(1)
Close #1

'Print values of screw pin tooling matrixs to verify
pth = "f:\wangzhijian\pinposition_veri.dat"
Open pth For Output As #2
```

```
  For i = 1 To Colpin
     For j = 1 To Colpin
       If Abs(scmatrix_max(i, j).z) - 0.000000001 > 0 Then
            Print #2, i, j; scmatrix_max(i, j).x, scmatrix_max(i, j).y,
                scmatrix_max(i, j).z
       End If
     Next
  Next
  Close #2


 MsgBox "screw information reading finished"
 Exit Sub
End Sub
```

'Sub function to import analysis input file, each node is mapped to certain screw pin area.

```
'The max and min Z values are calcuated in each screw pin area.

Private Sub screw_Z_Click()

' Sub function varible statements

Dim point_pos(3) As Double
Dim xpos, ypos, zpos As String
Dim r_temp, c_temp As Integer
Dim x, y, z, x0, y0, z0, dia As Double
Dim screw_temp As screw

   ' Open path for analysis input file

   ph = "f:\wangzhijian\smallcover.inp"

  Open ph For Input As #1

 'find the postion of x, y, and z

 Do
    Line Input #1, str_ln
```

```
    j = 0
    point_pos(0) = 0
    point_pos(1) = 0
    point_pos(2) = 0
    For i = 1 To Len(str_ln)

        If Mid(str_ln, i, 1) = "," Then
         point_pos(j) = i
         j = j + 1
    End If
Next

  'x,y,z position string

  If point_pos(0) > 0 And point_pos(1) > 0 Then
      xpos = Trim(Mid(str_ln, point_pos(0) + 1, point_pos(1) –
                point_pos(0) - 1))
     ypos = Trim(Mid(str_ln, point_pos(1) + 1, point_pos(2) –
                point_pos(1) - 1))
     zpos = Trim(Mid(str_ln, point_pos(2) + 1, Len(str_ln) - point_pos(2)))

     'x,y,z position in double

     x = CDbl(xpos) - 0.00000001
     y = CDbl(ypos) - 0.00000001
     z = CDbl(zpos)
     x = Format(x, "#0.000")
     y = Format(y, "#0.000")
     z = Format(z, "#0.000")

     ' check if the geometry of component within the pin area

     If x > scmatrix_max(1, 1).x And x < scmatrix_max(1, Colpin - 1).x
            And y > scmatrix_max(Rowpin, 1).y And y < scmatrix_max(1,
            1).y Then


            'Identify current node position in the screw pin tooling matrix

            c_temp = surface_position(x, y, Rowpin, Colpin, Xpin,
                          Ypin).col_pos
```

```
                r_temp = surface_position(x, y, Rowpin, Colpin, Xpin,
                          Ypin).row_pos

               'Initialize max Z value in a screw pin domain

               If scmatrix_max(r_temp, c_temp).z < 0.000001 And z >
                          0.000001 Then
                      scmatrix_max(r_temp, c_temp).z = z
               End If

              'Initialize min Z value in a screw pin domain

              If scmatrix_min(r_temp, c_temp).z < 0.000001 And z > 0.000001
              Then
                      scmatrix_min(r_temp, c_temp).z = z
               End If

              'find the max z positin within a screw pin domain

               If z > scmatrix_max(r_temp, c_temp).z Then
                       scmatrix_max(r_temp, c_temp).z = z
               End If

               'find the min z positin within a screw pin domain

               If z > 0.000000001 And z < scmatrix_min(r_temp, c_temp).z
               Then
                       scmatrix_min(r_temp, c_temp).z = z
               End If

         Else
             MsgBox "out of range"
         End If
     End If
     Loop Until str_ln = "*Element, type=S4R" Or EOF(1)

Close #1

     ' Open path for output the max Z value and the min Z value of each screw
pin
```

```
    pth = "f:\wangzhijian\smallcover_max.inp"
    pth1 = "f:\wangzhijian\smallcover_min.inp"

    Open pth For Output As #2
    Open pth1 For Output As #3

    ' Output the max Z value and the min Z value of each screw pin

    For i = 1 To Rowpin
        For j = 1 To Colpin
            If Abs(scmatrix_max(i, j).x) > 0.0000001 Or Abs(scmatrix_max(i,
              j).y) > 0.000000001 Or Abs(scmatrix_max(i, j).z) > 0.00001 Then
                Print #2, scmatrix_max(i, j).x & ",", scmatrix_max(i, j).y & ",",
                            scmatrix_max(i, j).z
                Print #3, scmatrix_min(i, j).x & ",", scmatrix_min(i, j).y & ",",
                            scmatrix_min(i, j).z
            End If
        Next
   Next
   Close #2
   Close #3

  MsgBox "programme finished"



End Sub
```

2. Point Processor (2)—sub programme

```
' This is a Virtual Basic sub programme for Point Processor

' Author: Zhijian WANG

' Data: May 2008



' Variable Statements


Public Type screw
    row_pos As Integer
    col_pos As Integer
    x As Double
    y As Double
    z As Double
End Type


Public Type matrix_position
   col_pos As Integer
   row_pos As Integer
End Type


Public Dpin, Lpin, Rowpin, Colpin As Integer

Public Xpin, Ypin, Xmin, Xmax, Ymin, Ymax As Double


' Function screw_position is to identify the screw position in the matrix

' according to its x, y coordinate values

Function screw_position(ByVal x1 As Double, ByVal y1 As Double, ByVal
Rowpin As Integer, ByVal Colpin As Integer, ByVal Xpin As Double, ByVal
Ypin As Double)  As matrix_position
```

```
    screw_position.row_pos = (Rowpin + 1) / 2 - y1 / Ypin ' row position

    If (screw_position.row_pos Mod 2) <> 0 Then 'col position

        screw_position.col_pos = (x1 + Colpin / 2 * Xpin) / Xpin 'colpin
    Else
        screw_position.col_pos = (x1 + (Colpin + 1) / 2 * Xpin) / Xpin
    End If

