Development and Evaluation of a Low-cost Computer Controlled Reconfigurable Rapid Tool

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ABSTRACT

This paper describes the development of a low-cost rapid tool that is easily re-configurable by a single computer-controlled actuator or conventional CNC machine. The bed-of-pins concept used in popular pin-art toys and by other researchers is enhanced with a novel approach of positioning and clamping the pins in a simple, low-cost and time-saving manner which is scalable to large size products. Different tool path strategies for positioning the pins by using a CNC machine are proposed and evaluated to obtain an optimal strategy. The position of the pins, and the NC code, is automatically derived from the 3D CAD model of the part. The concept has been tested on parts made from carbon fibre and thermoplastic moulding, and sheet metalforming. The scalability of the concept to large size objects is also demonstrated.

Keywords: Rapid Prototyping, Rapid Tooling, Reconfigurable Tooling.

1. INTRODUCTION

One of the strategies for reducing the cost and cycle time of products in manufacturing enterprises is the use of rapid tooling and manufacture (RT&M) fabrication methods. RT&M processes include rapid prototyping and manufacture (RP&M) based tools, electro-discharge machining, metal spray, silicone rubber moulding, composite moulding, injection moulding, profile edge lamination and reconfigurable tooling. This paper considers the Reconfigurable Rapid Tooling (RRT) approach.

Re-configurable tooling is a method in which a matrix of pins is stacked together to form the required shape. This method, found in popular pin-art toys, has been considered in one form or another in many patents and by many researchers because of its potential for rapid tooling. As the name suggests, the obvious advantage of a re-configurable tool is that the same tool can be used to form many different shapes in sheet metal forming, plastic moulding, electrochemical machining, and other manufacturing processes or in tool trials. Also, the same tool can be used as a die, mould or fixture. The lead-time and costs for developing and manufacturing a product using a re-configurable tool 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.

Despite the advantages of the re-configurable tool concept, this rapid tooling technology is not yet widely used. One reason for this is that difficulties are still associated with positioning and locking the pins of a reconfigurable tool. There is also the problem of scallops. Though several patents and research have contributed to addressing these needs, a method of reconfiguring the tool that is fast yet simple, low-cost and of industrial scale, has not been proposed. A graphical interface that facilitates the generation of the control information from a 3D surface CAD model is also required.

The research reported in this paper is a contribution to addressing these needs through the design, fabrication and evaluation of a prototype of a low cost computer-controlled reconfigurable tool scalable to large-scale industrial size and comparable in performance to conventional tools. Several tool path strategies that can be used by computer-controlled actuators or CNC machines are automatically obtained from a 3D CAD model and evaluated for optimality. Also the capabilities of the CNC-reconfigurable tool, such as overall accuracy and ease of reconfiguration are evaluated.

In this paper, a review of research contributions related to reconfigurable tooling is presented in section 2. Section 3 considers the design and fabrication of the prototype reconfigurable tool developed. The reconfiguration system, which is an interface between the user and the tool to allow an efficient method of reconfiguration, is the focus of section 4. Section 5 includes the results obtained from tests carried out with the CNC-reconfigurable tool and in section 6, conclusions and recommendations for further work are presented.

2. LITERATURE REVIEW

Walczyk and Hardt [1] review the history of advances in the development of reconfigurable tools from 1923 including a number of patents. The history, starting with the two-dimensional array of pins, varying in applications and degree of automation, clearly shows that the basic principle for re-configuration was established very early in the history of this rapid tooling approach.

