Wang, Y. and Wang, Z.-J. and Gindy, Nabil (2011) A method for representation of component geometry using discrete pin for reconfigurable moulds. Advances in Engineering Software, 42 (7). pp. 409-418. ISSN 1873-5339

A method for representation of component geometry using discrete pin for reconfigurable moulds

Y. Wang [a,*], Z.-J. Wang [b], N. Gindy [a]

[a] University of Nottingham, Ningbo Campus, China
[b] Department of Materials, Mechanical and Manufacturing Engineering, University of Nottingham, Nottingham NG7 2RD, UK

Keywords:
Representation of geometry
Discrete pin
Reconfigurable moulds
Part discretization
Pin matrix construction and adjustment
Pin matrix verification

ABSTRACT

Moulding plays a paramount role in our daily life. Traditional moulding is often dedicated and expensive. As the current market trend moves from mass production towards small batch and large variation production, the demand for a mould that can reconfigure itself for different components is greater than ever. The reconfiguration of mould is often realized through discrete pins. Previous research in that field had focused on the hardware of pin actuation in order to move pins up or down to represent different components and lock the pins at certain positions. Little research has been conducted into support software development that enables rapid reconfiguration of discrete pins to represent component geometry.

This paper addresses a new method of software development for the reconfigurable mould utilising discrete pins. The overall aim of the method is to provide an interface for generic discrete pin tooling in order to enable quick reconfiguration of the mould to represent component geometry. The software is composed of three parts: part discretization, pin matrix construction and adjustment and pin matrix verification.

1. Introduction

Moulding plays a paramount role in our daily life. Moulding, including Injection moulding, vacuum forming, casting, stamping and forging, is cost effective and is frequently used in mass production. Traditional moulding is often dedicated and expensive. Dedicated tooling means that a mould is made for a single product design and can only be used for production of that particular design. Any design changes lead to the tooling becoming unsuitable for its specific use, and a new one has to be made. Commercial justification for moulds is traditionally based on the amount of production volume required. The current manufacturing trend is moving away from mass production towards small batch and large variation production. Therefore traditional moulds are increasingly becoming both less efficient and less economical for the quantity required. This is simply because of the change-over time for moulds and the cost of designing and building mould used only for a short run. Therefore the need for a technology that is capable of rapid mould redesign and changeover in the same process thus enabling rapid customisation of a component in day to day operations is greater than ever in the manufacturing industry.

The solution is to replace the current dedicated moulds with reconfigurable ones which utilise discrete pins. These pins can be moved up or down in the direction of the central axis to represent the necessary component geometry. In this way, the same batch of pins can be reconfigured and reused many times. Reconfigurable moulding is well suited for components that are not of traditional parametric shapes, as with those commonly seen in industries such as marine, automotive, aerospace, energy and medical. An example of a reconfigurable mould that uses discrete pins for sheet metal forming processing is shown in Fig. 1.

The idea of using discrete pins to produce universal moulds and fixtures is already well over a century old. As identified by Munro [2], the first known US patent relating to pin-type reconfigurable tools was granted to Cochrane [3] in 1863. Since then, many patents regarding discrete pin mould have been granted. Applications have included that of sheet metal forming by using large thin-walled components which have a free-form surface, e.g. the front panel of the high speed train [4], composite forming [5], prosthesis for cranioplasty [6] and rapid prototyping [7].

The key to a configurable mould is the capability for its matrix of pins to move upward or downward to positions determined by the component geometry and to then lock the matrix of pins into position. Therefore, pin actuation is critical for the reconfigurable mould that uses discrete pins. As shown in Fig. 2, according to pin density, there are two types of pin arrangement: close-packed [3] where the pins are put next to each other, support each other, and uniform spaced [3] where pins are evenly distributed, but not in direct contact with each other. Limited by the space available for

---

* Corresponding author.
E-mail address: yan.wang@nottingham.ac.uk (Y. Wang).

Nomenclature

CN	the name of the component to be moulded
c	the number of columns of the discrete-pin matrix
CS	the coordination system of the discrete-pin matrix
$\mathbf{D}_\mathrm{p}$	the nominal diameter of the discrete pins
DPM	the discrete-pin matrix
$\mathbf{L}_\mathrm{p}$	the length of the discrete pins
M	types of pin distribution, $\mathbf{M} = 0$ for even distribution, $\mathbf{M} = 1$ for misaligned distribution
N	solutions to avoid dimples, $\mathbf{N} = 1$ for interpolator, $\mathbf{N} = 2$ for filler and $\mathbf{N} = 3$ for machining
$\mathbf{P}_{ij}$	the pin in the ith row and jth column of the discrete-pin matrix, $i \in [1, \mathbf{r}]$, $j \in [1, \mathbf{c}]$
$\mathbf{P}_{ij} \cdot a$	the amount of pin movement for pin $\mathbf{P}_{ij}$
$\mathbf{P}_{ij} \cdot mx$	the maximum Z value of the discrete point on the component in the area in response to $\mathbf{P}_{ij}$
$\mathbf{P}_{ij} \cdot mn$	the minimum Z value of the discrete point on the component in the area in response to $\mathbf{P}_{ij}$
$\mathbf{P}_{ij} \cdot rl$	the remaining length of pin $\mathbf{P}_{ij}$ after pin adjustment for machining operation on the pins
$\mathbf{P}_{ij} \cdot x$	the X coordinate value of pin $\mathbf{P}_{ij}$
$\mathbf{P}_{ij} \cdot y$	the Y coordinate value of pin $\mathbf{P}_{ij}$
$\mathbf{P}_{ij} \cdot z0$	the initial Z coordinate value of pin $\mathbf{P}_{ij}$
$\mathbf{P}_{ij} \cdot z1$	the final Z coordinate value of pin $\mathbf{P}_{ij}$ after adjustment
PN	the name of the discrete-pin matrix
$\mathbf{P}_{\mathrm{t}(x,y,z)}$	a node (point) on the component
r	the row number of the discrete-in matrix
t	thickness of interpolator
$\mathbf{X}_\mathrm{p}$	the distance between two pins next to each other in X direction 1
$\mathbf{Y}_\mathrm{p}$	the distance between two pins near to each other in Y direction

actuation devices, the actuation of uniform spaced pins is relatively easy compared to that of close-packed ones. For this reason, most early patents [8–11] of reconfigurable moulds were uniform spaced. However, there are many problems associated with uniform spaced screw-pins: lack of rigidity and there suitability for components with only simple geometry because of the space between the pins as it led to insufficiently supported pins and equally insufficiently represented component geometry from the pins.

Close-packed pin arrangement is better than uniform spaced pin moulds as the pins are engaged with each other, supporting each other to resist loadings from processes and better presentation of component geometry. However, because the pins are engaged with each other, leaving limited space for the actuation system, the whole mould system is far more complicated and expensive. Patents for close-packed screw-pins are reviewed below: Patent [12,13] described a device containing a matrix of close packed pins for reconfigurable sheet forming. A drive motor and drive shaft were used for each row/column of the pins. Pin motion was controlled by an inline clutch/brake combination through a computer controlled system based on feedback from an encoder attached to the lead screw on each pin. This device is very complicated, as it needs a large number of motors, shafts, worm gears and clutches, etc., which puts it out of reach of wider applications in industry.