End Function


' Function surface_position is to identify current node position in the matrix

' according to its x, y coordinate values

Function surface_position(ByVal x1 As Double, ByVal y1 As Double, ByVal
Rowpin As Integer, ByVal Colpin As Integer, ByVal Xpin As Double, ByVal
Ypin As Double) As matrix_position

  ' row position

  surface_position.row_pos = (Rowpin + 1) / 2 - Round(y1 / Ypin)

  'col position

  If (surface_position.row_pos Mod 2) <> 0 Then

       surface_position.col_pos = Round((x1 + Colpin / 2 * Xpin) / Xpin)
  Else
       surface_position.col_pos = Round((x1 + (Colpin + 1) / 2 * Xpin) / Xpin)
  End If

End Function
```

3. Fagor CNC main programme format for screw pin adjustment

```
%1111,MX,RT
N1;VACFORM MACHINE
G71 G90 G94
G0X -110.688Y   79.880
(P6=100)
G1X -110.688Y   79.880WP6 F10000
(PCALL 10, P1=    2.841, P2=   35.384)
G1X  -92.240Y   79.880WP6 F10000
(PCALL 10, P1=    2.505, P2=   51.932)
G1X  -73.792Y   79.880WP6 F10000
(PCALL 10, P1=    2.572, P2=   51.913)
G1X  -55.344Y   79.880WP6 F10000
(PCALL 10, P1=    2.757, P2=   51.737)
G1X  -36.896Y   79.880WP6 F10000
(PCALL 10, P1=    2.568, P2=   51.922)
G1X  -18.448Y   79.880WP6 F10000
(PCALL 10, P1=    2.690, P2=   51.799)
G1X     .000Y   79.880WP6 F10000
(PCALL 10, P1=    2.691, P2=   51.792)
…………………………………………

G1X  110.688Y   79.880WP6 F10000
(PCALL 10, P1=    2.801, P2=   34.546)
G1X -119.912Y   63.904WP6 F10000
(PCALL 10, P1=    2.592, P2=   21.884)
G1X -101.464Y   63.904WP6 F10000
(PCALL 10, P1=   25.168, P2=   36.832)
G1X  -83.016Y   63.904WP6 F10000
(PCALL 10, P1=   42.159, P2=   19.841)
…………………………………………

G1X   -9.224Y   63.904WP6 F10000
(PCALL 10, P1=   55.502, P2=    6.498)
G1X    9.224Y   63.904WP6 F10000
(PCALL 10, P1=   55.779, P2=    6.221)
G1X   27.672Y   63.904WP6 F10000
(PCALL 10, P1=   55.477, P2=    6.523)
G1X   46.120Y   63.904WP6 F10000
(PCALL 10, P1=   55.453, P2=    6.547)
```

```
G1X   64.568Y   63.904WP6 F10000
(PCALL 10, P1=   55.748, P2=    6.252)
G1X   83.016Y   63.904WP6 F10000
(PCALL 10, P1=   42.066, P2=   19.934)
G1X  101.464Y   63.904WP6 F10000
(PCALL 10, P1=   25.168, P2=   36.832)
…………………………………………….

G1X  110.688Y   47.928WP6 F10000
(PCALL 10, P1=    2.555, P2=   54.649)
G1X -119.912Y   31.952WP6 F10000
(PCALL 10, P1=    2.708, P2=   21.638)
G1X -101.464Y   31.952WP6 F10000
(PCALL 10, P1=   25.227, P2=   36.773)
……………………………………………

G1X  -36.896Y   15.976WP6 F10000
(PCALL 10, P1=   51.500, P2=   10.500)
G1X  -18.448Y   15.976WP6 F10000
(PCALL 10, P1=   51.500, P2=   10.500)
………………………………………………

G1X  119.912Y     .000WP6 F10000
(PCALL 10, P1=    2.586, P2=   21.890)
G1X   46.120Y  -63.904WP6 F10000
(PCALL 10, P1=   55.725, P2=    6.275)
G1X   64.568Y  -63.904WP6 F10000
(PCALL 10, P1=   55.618, P2=    6.382)
G1X   83.016Y  -63.904WP6 F10000
(PCALL 10, P1=   42.207, P2=   19.793)
……………………………………………..

G1X   73.792Y  -79.880WP6 F10000
(PCALL 10, P1=    2.499, P2=   52.001)
G1X   92.240Y  -79.880WP6 F10000
(PCALL 10, P1=    2.150, P2=   52.314)
G1X  110.688Y  -79.880WP6 F10000
(PCALL 10, P1=    2.878, P2=   35.052)
G0W100
M30
```

4. Fagor CNC sub programme for screw pin adjustment

```
%sub10,MX,RT,

N493 (SUB 10)
N494 ; SCREW UP
N495  G92 C0
N496  (P3=P1+10,P4=P1-1.5,P5=((P2/2.5)*360))
N497  G1WP3F3000
N498 G1WP4F100
N499  G91G1WP2CP5F5000
N500  G90G1W100F3000
N501  (RET)
%
```

5. Pin tooling adjustment simulation

$$ Pin tooling adjustment from old shape to a new shape

```
ENTITY/CYL1,PIN1(50,50),PIN2(50,50)

ENTITY/AJUST1(50,50),AJUST2(50,50)

ENTITY/BLOCK1

NUMBER/MAT1(12),MAT2(12)

NUMBER/Z1max(50,50),Z1min(50,50)

NUMBER/Z2max(50,50),Z2min(50,50)

NUMBER/Z1t(50,50),Z2t(50,50)

NUMBER/xt(50,50),yt(50,50),Zt(50,50)

NUMBER/Zo(50,50),Zn(50,50),Zd(50,50)


FDEL/'c:\phd\pingrip\test\pinposition.dat',IFERR,l5:

l5:

CREATE/TXT,1,'c:\phd\pingrip\test\pinposition.dat'

WRITE/1,'      Screw Pin Position      '