Nakajima [2] made the first attempt to create an automatically reconfigurable tool and tested some proposed methods to increase the load that the pins can support without slipping. In his research, he describes the use of a CNC milling machine to move the die pins, a method of holding the pins and applications of re-configurable tools. The moving techniques studied by Nakajima include point–to–point control and sweep control. In point–to–point control, a push-metal attached to the spindle of the CNC milling machines, is located above the end of each pin, and only one pin is positioned in the Z-axis direction at one time. Sweep control involves positioning more than one pin at a time through a knife blade attached to the spindle of the CNC milling machine, while being swept in one of the planar directions. In this case, the shape (depth) of the curved surface is restricted to the angle at the tip of the knife blade. With this type of control, it was difficult to move one pin without dragging the adjacent pins. Nakajima proposed increasing the load carrying capacity of the pins by packing a plaster or fusible alloy at the bottom of the pins. Furthermore, he demonstrated the application of re-configurable tools to sheet metal forming, electrolytic machining, compression moulding of plastics, vacuum forming of plastics and die-casting.

In 1980, the first self-contained automatically controlled 3D re-configurable tool was patented by Pinson [3]. Although it was similar to those developed earlier, it had the capability of being set automatically by computer-controlled servo-actuators connected to each pin.

Walczyk and Hardt [1] designed a reconfigurable tool which was capable of setting the pins automatically and served as a die for a forming press. Nakajima's problem of dragging the adjacent pins was solved by separating each row of pins using a sheet metal spacer, rigidly attached to the die frame. In this way, the maximum forming load per pin was limited by the failure of the row divider material. Walczyk and Hardt [1] proposed that the pins, in a densely packed die, should be square in cross section to ensure load path isolation and their tips be rounded to avoid piercing, thus enabling the formation of a smooth surface. The frame stiffness was confirmed using the finite element method wherein it was assumed that the clamping load is uniformly distributed over the pin matrix. The uniformity of the clamping force was also improved using a thin interpolating material layer between the wall that compresses the pins and the first row of pins.

Recently, Papazian et al [4] developed a reconfigurable tool for the stretch forming of sheet metal in aerospace applications. They claim very substantial reductions in tool fabrication cycle time and labour hours. The die, consisting of 1120 pins, was reconfigured using servo-actuators at each pin. 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 the residual stresses. However, the development costs of the die were over £1 million and therefore not affordable by small-to-medium scale manufacturing industries.

3. DESIGN AND FABRICATION OF THE RRT

The design of the re-configurable tool involved making decisions on the general configuration of the rapid tool and the specific shapes and sizes of the various subassemblies and components. These decisions were constrained by factors such as the desired cost of the tool, the load, size, finest detail to be captured and lead time required. The cost of the tool can be considered to be low if it is comparable or lower than the cost of moulds/dies made by conventional machining or layered manufacturing. A working volume of $10\times10\times10$ cm^3 which can be obtained even on a desktop milling machine, was deemed adequate for the prototype tool. This small size is, however, not a limitation as it can be scaled up by tiling many positioning pins sub-assemblies or shapes made by each tool. The degree of detail to be considered was determined by the average detail found in a part of this size. The load on the die from the most demanding application such as sheet metal forming was estimated as 24KN.

3.1 General Configuration of the RRT

The general form of the re-configurable tool (as shown in Fig. 1) involves two main sub-assemblies: the pin-matrix sub-assembly and the positioning pins sub-assembly. The pin-matrix sub-assembly consists of closely packed pins which form on their upper surface the required shape while their other end interfaces with the positioning pins sub-assembly. The positioning pins sub-assembly consists of pins spaced apart and aligned such that the axis of each pin is co-axial with the centre line of each upper pin. For manufacturing processes like sheet metal forming, two sets of pin-matrix sub-assemblies are required, one to act as a punch and the other as a die. A conventional CNC machine tool was used to move the pins to their required heights. The use of such an approach reduces the complexity and cost of the tool and uses equipment that is readily available to or affordable by those likely to need the tooling.