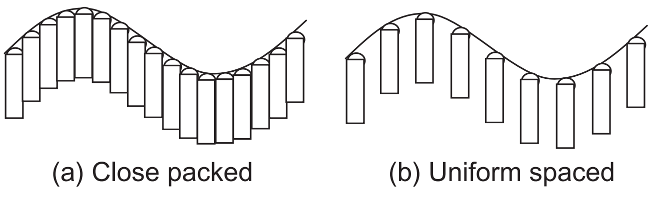
Patents [14,15] were related to reconfigurable moulds and fixtures using interlocking screw-pins. Each of the screw-pins was actuated by computer controlled motors in a serial order. The pins could be adjusted to a pre-determined position by step motors or through use of a servo motor with encoder allowing the pins to stay in position without extra a locking mechanism as it is mechanically locked and supported by the surrounding pins. The actuation of the pins is relatively easy and the mould is rigid.

The Reconfigurable Pin Tooling™ technology was developed by Surface Generation plc [16] using patented pin technology [17–19]. 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 being adjusted can be separated automatically to allow individual pins, which are mounted on screws, to be adjusted vertically by rotating them around the central axis. After adjustment, all the square pins are oriented 45° to allow efficient packing with adjacent rows. Finally, the rough upper surface composed of adjusted pin ends is CNC machined to produce the final tool shape without the need for excessive material waste. In this device, pin tooling is integrated with NC machining, which is considered a breakthrough in comparison with other prior methods.

Academically, the research group led by Prof. D. Hardt at Massachusetts Institute of Technology (MIT) [20–24] was the original pioneer in the field of reconfigurable pin tooling during the 1980s and 1990s and accordingly conducted systematic analyses into the impact of discrete pins on moulded components and optimization of pin mould design.

Given the importance of the pin actuation method in the field of reconfigurable moulds using discrete pins, the focus of prior research was overwhelmingly centred on hardware development, concentrating on new concepts of pin actuation.

Fig. 1. Reconfigurable mould for sheet metal processing [1].



(a) Close packed

(b) Uniform spaced

Fig. 2. The two types of pin layout.

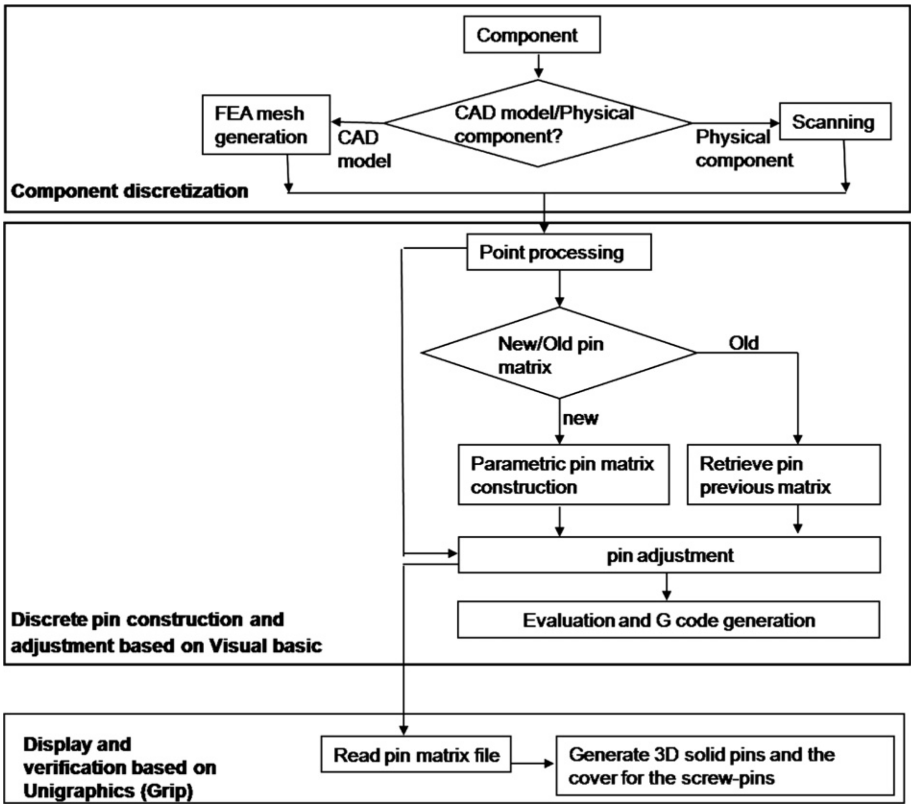


Fig. 3. Framework of the methodology.

The attention paid to the development of support software is also limited. Indeed, in order for any new concepts of reconfigurable moulds to be applied widely in industry, it is essential for them to be integrated with several other cutting edge technologies, e.g. CAD/CAM, reverse engineering and mould machinery in order to facilitate an automated representation of discrete pins of components that enable rapid mould reconfiguration. This has not been seen in prior research.

This paper addresses a new method of software development for reconfigurable moulds utilising discrete pins. The overall aim of the method is to provide a generic interface for general discrete pin tooling to enable a quick reconfiguration of the mould to represent component geometry. The software is composed of three parts: part discretization, pin matrix construction and adjustment and pin matrix verification. The overall framework of the methodology is demonstrated in Fig. 3. The second part of the software, the pin matrix construction and adjustment, will also be explained in detail in this paper.

2. Discretization of candidate parts

The candidate parts to be moulded may come from virtual parts created in commercial CAD software (e.g. Fig. 4a) and physical parts (e.g. Fig. 4c). In the case of the former, part geometry is usually continuous and parametric, and the position of a component regarding the individual pins is not available. It is thus essential to divide the continuous surface into many small patches, so that the position of the pins to these small patches can be calculated. Dividing the continuous surface into small pieces is also called discretization. A part discretization function is generally not available in standard commercial CAD software, but is a standard function of the commercial Finite Element Analysis (FEA) software and is called mesh generation function, therefore, part discretization is conducted using the commercial FEA software ABAQUS (e.g. Fig. 4b). In the latter's case, which is normally used when a physical part instead of a virtual CAD model is available, 3D digital scanning of the physical part may take place to obtain point cloud information (e.g. Fig. 4d). In this study, the 3D scanning of the physical part was undertaken using the Gom ATOSII optical scanner.

3. Discrete pin construction and adjustment

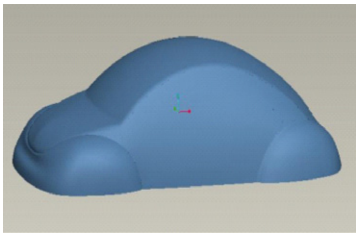
Visual Basic software is used to develop a user friendly interface to allow users to process the output file based on the previous discretization process to obtain point position, and make a decision about whether a new discrete-pin matrix or previous discrete-pin matrix should be used. If a new discrete-pin matrix is needed, it will be constructed parametrically, otherwise, the previous discrete-pin matrix will be retrieved. After this process, the amount of discrete-pin adjustment will be calculated based on the height difference between the discrete-pin matrix and the component geometry; and assessment will be made into whether the discrete-pin matrix is suitable for the component; if not satisfactory, it will give feedback for the purpose of avoiding problems at a later stage.