WRITE/1,'-------------------------------------------'


l10:

    choose/'Choose diameter','Dia 20','Dia 30','Dia 40','Dia 50',resp

    jump/l10:,trm:,,,l20:,l30:,l40:,l50:,resp
```

```
l20:
    Dpin=20
    Xpin=18.448
    Ypin=15.976
    WRITE/1,'Dpin=20'
    WRITE/1,'Xpin=18.448'
    WRITE/1,'Ypin=15.976'
    jump/l110:
l30:
    Dpin=30
    Xpin=27.5
    Ypin=23.5
    WRITE/1,'Dpin=30'
    WRITE/1,'Xpin=27.5'
    WRITE/1,'Ypin=23.5'
    jump/l110:

l40:
    Dpin=40
    Xpin=35.5
    Ypin=32.5
```

```
    WRITE/1,'Dpin=40'

    WRITE/1,'Xpin=35.5'

    WRITE/1,'Ypin=32.5'

    jump/l110:


l50:

    Dpin=50

    Xpin=43.5

    Ypin=41.0

    WRITE/1,'Dpin=50'

    WRITE/1,'Xpin=43.5'

    WRITE/1,'Ypin=41.0'

    jump/l110:


l110:

    choose/'Choose length','Length 200','Length 250',$
             'Length 300','Length 400',resp

    jump/l110:,trm:,,,l120:,l130:,l140:,l150:,resp


l120:

    Lpin=200

    WRITE/1,'Lpin=200'

    jump/l210:
```

```
l130:

    Lpin=250

    WRITE/1,'Lpin=250'

    jump/l210:


l140:

    Lpin=300

    WRITE/1,'Lpin=300'

    jump/l210:


l150:

    Lpin=400

    WRITE/1,'Lpin=400'

    jump/l210:


l210:

    choose/'Choose Mold Size','Matrx 20x19','Matrx 30x29',$
            'Matrx 40x39','Matrx 50x49',resp

    jump/l210:,trm:,,,l220:,l230:,l240:,l250:,resp


l220:

   ROWpin=19

   COLpin=20
```

```
    BLOCK1=SOLBLK/ORIGIN,-300,-250,-71,SIZE,600,500,70
    &COLOR(BLOCK1)=&ORANGE
    WRITE/1,'ROWpin=19'
    WRITE/1,'COLpin=20'
    jump/l300:
l230:
    ROWpin=29
    COLpin=30
    BLOCK1=SOLBLK/ORIGIN,-300,-250,-71,SIZE,600,500,70
    &COLOR(BLOCK1)=&ORANGE
    WRITE/1,'ROWpin=29'
    WRITE/1,'COLpin=30'
    jump/l300:
l240:
    ROWpin=39
    COLpin=40
    BLOCK1=SOLBLK/ORIGIN,-300,-250,-71,SIZE,600,500,70
    &COLOR(BLOCK1)=&ORANGE
    WRITE/1,'ROWpin=39'
    WRITE/1,'COLpin=40'
    jump/l300:
```

```
l250:
   ROWpin=49
   COLpin=50
   BLOCK1=SOLBLK/ORIGIN,-300,-250,-71,SIZE,600,500,70
   &COLOR(BLOCK1)=&ORANGE
   WRITE/1,'ROWpin=49'
   WRITE/1,'COLpin=50'
   jump/l300:
 l300:
   WRITE/1,'-----------------------------------------'
   WRITE/1,'     X                Y              Z  '
   $$ Old tooling position
   FETCH/TXT,6,'c:\phd\pingrip\test\small_cover_min.inp'

   RESET/6
   do/loop1:,i,1,ROWpin
     IFTHEN/MODF(i,2)<>0
       do/loop2:,j,1,COLpin-1
       READ/6,Xorig,Yorig,Zorig
       Zo(i,j)=Zorig
       x1=-(COLpin/2-j)*Xpin
```

```
  y1=((ROWpin+1)/2-i)*Ypin

  z1=(-1)*Lpin+Zo(i,j)

  WRITE/1,USING,'#@@@@.@@@',x1,',',y1,',',z1

  PIN1(i,j)=SOLCYL/ORIGIN,x1,y1,z1,HEIGHT,Lpin,DIAMTR,Dpin

  $$ &COLOR(PIN1(i,j))=&DKRED

  loop2:

 ELSE

  do/loop3:,j,1,COLpin

  READ/6,Xorig,Yorig,Zorig

  Zo(i,j)=Zorig

  x1=-((COLpin+1)/2-j)*Xpin

  y1=((ROWpin+1)/2-i)*Ypin

  z1=(-1)*Lpin+Zo(i,j)

  WRITE/1,USING,'#@@@@.@@@',x1,',',y1,',',z1

  PIN1(i,j)=SOLCYL/ORIGIN,x1,y1,z1,HEIGHT,Lpin,DIAMTR,Dpin

  $$ &COLOR(PIN1(i,j))=&GRAY

  loop3:


 ENDIF


loop1:
```

```
FILE/TXT,1,'c:\phd\pingrip\test\pinposition.dat'

FTERM/TXT,1

$$ New POSITION

$$ FDEL/'c:\phd\pingrip\test\readposition.dat'

$$ CREATE/TXT,3,'c:\phd\pingrip\test\readposition.dat'

FETCH/TXT,2,'c:\phd\pingrip\small cover\smallcover_max.inp'

$$ FETCH/TXT,2,'c:\phd\pingrip\test\pinposition2.dat'

$$ FETCH/TXT,2,'c:\phd\pingrip\test\small_cover_min.inp'

$$ FETCH/TXT,2,'c:\phd\pingrip\test\small_cover_max.inp'