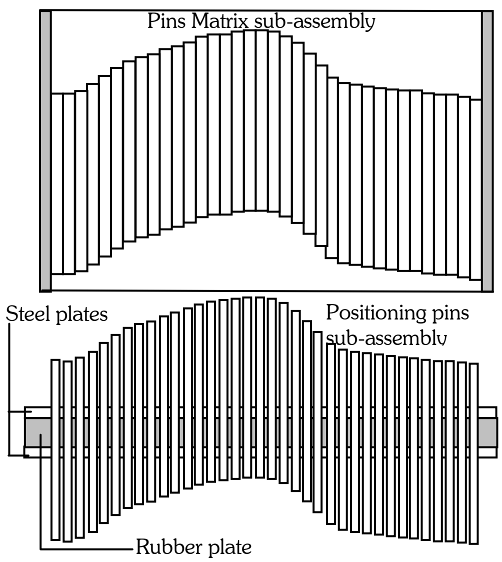


Fig. 1. General configuration of the RRT.

3.2 Design of Upper Pin Matrix

In order to form a rigid tool which can be well-clamped, pins with a square cross-section were selected in line with the suggestion made in [1]. Taking into account the fabrication time, the stiffness of each pin and the detail that can be reproduced, it was decided that the cross-section of each pin is of size 5x5 mm. For a pin to have an effective displacement of 50 mm, some support length would be required if the matrix of pins is used as a punch. Assuming a support length of 50 mm, the length of the each pin is 100 mm. If the entire length of the pin is supported, then a box of 100 x 100 x 100 mm is required. The pins are made from key steel material, which is equivalent to EN6 or BS970-080M30 (AISI 1030).

In order to withstand the high forming loads that occur in sheet metal forming, each pin in the matrix should be firmly locked into position. As described in [1], three methods to temporarily lock each pin in the die include individually locking each pin, backfilling the non-forming side of the discrete die with some particulate material, and clamping the elements from one side with a high force so that the frictional resistance between pins can counteract the operational load. In this research, a combination of methods 2 and 3 has been selected. Method 1 is not considered because it usually means an increase in the cost of the tool. The two selected methods complement each other i.e. if an operating load greater than that provided by the clamping system is required, a particulate material on the non-forming side of the tool is used to increase the locking force.

To support and lock the 400 pins, a cage of 100 mm x 100 mm was adopted. In order to produce the clamping force, 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 (as shown in Fig. 2).

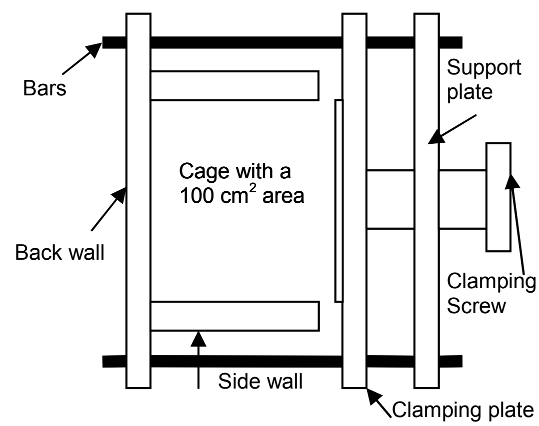


Fig.2. Configuration of the Upper pin sub-assembly.

The dimensions of the frame were determined by estimating the minimum clamping force required for the most demanding application of the reconfigurable tool such as sheet metal forming. By equating the frictional force arising from the clamping to the maximum load (24 KN) and assuming a coefficient of friction of 0.19, the maximum clamping force required to lock the pins was determined as 63KN. A class 8.8 (medium carbon, quenched and tempered) screw M14 of strength Sp = 600 MPa would withstand this load but an M12 screw was selected because, when required, its strength can be complemented by using particulate backing material. By considering the back wall as a beam subjected to two opposing moments, the side walls to be plates undergoing buckling and the bars as beams in tension, the thicknesses of the back wall plate and side walls were determined as 5 and 3.6 mm respectively. For the sake of uniformity, the latter was increased to 5mm. The diameter of the bars was determined as 12mm.