In summary, the discrete pin construction and adjustment package is composed of five parts: (1) Point processing: to process the FEA file and scanned component file (point cloud file) to obtain point (node) coordinate positions; (2) Discrete-pin matrix construction: to construct a new discrete-pin matrix based on the parameters input by the user; (3) Discrete-pin adjustment: to calculate the amount of adjustment required of each discrete-pin; (4) Saving and retrieval of discrete-pin matrix; (5) Evaluation: to assess whether or not the overall size of a discrete-pin matrix and the remaining length of individual pins are sufficient for the new component.

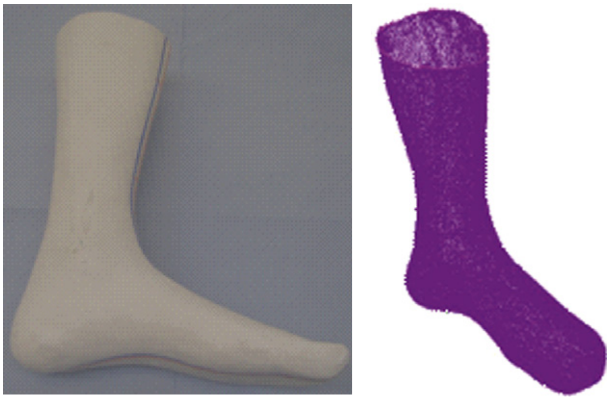
3.1. Point processing

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, material properties, etc. The point processing program is developed to read the component discretization file and obtain point (node) position information and discard any irrelevant information.

The Visual Basic programme opens the discretized component file (∗.inp file) as generated by Finite Element (FE) software ABAQUS and read the text line by line and process it. The useful information within the file (∗.inp file) is the node definition that

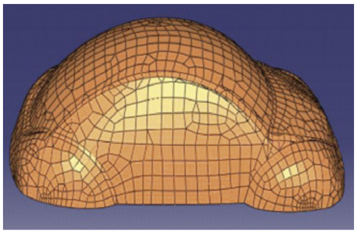


(a) CAD model



(c) Physical model

(d) Scanned model



(b) Discretization of CAD model

Fig. 4. Examples of part discretization.

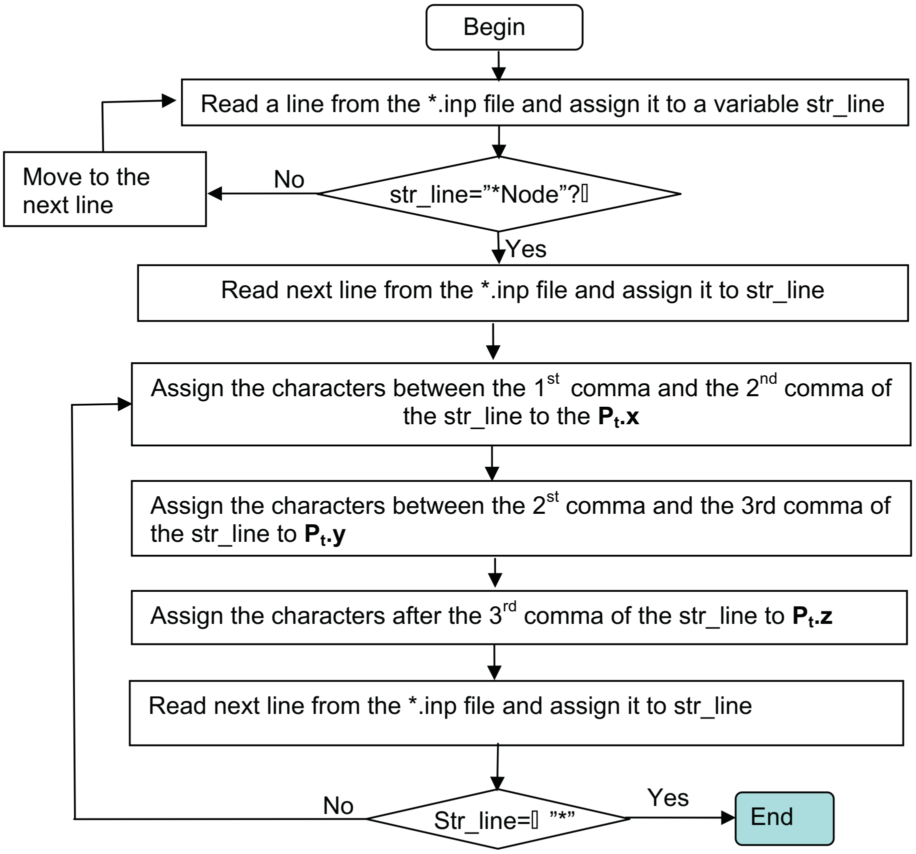
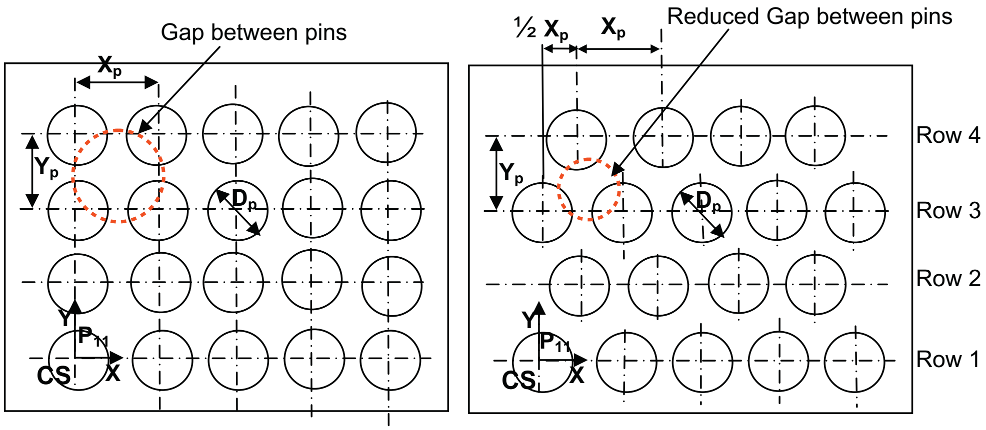


Fig. 5. Flow chart of point processing for ABAQUS FEA file.



(a) evenly distributed

(b) misaligned distribution

Fig. 6. The layout of discrete pins.

contains the node coordinate positions. The node definition starts from the line "∗ Node", and is followed by a number of lines, each of which defines a node $\mathbf{P}_t(x,y,z)$ containing a node identity number, *x*, *y* and *z* coordinate values of the node with a "," to separate them. The line "∗" indicates the end of the node definition. The flow chart of the program to read a node position $\mathbf{P}_t(x,y,z)$ is shown in Fig. 5.