RESET/2


do/loop10:,i,1,ROWpin

      IFTHEN/MODF(i,2)<>0

        do/loop11:,j,1,COLpin-1

          READ/2,Xpos,Ypos,Zpos

          Zn(i,j)=Zpos

          Zd(i,j)=Zn(i,j)-Zo(i,j)

          $$ WRITE/3,USING,'#@@@@.@@@',Xpos,Ypos,Zpos

          xt(i,j)=xpos

          yt(i,j)=ypos

          Zt(i,j)=Zd(i,j)
```

```
    loop11:
   ELSE
    do/loop12:,j,1,COLpin
      READ/2,Xpos,Ypos,Zpos
      Zn(i,j)=Zpos
      Zd(i,j)=Zn(i,j)-Zo(i,j)
     $$ WRITE/3,USING,'#@@@@.@@@',Xpos,Ypos,Zpos
      xt(i,j)=xpos
      yt(i,j)=ypos
      Zt(i,j)=Zd(i,j)
    loop12:

   ENDIF
  loop10:
 $$ FILE/TXT,3,'c:\phd\pingrip\test\readposition.dat'

l700:
   choose/'Shape Adjustment Method','Near Shape','Subtractive Shape',resp
   jump/l700:,trm:,,,l710:,l720:,resp
l710:
   Z1t(50,50)=Z1min(50,50)
   Z2t(50,50)=Z2min(50,50)
```

```
    jump/l800:
l720:
    Z1t(50,50)=Z1max(50,50)
    Z2t(50,50)=Z2max(50,50)
    jump/l800:
l800:
   do/loop20:,i,1,ROWpin
     IFTHEN/MODF(i,2)<>0
       do/loop21:,j,1,COLpin-1
         IFTHEN/Zt(i,j)<>0
           MAT1=MATRIX/TRANSL,0,0,Zt(i,j)+2
           AJUST1(i,j)=TRANSF/MAT1,PIN1(i,j)
           &COLOR(AJUST1(i,j))=&DKRED
           DELETE/PIN1(i,j)
         ENDIF
       loop21:
     ELSE
       do/loop22:,j,1,COLpin
         IFTHEN/Zt(i,j)<>0
           MAT1=MATRIX/TRANSL,0,0,Zt(i,j)+2
           AJUST1(i,j)=TRANSF/MAT1,PIN1(i,j)
```

```
            &COLOR(AJUST1(i,j))=&DKRED

            DELETE/PIN1(i,j)

          ENDIF

        loop22:

      ENDIF

   loop20:

$$ Start to write Fagor CNC Programme

$$ FDEL/'c:\phd\pingrip\test\fagorcnc.pim',IFERR,l900:

FDEL/'c:\phd\pingrip\test\fagorcncmax.pim',IFERR,l900:

l900:

$$ CREATE/TXT,4,'c:\phd\pingrip\test\fagorcnc.pim'

CREATE/TXT,4,'c:\phd\pingrip\test\fagorcncmax.pim'

WRITE/4,'%1111,MX,RT'

WRITE/4,'N1;VACFORM MACHINE'

WRITE/4,'G71 G90 G94'

$$ WRITE/4,'G51 E.01'
$$ Tooling to start point to be adjusted

 do/loop60:,i,1,ROWpin

      IFTHEN/MODF(i,2)<>0

        do/loop61:,j,1,COLpin-1
          IFTHEN/Zt(i,j)<>0

           WRITE/4,USING,'G0X#@@@@.@@@Y#@@@@.@@@',$
```

```
            xt(i,j),yt(i,j)

        JUMP/loop777:

        ENDIF

      loop61:

     ELSE

      do/loop62:,j,1,COLpin

        IFTHEN/Zt(i,j)<>0

         WRITE/4,USING,'G0X#@@@@.@@@Y#@@@@.@@@',$
            xt(i,j),yt(i,j)

        JUMP/loop777:

        ENDIF

      loop62:

     ENDIF

loop60:

$$Start to list all screws to be adjusted

loop777:

$$ WRITE/4,'G0W20'

WRITE/4,'(P6=100)'

   do/loop30:,i,1,ROWpin

     IFTHEN/MODF(i,2)<>0
      do/loop31:,j,1,COLpin-1

        IFTHEN/Zt(i,j)<>0
```

```
        WRITE/4,USING,'G1X#@@@@.@@@Y#@@@@.@@@WP6 $
                    F10000', xt(i,j),yt(i,j)

        WRITE/4,USING,'(PCALL 11, P1=#@@@@.@@@, $
                    P2=#@@@@.@@@)',Zo(i,j),zt(i,j)

      ENDIF

    loop31:

   ELSE

    do/loop32:,j,1,COLpin

      IFTHEN/Zt(i,j)<>0

        WRITE/4,USING,'G1X#@@@@.@@@Y#@@@@.@@@WP6$
                    F10000',xt(i,j),yt(i,j)

        WRITE/4,USING,'(PCALL 11, P1=#@@@@.@@@,$
                    P2=#@@@@.@@@)',Zo(i,j),zt(i,j)

      ENDIF

    loop32:

   ENDIF

  loop30:

WRITE/4,'G0W100'

WRITE/4,'M30'

FILE/TXT,4,'c:\phd\pingrip\test\fagorcncmax.pim'

FTERM/TXT,4

trm:

  HALT
```

Appendix C

1. Repeatability tests of screw pin adjustment

1) Test results for 50mm adjustment

	Serial 1	Serial 2	Serial 3
Initial position	50.05	50.03	50.09
1	50.12	50.08	50.20
2	50.06	50.12	50.29
3	50.11	50.21	50.12
4	50.15	50.04	50.19
5	50.17	49.87	50.29
Repeatability error calculation			
1	0.07	0.05	0.11
2	0.01	0.09	0.10
3	0.06	0.18	0.03
4	0.10	0.01	0.26
5	0.12	-0.16	0.20
Average	0.07	0.03	0.11
Standard Deviation	0.04	0.13	0.06

2) Test results for 100mm adjustment

	Serial 1	Serial 2	Serial 3
Initial position	100.07	100.33	100.15
1	100.10	100.20	100.15
2	100.19	100.27	100.24
3	99.97	100.36	100.27
4	100.23	100.45	100.35
5	100.15	100.25	100.09
Repeatability error calculation			
1	0.03	-0.13	0
2	0.12	-0.06	0.09
3	-0.10	0.03	0.12
4	0.16	0.12	0.20
5	0.08	-0.08	-0.06
Average	0.04	-0.02	0.07
Standard Deviation	0.10	0.10	0.10

3) Test results for 150mm adjustment

	Serial 1	**Serial 2**	**Serial 3**
Initial position	150.12	150.35	150.20
1	150.25	150.45	150.23
2	150.18	150.37	149.98
3	150.30	150.29	150.32
4	150.17	150.42	150.26
5	150.20	150.39	150.28
Repeatability error calculation			
1	0.13	0.10	0.03
2	0.06	0.02	-0.22
3	0.18	-0.06	0.12
4	0.05	0.07	0.06
5	0.08	0.04	0.08
Average	0.10	0.03	0.01
Standard Deviation	0.05	0.06	0.13

4) Test results for 200mm adjustment

	Serial 1	**Serial 2**	**Serial 3**
Initial position	200.07	200.28	200.32
1	200.15	200.40	200.22
2	200.19	200.37	200.44
3	200.09	200.43	200.48
4	200.37	200.47	200.36
5	200.12	200.33	200.45
Repeatability error calculation			
1	0.08	0.12	-0.10
2	0.12	0.09	0.12
3	0.02	0.15	0.16
4	0.30	0.19	0.04
5	0.05	0.05	0.13
Average	0.11	0.12	0.07
Standard Deviation	0.11	0.05	0.10

2. Accuracy tests of screw pin adjustment

1) 50mm adjustment distance

	Serial 1	**Serial 2**	**Serial 3**
1	50.07	50.13	50.19
2	50.22	50.16	50.19
3	50.26	50.07	50.10
4	50.05	50.23	49.92
5	49.89	50.25	50.05
Accuracy error calculation			
1	0.07	0.13	0.19
2	0.22	0.16	0.19
3	0.26	0.07	0.10
4	0.05	0.23	-0.08
5	-0.11	0.25	0.05
Average	0.10	0.17	0.09
Standard Deviation	0.15	0.07	0.11

2) 100mm adjustment distance

	Serial 1	**Serial 2**	**Serial 3**
1	100.19	100.32	99.82
2	100.14	100.28	100.12
3	100.09	100.17	10026
4	100.36	100.22	100.33
5	100.25	100.13	100.21
Accuracy error calculation			
1	0.19	0.32	-0.18
2	0.14	0.28	0.12
3	0.09	0.17	0.26
4	0.36	0.22	0.33
5	0.25	0.13	0.21
Average	0.21	0.22	0.15