3.3 Design of Positioning Pins Sub-assembly

For the positioning pins to retain the position they have been moved to by the CNC machine, each pin is designed to pass through three co-axial holes, two of which are in thick steel plates and the third in a rubber sheet (Fig. 1). The rubber sheet is sandwiched between the two steel plates and all three of them have drilled in them, a matrix of holes. As each one of the positioning pins has to move a particular pin on the upper matrix and needs to have a space of rubber between it and the adjacent pins, it should have cross-sectional dimensions smaller than the pins on the upper matrix. Since the upper pins have a cross sectional dimension of 5x5 mm, the centres of the positioning pins have to be 5 mm apart from each other. In addition, to minimize the tearing and wearing out of the rubber, a reasonable quantity of it has to be left between the positioning pins. Consequently, there has to be a balance between the size of the rubber gap between the pins and the size of the pins, i.e. if the pins are too large to increase their stiffness, the size of the gap will be too small increasing the risk of the rubber being worn out or tearing in the early stages of its use.

From preliminary experiments, it was found that the gap between elements is required to be greater than 1 mm to avoid any interference or distortion in the steel and rubber plates due to machining effects. By setting the gap to 2 mm, the diameter of the positioning pins becomes 3 mm. With pins made from silver steel (equivalent to BS1407), having a Young's Modulus of 205 GPa, it was found that each pin will support a load of 0.8 kN which was far greater than the self-weight of the upper pin as well as the push force for positioning the pin.

Whilst the holes in the steel plates had to be the same diameter as the pins, the holes in the rubber plate were slightly smaller in diameter thus providing a gripping force on the pin and keeping it in position. Since these types of elastomers have a spring-back behaviour that is difficult to predict, experiments were carried out to determine how the rubber behaves after it has been drilled. Different hole sizes were tried and it was found that a 2.9 mm hole gave the best gripping force but still permitted movement.

4. CAD-DRIVEN COMPUTER-CONTROLLED CONFIGURATION SYSTEM

The system developed obtains, from a CAD model of the part, the NC code to drive one of the CNC machines in the department. For the automatic generation of the NC code, the vertical position of the positioning pins has to be determined and this is described below. Also discussed below are the different positioning strategies.

4.1 Determination of Pin Positions from a 3D CAD Model

The input to the reconfiguration system is a surface model whose shape and orientation are such that all parts of the surface can be approached in the axial direction of the pins. The size of the surface has to be smaller than that of the re-configurable tool and if it is larger then it has to be scaled down appropriately. To determine the height of a positioning pin, a line coinciding with the centre-line of the positioning pin is constructed and intersected with the surface representing the part.

4.2 Generating Optimal Tool Path and NC Code

With the array of pin heights determined, software was developed to generate the toolpath and the corresponding NC code for driving the CNC machine. Since the CNC tool has to push/pull many pins to their position, optimisation of the toolpath is important. Five strategies were considered and evaluated to determine the most efficient tool path. These strategies are: pin-to-pin zig movement; pin-to-pin zigzag movement, pin height differential movement, simultaneous movement of row of pins and simultaneous movement of matrix of pins. These are possible strategies that can be used to move a matrix of pins using only one actuator or a CNC machine and they vary from the simplest to the most complex.

(i) Zig movement

Here the tool sets the pins in a row one at a time, and when it finishes, the tool is retracted to start the next row. The starting points of all the rows are on the same side. This method (illustrated in Fig. 3(a)) is the simplest method to move the tool.

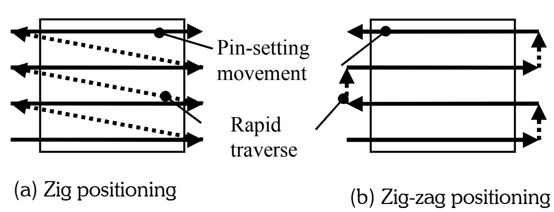


Fig. 3. Pin-to-pin positioning strategies.