The output file obtained from a 3D digital scan of a physical part is a point cloud file which is a very straight forward format and has many lines of text, each of which contain the *x*, *y*, *z* coordinate values of a point $\mathbf{P}_t(x,y,z)$. The point processing programme used to obtain point information is similarly shown in Fig. 5.

3.2. Discrete-pin matrix construction

Assuming that all of the pins employed in a reconfigurable mould are of the same size, the parameters of a discrete pin tooling include number of rows $\mathbf{r}(\mathbf{r} > 1)$, number of columns of pin $\mathbf{c}(\mathbf{c} > 1)$, pin diameter ($\mathbf{D}_p$), length ($\mathbf{L}_p$), and the distance between two discrete-pin central axes in *X* and in *Y* directions, designated as $\mathbf{X}_p$ and $\mathbf{Y}_p$, respectively. Uniform spaced pin distribution is considered, whilst the close-packed pin arrangement is treated as a special case of uniform space pin distribution with the condition that $\mathbf{X}_p = \mathbf{Y}_p = \mathbf{D}_p$.

Let $\mathbf{P}_{ij}$ be the pin at *i*th row and *j*th column of the discrete-pin matrix ($i \in [1,\mathbf{r}]$ and $j \in [1,\mathbf{c}]$), $\mathbf{P}_{ij}$ is defined as a structure containing *x*, *y*, *z*0, *z*1, *mx*, *mn*, *a* and *rl* variables in Visual Basic as below.

Dim $\mathbf{P}_{ij}$ as structure

{*x* as double, *y* as double, *z*0 as double, *z*1 as double,
mx as double, *mn* as double, *rl* as double, *a* as double}

where $\mathbf{P}_{ij}\cdot x$ and $\mathbf{P}_{ij}\cdot y$ are the *X* and *Y* coordinate values of the centre point on the top surface of the pin $\mathbf{P}_{ij}$, respectively; $\mathbf{P}_{ij}\cdot z0$ and $\mathbf{P}_{ij}\cdot z1$ are the *Z* coordinate values of the centre point of the top surface of the pin $\mathbf{P}_{ij}$ before adjustment and after adjustment, respectively; $\mathbf{P}_{ij}\cdot mx$ and $\mathbf{P}_{ij}\cdot mn$ are the maximum and minimum *Z* values of the discretized point on the patch of the components in response to which the discrete-pin $\mathbf{P}_{ij}$ is to be adjusted; $\mathbf{P}_{ij}\cdot rl$ is the remaining length of the discrete-pin $\mathbf{P}_{ij}$ after machining (to be explained later) and $\mathbf{P}_{ij}\cdot a$ is the amount of adjustment that the discrete-pin $\mathbf{P}_{ij}$ will be moved;

Two types of discrete-pin layout are considered: the pins are evenly distributed as shown in Fig. 6a and misaligned distribution as shown in Fig. 6b, in which the pins in the even rows have one pin fewer than those in the odd rows and the centre axis position of the pin in even rows is misaligned $\mathbf{X}_p/2$ in *X* direction from that in the odd rows. Compared to evenly distributed pin layout, the misaligned pin distribution has a better pin density, offering better support to the part for the moulding process because of the reduced gap between pins.

The coordinate system **CS** for the pin matrix is to be assigned at the top centre position of the $\mathbf{P}_{11}$ as shown in Fig. 6. In this event, for both even and misaligned pin distributions:

$$\mathbf{P}_{ij}\cdot y = \mathbf{Y}_p^*(i-1);\quad i \in [1,\mathbf{r}],\ j \in [1,\mathbf{c}] \tag{1}$$

For evenly distributed discrete pins shown in Fig. 6a:

$$\mathbf{P}_{ij}\cdot x = \mathbf{X}_p^*(j-1);\quad i \in [1,\mathbf{r}],\ j \in [1,\mathbf{c}] \tag{2}$$

For misaligned distributed pin matrix shown in Fig. 6b,

$$\mathbf{P}_{ij}\cdot x = \mathbf{X}_p^*(j-1);\quad i \in [1,\mathbf{r}],\ i \text{ is odd},\ j \in [1,\mathbf{c}] \tag{3}$$

$$\mathbf{P}_{ij}\cdot x = \mathbf{X}_p^*(j-1) + 1/2^*\mathbf{X}_p;\quad i \in [1,\mathbf{r}];\ i \text{ is even},\ j \in [1,\mathbf{c}-1] \tag{4}$$

3.3. Discrete-pin matrix adjustment

As illustrated in Fig. 7, when a node $\mathbf{P}_t(x,y,z)$ on the component is read by the programme, it is firstly processed to identify the closest pin within which the point is located. Let $\mathbf{P}_{ij}$ be the closest pin to $\mathbf{P}_t(x,y,z)$ in the XY plane of the **CS**, and 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, Thus, for both

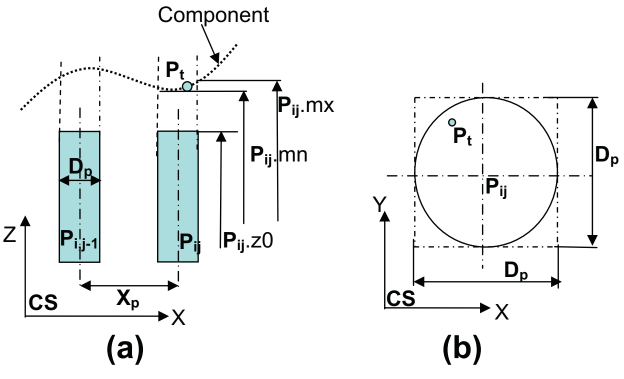


Fig. 7. Point $\mathbf{P}_t(x,y,z)$ on component and the Pin $\mathbf{P}_{ij}$.

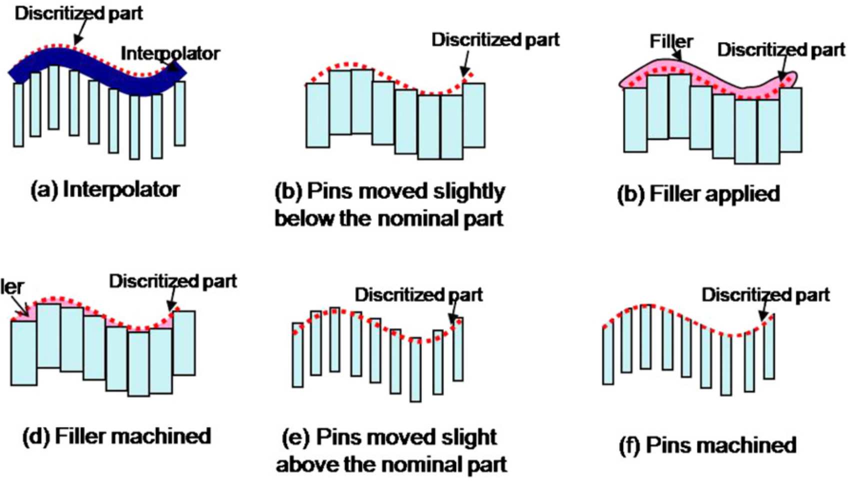
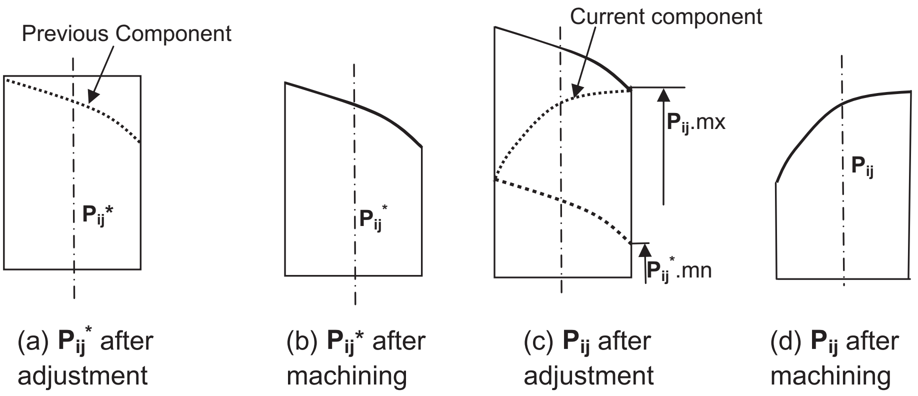