Standard Deviation	0.10	0.08	0.20

3) 150mm adjustment distance

	Serial 1	**Serial 2**	**Serial 3**
1	150.16	150.29	150.34
2	150.34	150.38	150.26
3	150.42	150.15	150.20
4	150.22	149.84	150.38
5	149.76	150.17	149.92
Accuracy error calculation			
1	0.16	0.29	0.34
2	0.34	0.38	0.26
3	0.42	0.15	0.20
4	0.22	-0.16	0.38
5	-0.24	0.17	-0.08
Average	0.18	0.17	0.22
Standard Deviation	0.26	0.20	0.18

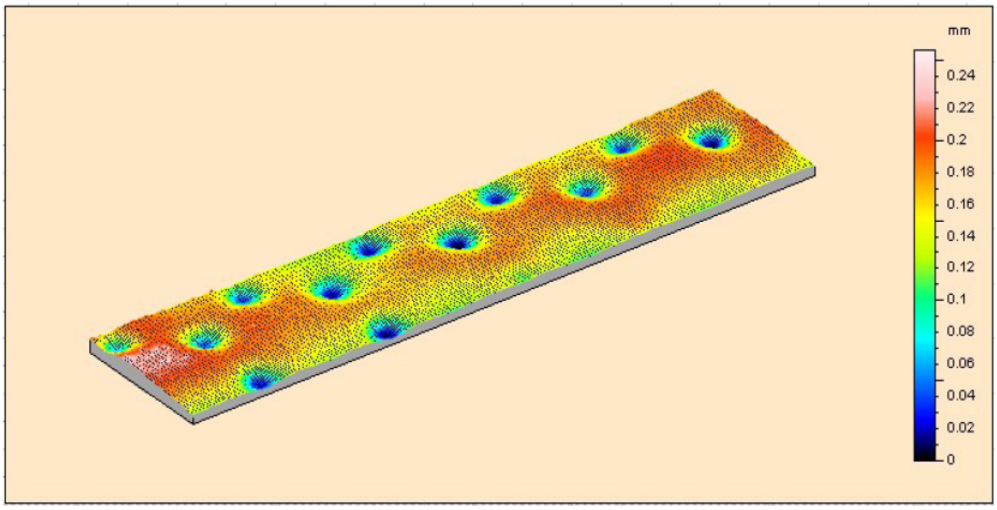
4) 200mm adjustment distance

	Serial 1	**Serial 2**	**Serial 3**
1	200.25	200.34	200.30
2	200.46	200.28	200.44
3	200.33	199.82	200.37
4	199.68	200.42	200.19
5	200.42	200.37	200.26
Accuracy error calculation			
1	0.25	0.34	0.30
2	0.46	0.28	0.44
3	0.33	-0.18	0.37
4	-0.32	0.42	0.19
5	0.42	0.37	0.26
Average	0.23	0.25	0.31
Standard Deviation	0.32	0.24	0.10

3. Measurement of formed plastic components

1) Measurement of HIPS vacuum formed components

(a) Sample of measured top surface section of formed HIPS component

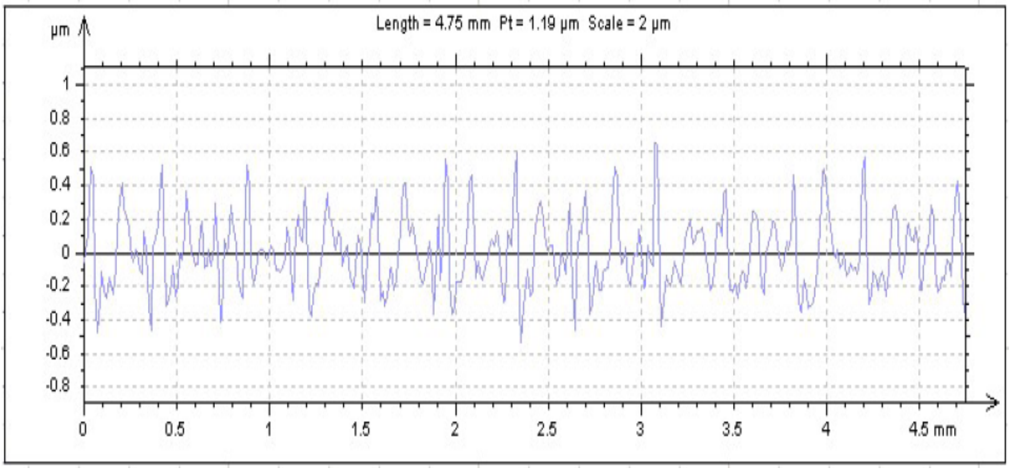


(b) Surface measurement summary of HIPS formed components

	Vacuum Pressure	*Sa*	*Sv*
1mm	5 Hg	0.02	0.27
1mm	10 Hg	0.03	0.52
1mm	12 Hg	0.04	0.53
1mm	15 Hg	0.06	0.62
1mm	20 Hg	0.08	0.67
3mm	10 Hg	0.02	0.11
3mm	12 Hg	0.03	0.16
3mm	15 Hg	0.04	0.38
3mm	20 Hg	0.06	0.45
5mm	20 Hg	0.05	0.14
6mm	20 Hg	0.04	0.1

2) Roughness measurement

(a) 5mm vacuum formed components surface measurement

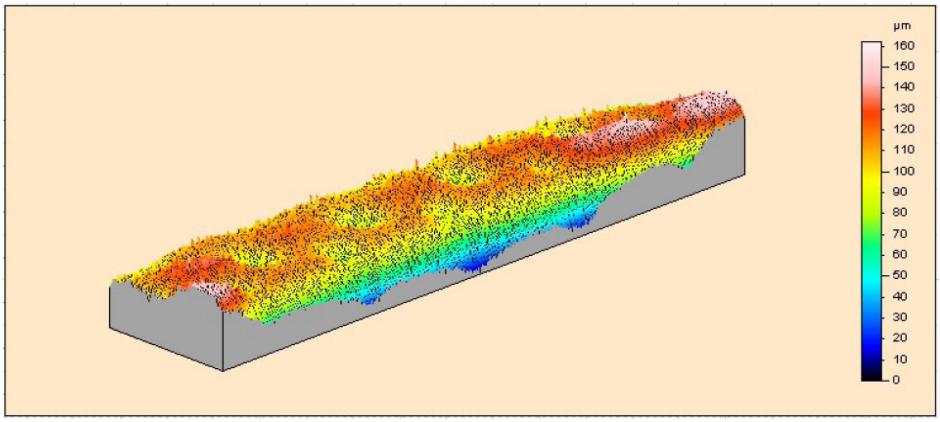


(b) Roughness measurements summary

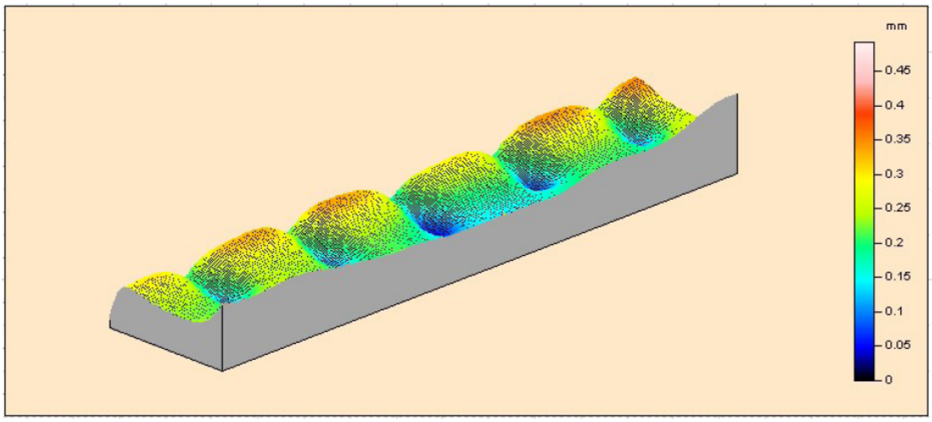
	Ra (um)	*Rt* (um)
ABS	0.547	2.87
HIPS	0.366	2.51
PC	0.609	3.46
PMMA	0.92	4.32

3) Surface measurement of components formed by 5mm thickness thermoplastic sheets

(a) Sample of measured top surface section of formed component



(b) Sample of side surface section of measured component

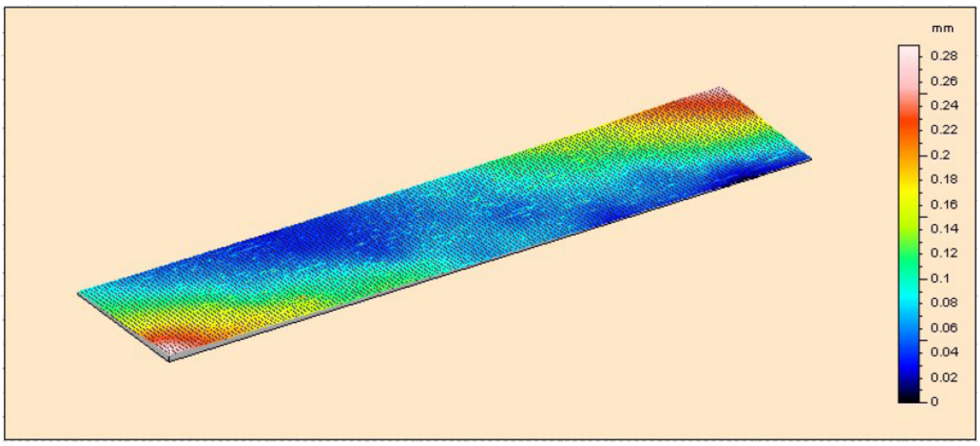


(c) Surface measurements summary

		Sa	*Sv*
ABS	TOP	0.06	0.33
ABS	SIDE	0.1	0.46
HIPS	TOP	0.03	0.14
HIPS	SIDE	0.07	0.25
PC	TOP	0.02	0.06
PC	SIDE	0.05	0.23
PMMA	TOP	0.03	0.12
PMMA	SIDE	0.06	0.38

4) Sacrificial surface measurement

(a) Sample of measured sacrificial surface section of formed component



(b) Sacrificial surface measurement summary

	Sa (mm)	*Sv* (mm)
ABS	0.01	0.26
HIPS	0.01	0.04
PC	0.01	0.23
PMMA	0.01	0.03

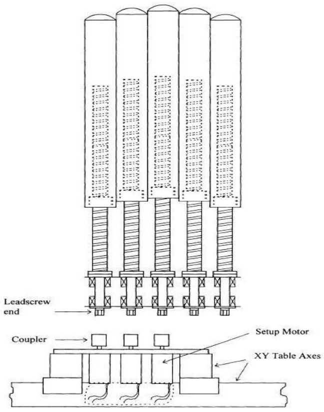
(c) Sacrificial material introduction