The rapid traverse and normal feed lengths L_{rapid} and $L_{setting}$ are expressed by Eqn. (1) and Eqn. (2) respectively.

$$L_{rapid} = (N_{pins} - 1)(L^2 + l^2) + \sum_{i=1}^{n} [(H - h_i) + l] \quad (1)$$

$$L_{setting} = \sum_{i=1}^{n} (H - h_i) \quad (2)$$

where N_{pins} is the number of pins in a row, L is the length of the row, l is the length between pins,
H is the height of the pin, h_i is the axial position of the pin and n is the number of pins.

(ii) Zigzag movement
In this strategy the tool sets the pins in a row one at a time, and when it finishes, the tool moves to the next row without retracting. This results in the starting points of consecutive rows being at opposite ends, forming a zigzag pattern as shown in Fig. 3(b). The lengths L_{rapid} and $L_{setting}$ are as expressed in Eqn. (3) and Eqn. (4).

$$L_{rapid} = 2l(N_{pins} - 1) + \sum_{i=1}^{n} (H - h_i) \quad (3)$$

$$L_{setting} = \sum_{i=1}^{n} (H - h_i) \quad (4)$$

(iii) Pins height differential movement
In this case, all the pins in a row are set to the same depth as the first pin. Then, starting from the second pin, the tool moves either up or down depending on the difference in height between the current and previous pin. The resulting toolpaths are in the form of a staircase (see Figure 3). In order to have push and pull movements, the tool should be C-shaped. The resulting expressions for L_{rapid} and $L_{setting}$ are given by Eqn. (5) and Eqn. (6).

$$L_{rapid} = (N_{pins} - 1)(2L + l) \quad (5)$$

$$L_{setting} = \sum_{i=1}^{n} \left| h_i - h_{i-1} \right| \quad (6)$$

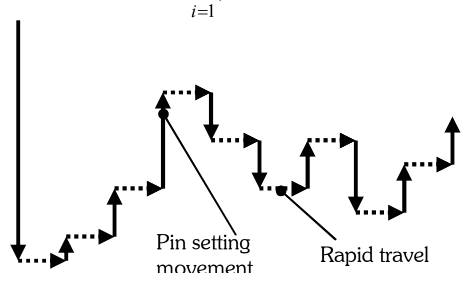


Fig. 4. Toolpath using row of pins strategy.

(iv) Simultaneous movement of row of pins

Here, all the pins in a row are moved at the same time and individual pins are locked when their positions are reached leaving the tool to move the other pins. This method avoids the horizontal and vertical travel between all the pins in a row thus reducing the length travelled to the sum of the differences between the highest and lowest pins in each row plus the horizontal displacement between rows. L_{rapid} and $L_{setting}$ are expressed in this case by Eqn. (7) and Eqn. (8).

$$L_{rapid} = l \cdot (N_{pins} - 1) \quad (7)$$

$$L_{setting} = \sum_{i=1}^{m} h_{\max,i} - h_{\min,i} \quad (8)$$

where $h_{max,i}$ and $h_{min,i}$ are the maximum and the minimum lengths that the pins are moved in row i and m is the number of rows.

(v) Simultaneous movement of matrix of pins
This strategy moves all the pins of the matrix at the same time. Therefore, it is the method that requires the least time, which is the time required to set the pin that has to be moved through the maximum distance. In this case the length of the setting movement is obtained from Eqn. (9).

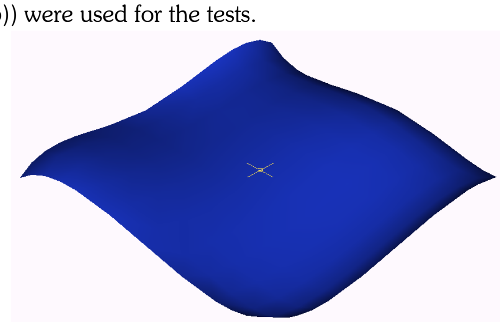
$$L_{setting} = h_{\max} - h_{\min} \quad (9)$$

The way to compare the methods is by calculating the approximate time to set the entire matrix. The total time, t, can be calculated from Eqn. (10) given the rapid and normal feedrates $V_{traverse}$ and F.