Fig. 8. Three solutions to avoid dimples on moulded components.



(a) $\mathbf{P}_{ij}^*$ after adjustment
(b) $\mathbf{P}_{ij}$* after machining
(c) $\mathbf{P}_{ij}$ after adjustment
(d) $\mathbf{P}_{ij}$ after machining

Fig. 9. Machining operation on $\mathbf{P}_{ij*}$ and $\mathbf{P}_{ij}$.

evenly and misaligned distributed pin layout shown in Fig. 6a and b,

$$i = \mathbf{Round}(\mathbf{P}_t \cdot y/\mathbf{Y}_p) + 1 \quad \text{and } i \in [1, \mathbf{r}] \tag{5}$$

For even distribution of pin layout,

$$j = \mathbf{Round}(\mathbf{P}_t \cdot x/\mathbf{X}_p) + 1 \quad \text{and } j \in [1, \mathbf{c}] \tag{6}$$

For misaligned distribution of pin layout,

$$\text{if } i \text{ is odd, then } j = \mathbf{Round}(\mathbf{P}_t \cdot x/\mathbf{X}_p + 1), \quad \text{and } j \in [1, \mathbf{c}] \tag{7}$$

$$\text{if } i \text{ is even, then } j = \mathbf{Round}(\mathbf{P}_t \cdot x/\mathbf{X}_p + 1/2), \quad \text{and } j \in [1, \mathbf{c} - 1] \tag{8}$$

CN, PN, $\mathbf{D}_p$, $\mathbf{X}_p$, $\mathbf{Y}_p$, $\mathbf{L}_p$, M, N, t
1, 1, $\mathbf{P}_{11}$.x, **$\mathbf{P}_{11}$**.y, **$\mathbf{P}_{11}$**.z0, **$\mathbf{P}_{11}$**.z1, **$\mathbf{P}_{11}$**.mx, **$\mathbf{P}_{11}$**.mn, **$\mathbf{P}_{11}$**.a, **$\mathbf{P}_{11}$**.sl
1, 2, $\mathbf{P}_{12}$.x, **$\mathbf{P}_{12}$**.y, **$\mathbf{P}_{12}$**.z0, **$\mathbf{P}_{12}$**.z1, **$\mathbf{P}_{12}$**.mx, **$\mathbf{P}_{12}$**.mn, **$\mathbf{P}_{12}$**.a, **$\mathbf{P}_{12}$**.sl
…
i, j, $\mathbf{P}_{ij}$.x, $\mathbf{P}_{ij}$.y, $\mathbf{P}_{ij}$.z0, $\mathbf{P}_{ij}$.z1, $\mathbf{P}_{ij}$.mx, $\mathbf{P}_{ij}$.mn, $\mathbf{P}_{ij}$.a, $\mathbf{P}_{ij}$.sl
…

Fig. 10. The format of the discrete-pin matrix for saving and retrieval.

Once the closest Pin $\mathbf{P}_{ij}$ to the $\mathbf{P}_t(x,y,z)$ is identified, it is necessary to evaluate whether or not the $\mathbf{P}_t(x,y,z)$ is within the area of the $\mathbf{P}_{ij}$ in XY plane of the **CS**. The $\mathbf{P}_t(x,y,z)$ on the component that is outside the area will be discarded, as illustrated in Fig. 7b:

$$|\mathbf{P}_t(x,y,z) \ \cdot \ x - (i-1)^*\mathbf{Xp}| < \mathbf{D}_p/2 \tag{9}$$

$$|\mathbf{P}_t(x,y,z) \ \cdot \ y - (j-1)^*\mathbf{Yp}| < \mathbf{D}_p/2 \tag{10}$$

The $\mathbf{P}_{ij} \cdot mx$ and $\mathbf{P}_{ij} \cdot mn$ are obtained from the statement shown as below:

$$\text{If } \mathbf{P}_t \cdot z > \mathbf{P}_{ij} \cdot mx, \quad \text{then } \mathbf{P}_{ij} \cdot mx = \mathbf{P}_t \cdot z \tag{11}$$

$$\text{If } \mathbf{P}_t \cdot z < \mathbf{P}_{ij} \cdot mn, \quad \text{then } \mathbf{P}_{ij} \cdot mn = \mathbf{P}_t \cdot z \tag{12}$$

A common problem associated with the discrete pin mould is that discrete pins are in direct contact with components, and loadings are concentrated on the pins, leaving dimples on the moulded components and resulting in a poor surface finish. To avoid such a problem, three prior solutions have been proposed:

(1) Interpolator (see Fig. 8a); A rubber like interpolator was put between discrete pins and the component; The interpolator is well suited for application when the component geometry is simple and there are no detailed small features; An example of the interpolator can be found in references [1,14,15];

(2) Filler; pins are moved to near-net positions (slightly below the nominal part position as shown in Fig. 8b) filler is applied to the top of the pins (Fig. 8c), and is machined off (Fig. 8d), so that the filler after machining on the pins is conformable to component geometry. It should be noted that applying filler to the discrete pins is suitable only for close-packed discrete pins, where $\mathbf{X}_p = \mathbf{Y}_p = \mathbf{D}_p$.
(3) Machining; pins are moved to near net positions (slightly above the nominal part position as shown in Fig. 8e) and are then machined off (Fig. 8f), such that the contact surface of the pins is conformable with that of the part.

It is possible for discrete pins for interpolator and filler to be reused many times; however, if there is machining on the pins, the pins will be shortened after each machining operation, therefore, it is necessary to assess the remaining length of the pins after pin adjustment and machining to ensure the sufficient length of pins is left for the next operation.