Thermoplastic Material	**Rec. Forming Temperature**	**Molecular structure**	**Max. Continuous service temperature**	**Price 600x600x5 (mm)**
Acrylonitrile Butadiene Styrene (ABS)	150 -180 °C	amorphous	80 – 95 Rigid, good dimensional stability	£11.5
Polystyrene (HIPS)	150 -175 °C	amorphous	60 - 80	£10.25
Polycarbonate (PC)	170 - 205 °C	amorphous	Hard, rigid 125	£16.54
Acrylic (PMMA)	142-160ºC	amorphous	80	£13.27

Appendix D

1. Cost summary of sequential set-up reconfigurable pin tooling design

(a) Cost summary of Sequential Set-up design by Walczyk *et al.* (2000)



Cost Summary of SSU Design

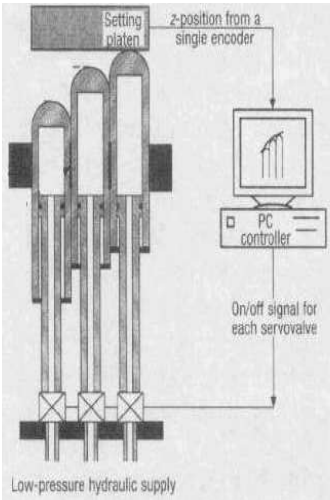
Sequential Set-up Reconfigurable Die	Cost
Pins and leadscrews	$259,000
Die frame	$57,650
Control boards	$1000
Encoded pin-setting motors	$2000
Module housing	$34,700
Sequential set-up mechanism	$13,200
Components	$75,000
Logic power supply	$24,000
Motor power supply	$15,000
Total	**$481,550**

(b) Cost reclassification

Parameters	Sequential set-up reconfigurable pin tooling	Cost
C_{pins}	**Pins**	**$259,000**
	Steel pins and leadscrews (Φ28.6x95) SSU tooling pin matrix (42x64=2688)	$96.35 $259,000
C_{frame}	**Pin clamping frame**	**$57,650**
	Die frame	$57,650
$C_{control}$	**Control system**	**$14,200**
	Control boards Sequential set-up mechanism	$1,000 $13,200
$C_{hardware}$	**Pin setting hardware**	**$77,000**
	Encoded pin-setting motors Components	$2,000 $75,000
C_{others}	**Others**	**$73,700**
	Module housing Logic power supply Motor power supply	$34,700 $24,000 $15,000
C_t	**Total**	**$481,550**

2. Cost summary of hydraulically actuated (HA) pin tooling design

(a) Cost summary of hydraulically actuated design by Walczyk *et al.* (2000)



Cost Summary of HA Design

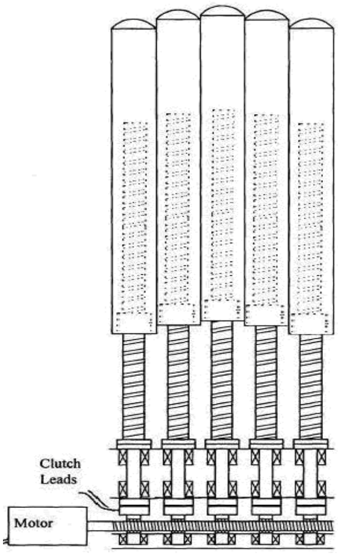
Hydraulically Actuated Reconfigurable Die	Cost
Pins and inside tube parts	$107,000
Motor support and parts for die	$30,000
Motor and driver	$10,000
Linear guide and gear assembly	$4000
Motion controller and 200 I/O cards	$21,000
Electronic components and drivers	$58,333
Hydraulic fluid accessories and valves	$169,450
Hydraulic pump and module reservoir	$20,000
Total	**$419,783**

(b) Cost reclassification

Parameters	Hydraulically actuated pin tooling	Cost
C_{pins}	**Pins**	**$107,000**
	Steel Pins and inside tube parts (Φ25.4x330)	$30.96
	HA tooling pin matrix (48x72=3456)	$107,000
C_{frame}	**Pin clamping frame**	**$30,000**