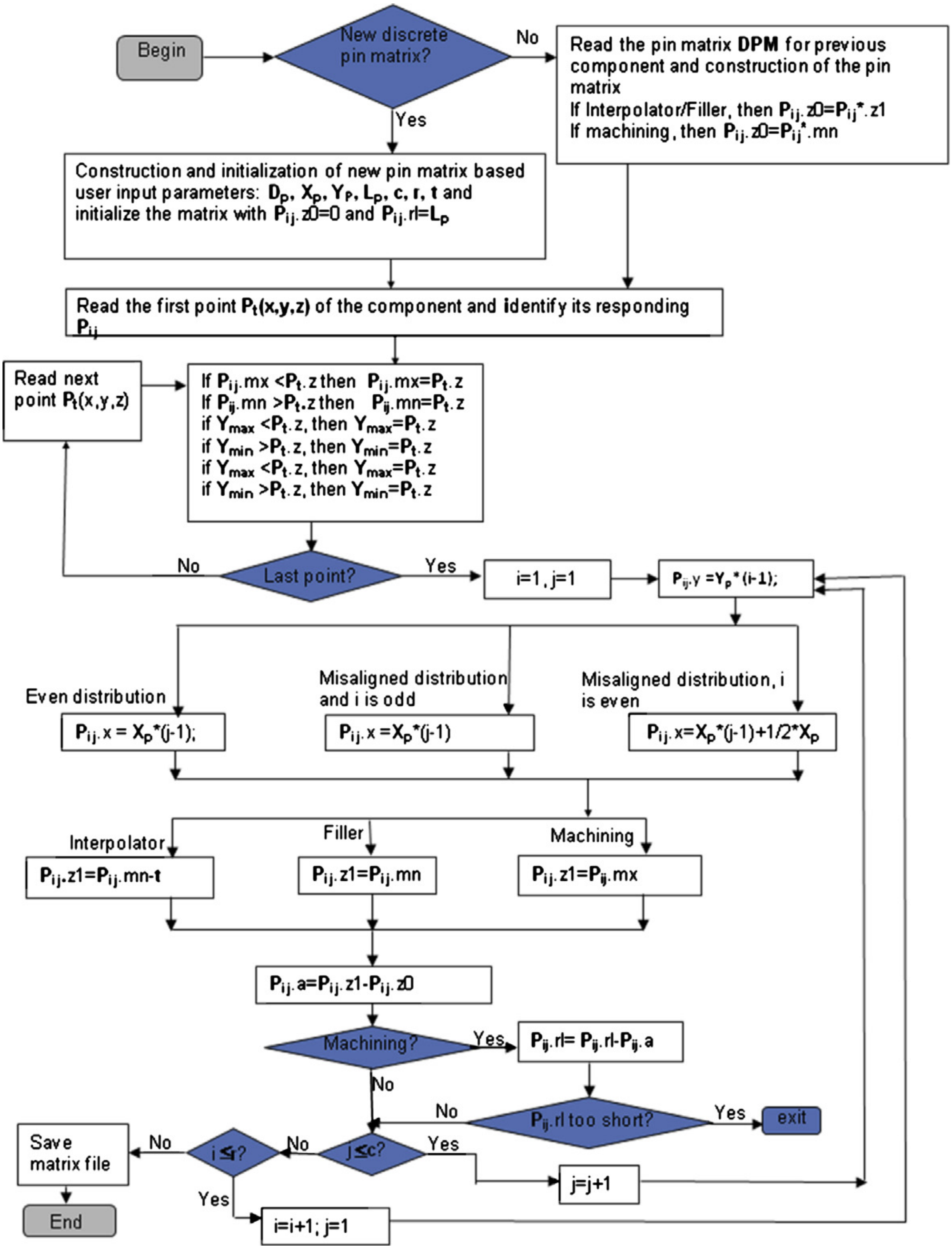


Fig. 11. Flow chart of the programme written using Visual Basic.

In the case of the interpolator, let the thickness of the interpolator be $\mathbf{t}$ ($\mathbf{t} = 0$ for filler and machining operation), and $\mathbf{d}$ is the deformation of the interpolator generated during mould and can be obtained from FEA simulation or from experiments, then the pin position after adjustment will be:

$$\mathbf{P}_{ij}\cdot z1 = \mathbf{P}_{ij}\cdot mn - \mathbf{t} - \mathbf{d} \tag{13}$$

In the case of using filler, which is applicable only for close packed pins, where $\mathbf{D}_p = \mathbf{X}_p = \mathbf{Y}_p$, in order to apply minimal filler material, the pin position should be:

$$\mathbf{P}_{ij}\cdot z1 = \mathbf{P}_{ij}\cdot mn \tag{14}$$

In the case of applying machining on the pins, it is necessary to move the pins above the components for machining operation. In order for minimal material to be removed, the pin position after adjustment is:

$$\mathbf{P}_{ij}\cdot z1 = \mathbf{P}_{ij}\cdot mx \tag{15}$$

If a new pin matrix is constructed to represent a new component, then:

$$\mathbf{P}_{ij}\cdot z0 = 0 \quad \text{and} \quad \mathbf{P}_{ij}\cdot rl = 0 \tag{16}$$

Otherwise, let the $\mathbf{P}_{ij}{}^{*}$ be the $\mathbf{P}_{ij}$ of the previous component. The final position of the $\mathbf{P}_{ij}{}^{*}$ will be the start position of the $\mathbf{P}_{ij}$ for the solutions of interpolator and filler, then:

$$\mathbf{P}_{ij}\cdot z0 = \mathbf{P}^{*}_{ij}\cdot z1 \tag{17}$$

When the machining operation is undertaken on discrete pins $\mathbf{P}_{ij}$, the $\mathbf{P}_{ij}{}^{*}$ is firstly adjusted to the maximum height of the patch of the component in response to the $\mathbf{P}_{ij}{}^{*}$, as shown in Fig. 9a, then is machined according to the component profile as shown in Fig. 9b. In order for the $\mathbf{P}_{ij}$ to have sufficient material to cover the component patch shown in as shown in Fig. 9c and d, then:

$$\mathbf{P}_{ij}\cdot z0 = \mathbf{P}^{*}_{ij}\cdot mn \tag{18}$$

$\mathbf{P}_{ij}\cdot a$, which is the amount of movement of the pin $\mathbf{P}_{ij}$, is the difference between the final position and the initial position of the pin, then:

$$\mathbf{P}_{ij}\cdot a = \mathbf{P}_{ij}\cdot z1 - \mathbf{P}_{ij}\cdot z0 \tag{19}$$

Then, the remaining length of the pin after machining is:

$$\mathbf{P}_{ij}\cdot rl = \mathbf{P}_{ij}\cdot rl - \mathbf{P}_{ij}\cdot a \tag{20}$$

3.4. Discrete-pin matrix saving and retrieval

In order for the pin matrix to be adjusted to represent a new component from the current position which is used to represent another different component, it is essential to save and retrieve the pin matrix.