	Motors support and parts for tooling	
$C_{control}$	**Control system**	**$21,000**
	Motion controller and 200 I/O cards	$21,000
$C_{hardware}$	**Pin setting hardware**	**$247,783**
	Electronic components and drivers	$58,333
	Hydraulic fluid accessories and valves	$169,450
	Hydraulic pump and module reservoir	$20,000
C_{others}	**Others**	**$14,000**
	Linear guide and gear assembly	$4,000
	Motor and driver	$10,000
C_t	**Total**	**$419,783**

3. Cost summary of shaft-driven leadscrew pin tooling design

(a) Cost summary of shaft-driven leadscrew design by Walczyk *et al.* (2000)



Cost Summary of SDL Design

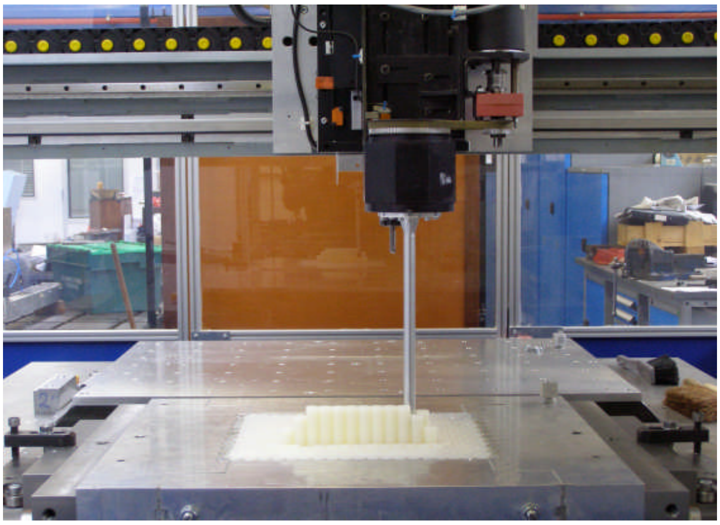
Shaft-driven Leadscrew Reconfigurable Design	Cost
Pins and leadscrews	$259,000
Pin container	$57,650
Clutch drive train	$286,814
Module housing	$34,700
Clutches	$50,000
Motor drive train	$139,200
Drive motors	$8000
Control system	$40,000
Total	**$875,864**

(b) Cost reclassification

Parameters	Shaft-driven leadscrew pin tooling	Cost
C_{pins}	**Pins**	**$259,000**
	Steel pins and leadscrew (Φ28.6x95)	$96.35
	SSU tooling pin matrix (42x64=2688)	$259,000
C_{frame}	**Pin clamping frame**	**$57,650**
	Pin container	$57,650
$C_{control}$	**Control system**	**$40,000**
	Control system	$40,000
$C_{hardware}$	**Pin setting hardware**	**$484,014**
	Clutch drive train	$286,814
	Clutches	$50,000
	Motor drive train	$139,200
	Drive motors	$8,000
C_{others}	**Others**	**$34,700**
	Module housing	$34,700
C_t	**Total**	**$875,864**

4. Cost summary of screw-pin tooling system design

(a) Constructed screw-pin tooling system

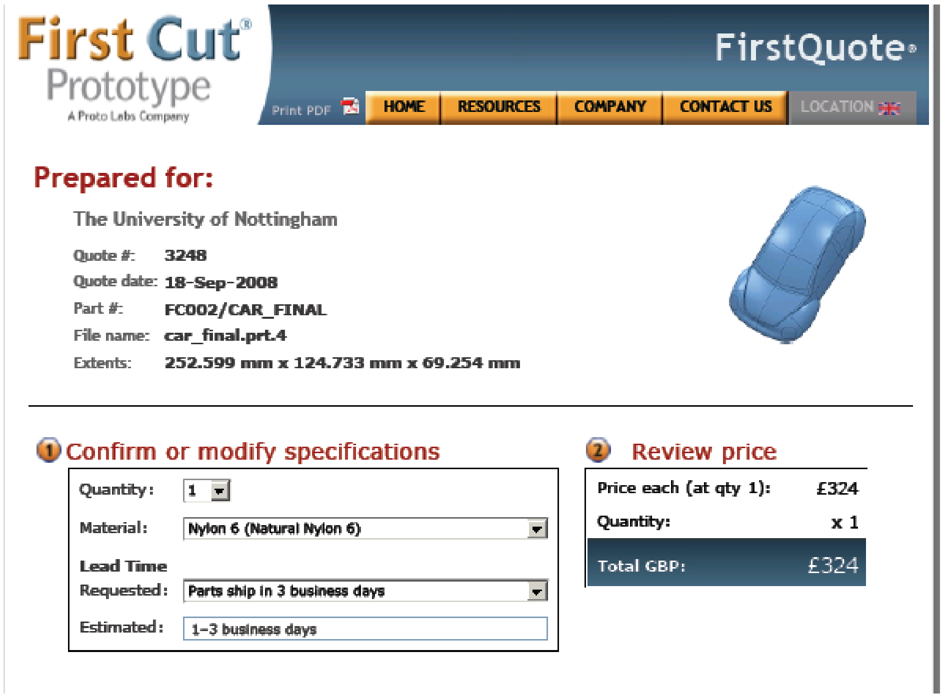


(b) Cost classification

Parameters	Screw pin tooling	Cost
C_{pins}	**Pins**	**$14,333**
	Nylon screw pins (M20x300)	$2.25 each
	Screw pin tooling matrix (65x98=6370)	$14,333
C_{frame}	**Pin clamping frame**	**$1,725**
	Four piece aluminium blocks	$1,725
$C_{control}$	**CNC control system**	**$43,202**
	Fagor control system	$8,475
	Control panel	$3,000
	CNC retrofit	$31,727
$C_{hardware}$	**Pin setting hardware**	**$94,200**
	Encoded pin-setting motors	$1,500
	Milling drive motors	$1,200
	Components of dual tooling heads	$1,500
	Gantry machine frame	$90,000
C_{others}	**Others**	**$4,500**
	Other components and accessories	$4,500
C_t	**Total**	**$157,960**

5. Mould manufacturing cost quotation from First Cut Ltd.

a) Beetle car quotation



b) Rectangular cover