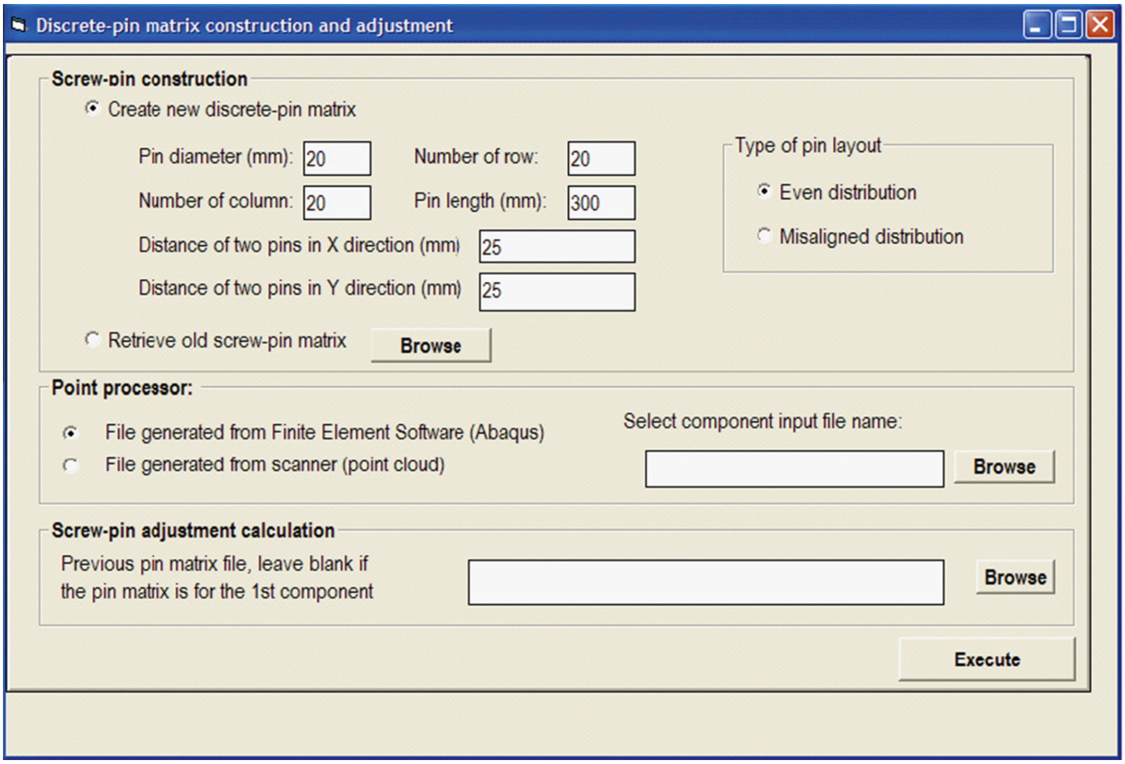
The discrete-pin matrix, designated as **DPM** is constructed as below:

$$\mathbf{DPM} = \{\mathbf{CN}, \mathbf{PN}, \mathbf{c}, \mathbf{r}, \mathbf{D}_p, \mathbf{X}_p, \mathbf{Y}_p, \mathbf{L}_p, \mathbf{M}, \mathbf{N}, \mathbf{t}, i, j, \mathbf{P}_{11}, \ldots, i, j, \mathbf{P}_{ij}, \ldots\}$$

where **CN** is the component name, **PN** is the pin matrix name, **M** represents the type of pin layout, and is Boolean type; **M** = 0 for evenly distributed pin layout; **M** = 1 for misaligned pin layout. **N** is the type of operation conducted on the pins, **N** = 1 for interpolator, **N** = 2 for filler and **N** = 3 for machining operation. Information for the whole discrete-pin matrix **DPM** is saved according to the format shown in Fig. 10.

3.5. Evaluation, programme flowchart and interface

Evaluation is required in order to assess whether or not the discrete-pin matrix is suitable for the component or not. The evaluation criteria are: the component size should be smaller than that of the overall discrete-pins and the remaining length of each



Discrete-pin matrix construction and adjustment

Screw-pin construction

● Create new discrete-pin matrix

Pin diameter (mm): 20

Number of row: 20

Number of column: 20

Pin length (mm): 300

Distance of two pins in X direction (mm) 25

Distance of two pins in Y direction (mm) 25

Type of pin layout

● Even distribution

○ Misaligned distribution

○ Retrieve old screw-pin matrix

Point processor:

● File generated from Finite Element Software (Abaqus)

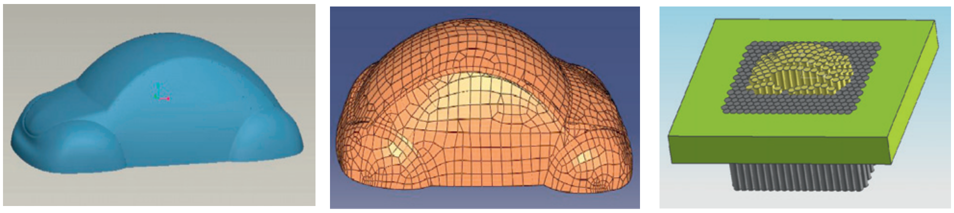
○ File generated from scanner (point cloud)

Select component input file name:

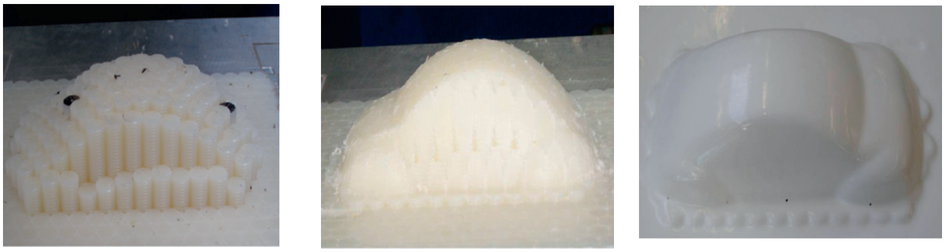
Screw-pin adjustment calculation

Previous pin matrix file, leave blank if the pin matrix is for the 1st component

Fig. 12. Interface of Visual Basic programme.



(a) CAD model (b) part discretized (c) pin adjusted virtually



(d) pin adjusted physically (e) Pin machined (f) Vacuum formed component

Fig. 13. Example of reconfigurable mould.

individual pin should be sufficient for the amount of adjustment, e.g. 20% of the original length of the pin. The programme first calculates the maximum *X* and *Y* positions of the discretized components using the statement below for every point read by the program:

$$\text{If } \mathbf{P}_{\mathrm{t}} \cdot y > \mathbf{Y}_{\max}, \quad \text{then} \quad \mathbf{Y}_{\max} = \mathbf{P}_{\mathrm{t}} \cdot y \tag{21}$$

$$\text{If } \mathbf{P}_{\mathrm{t}} \cdot y < \mathbf{Y}_{\min}, \quad \text{then} \quad \mathbf{Y}_{min} = \mathbf{P}_{\mathrm{t}} \cdot y \tag{22}$$

$$\text{If } \mathbf{P}_{\mathrm{t}} \cdot x > \mathbf{X}_{max}, \quad \text{then} \quad \mathbf{X}_{\max} = \mathbf{P}_{\mathrm{t}} \cdot x \tag{23}$$

$$\text{If } \mathbf{P}_{\mathrm{t}} \cdot x < \mathbf{X}_{\min}, \quad \text{then} \quad \mathbf{X}_{\min} = \mathbf{P}_{\mathrm{t}} \cdot x \tag{24}$$

As the coordinate system is put on pin $\mathbf{P}_{11}$, the valuation is to ensure that:

$$\mathbf{P}_{\mathrm{i}1} \cdot x < \mathbf{X}_{\min} \quad \text{and} \quad \mathbf{P}_{1\mathrm{j}} \cdot \mathbf{y} < \mathbf{Y}_{\min} \tag{25}$$

$$\mathbf{P}_{\mathrm{ic}} \cdot x > \mathbf{X}_{\max} \quad \text{and} \quad \mathbf{P}_{\mathrm{rj}} \cdot \mathbf{y} > \mathbf{Y}_{\max} \tag{26}$$

$$\mathbf{P}_{ij} \cdot rl > 0.2^{*}\mathbf{L}_{\mathrm{p}} \tag{27}$$

As G code will be generated automatically from the software to drive machine tools for machining, part geometry limitation is important for the cases of machining of pins and machining of filler. Without these limitations, the machine tool may be driven by G codes to machine the base of the discrete pin or the base of the machine, instead of the pins, the result can be catastrophic

The programme flow chart and interface for discrete pin construction, adjustment and evaluation are shown in Figs. 11 and 12, respectively.

4. Display and verification

After calculating the adjustment of the discrete-pins, it may be necessary to display the discrete-pin matrix within in a CAD/CAM environment in order to verify whether or not the discrete-pins are in the correct position before any physical operations are carried out on the discrete-pin matrix. The geometry and the final position of the discrete-pin matrix after adjustment are generated automatically based on the discrete-pin matrix file saved for retrieval by the programme developed within the Unigraphics/Grip environment.

5. Case study

A car model was generated within a commercial CAD software and saved as a neutral file format (∗.igs) as shown in Fig. 13a. The car model was inputted into ABAQUS CAD and discretized as shown in Fig. 13b. The meshed file was processed by the Visual Basic programme using the interface shown in Fig. 12 to calculate the amount of discrete-pin adjustment. The final position of the discrete-pin was saved as a txt file and exported to CAD software Unigraphics using the GRIP programme, and a 3D simplified pin matrix was created automatically as shown in Fig. 13c, making it possible for it to be compared to the original CAD model. Once the position of the discrete-pins is verified, the pin matrix file will be used as input for the physical pin adjustment (Fig. 13d). After the adjustment, the surface can be subsequently machined as shown in Fig. 13e. A vacuum formed product using the pin mould can be found in Fig. 13f.

6. Conclusions

Traditional moulds are expensive and dedicated. The demand for a reconfigurable mould is greater than ever in the modern manufacturing environment. The focus of prior research was overwhelmingly placed on hardware development, concentrating on new concepts of pin actuation. The attention of the support software development to enable an automated reconfiguration of discrete pins is limited. A new method of software development can be conducted with the purpose of producing a rapid representation of component geometry and automating the calculation of pin adjustment based on the difference of the geometry of current and previous components.

The 3D geometry of a component is firstly discretized using an FE mesh generator or from 3D digital scanning, and the geometry information of the component is processed to calculate the amount of pin adjustment. The matrix of pins after adjustment is saved and retrieved for reuse in the subsequent component. Evaluation is conducted to ensure that pin matrix is suitable for the component. The pin matrix file can be read by CAD software in order to display the pin position for visually assessing whether all the pins are in the right position. A close packed discrete pin matrix with a misaligned layout for the vacuum forming process has been demonstrated as a case study.

References

[1] Liu C, Li M, Fu W. Principles and apparatus of multi-point forming for sheet metal. Int J Adv Manuf Technol 2008;35:1227–33.

[2] Munro C, Walczyk D. Reconfigurable pin-type tooling: a survey of prior art and reduction to practice. J Manuf Sci Eng, Trans ASME 2007;129(3):551–65.

[3] Cochrane J. Bending metal plates. US Patent No. 39,886; 1863.

[4] Avant-Garde Communication Ltd. Online international aviation news magazine. <http://www.skycontrol.net/industry/dataform-flexible-and-reconfigurable-tooling-for-manufacturing-aircraft-panels/> [last logged on 05.04.09].

[5] Walczyk DF, Hosford JF, Papazian JM. Using reconfigurable tooling and surface heating for incremental forming of composite aircraft parts. J Manuf Sci Eng 2003;125:333–43.

[6] Tan FX, Li M-Z, Lai ZY. Research on the process of multi-point forming for the customised titanium alloy cranial prosthesis. J Mater Process Technol 2007;187–188:453–7.

[7] Kelkar A, Nagi R, Koc B. Geometric algorithms for rapidly reconfigurable mold manufacturing of free-form objects. Comput-Aided Des 2005;37:1–16.

[8] Pinson GT. Apparatus for forming sheet metal. US Patent No. 4,212,188; 1980.

[9] Fuchs A, Radolfzellerstr LL, Konstanz DE. Method and arrangement for reducing a curved sail. US Patent No. 4,309,824; 1982.

[10] Kommineni P, Hollandsworth PE, Jones JW. Method of shaping an antenna panel. US Patent No. 4,731,144; 1988.

[11] Sherrill DE, Young KG. Apparatus for constructing a composite structure. US Patent No. 6,298,896 B1; 2001.

[12] Haas EG, Kesselman M. Adjustable form die. US Patent No. 5,546,784; 1996.

[13] Sullivan EV, Haas EG, et al. Individual motor pin module. US Patent No. 6,012,314; 2000.

[14] Berteau J. Variable-shape mold. US Patent No. 5,330,343; 1994.

[15] Schroeder T, Stevenson R. Device for generating a fixture. US Patent No. 5,738,345; 1998.

[16] Surface Generation Ltd. <http://www.surface-generation.com/iexplorer/index.htm>.

[17] Halford B. Improved tooling system. World Intellectual property organisation. Patent No. WO2005/061183 A2; 2005.

[18] Halford B. Workpiece support. World Intellectual property organisation. Patent No. WO2005/061182 A2; 2005.

[19] Halford B. Tooling system with array of longitudinally movable elements. World Intellectual property organisation patent. Patent No. WO2006/00817 A1; 2006.

[20] Walczyk DF, Hardt DE. Design and analysis of reconfigurable discrete dies for sheet metal forming. J Manuf Syst 1998;17(6):436–54.

[21] Robinson HRE. Design of an automated variable configuration die and press for sheet metal forming. MS thesis, Massachusetts Institute of Technology; 1987.

[22] Knapke JA. Evaluation of variable configuration die sheet metal forming machine. MS thesis, Massachusetts Institute of Technology; 1988.

[23] Ousterhout KB. Design and control of a flexible process for three dimensional sheet metal forming. PhD thesis, Massachusetts Institute of Technology; 1991.

[24] Eigen GF. Smoothing methods for discrete die forming. MS thesis, Massachusetts Institute of Technology.