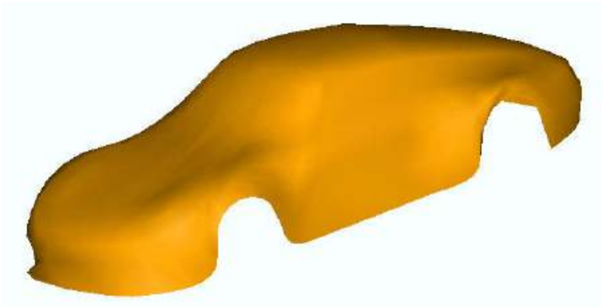
$$t = \left(\frac{L_{rapid}}{V_{traverse}} \right) + \left(\frac{L_{setting}}{F} \right) \quad (10)$$

5. IMPLEMENTATION, TEST RESULTS AND DISCUSSION

The reconfiguration system described in section 4 has been implemented in C++ as part of the UMIST CAD/CAM test bed using Spatial Technology ACIS 3D geometry modeling Kernel. A bi-cubic surface termed “wiggle” and a car model (shown in Fig. 4(a) and Fig. 4(b)) were used for the tests.



(a) Surface model of “wiggle”



(b) Surface model of a car

Fig. 5. Surface models used as test components.

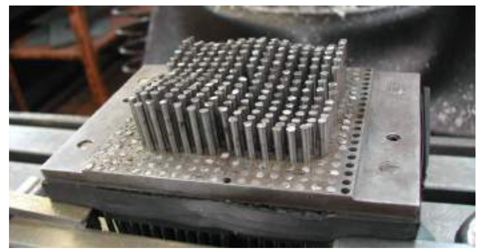
The intersection points were used to generate the NC code for the Denford TRIAC machine. The times required for configuring the tool for the five tool path strategies are shown in Tab. 1 and the set positioning pins for the wiggle and the car model are shown in Fig. 6(a), Fig.6(b) and Fig. 11 respectively.

Method	Configuration time [min]	
	Wiggle	Car model
Pin-to-pin zig	280.46	288.67
Pin-to-pin zigzag	108.59	116.82
Pins height differential	5.36	4.29
Simultaneous row of pins	0.51	0.31
Simultaneous matrix	0.05	0.05

Tab. 1. Time for reconfiguring RRT using different strategies.

It was found that the rubber exerted enough gripping force on the pins and thus preventing their slippage. These results demonstrate the ease of setting and clamping the positioning pins. As an alternative method, the positioning pins for the car model were set with a manual press. However, the accuracy could be influenced by human error. Using the pin to pin movement, the time for configuring the tool was nearly 5 hours. This manual setting method demonstrates that simple surfaces used for fibre-reinforced plastic moulding and other manufacturing processes that do not need a precise mould, can be configured without the need for a CNC machine or an actuator in a reasonable time.

(a) After position (4,16)



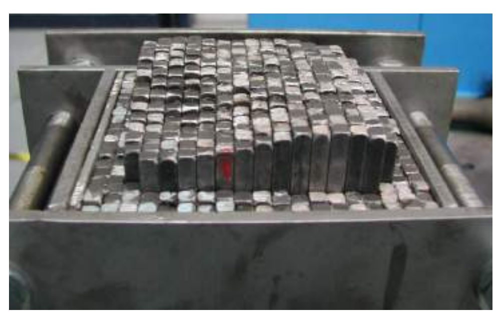
(b) After completing the positioning

Fig. 6. Positioning the pins on a CNC Machine.

The positioning pins sub-assembly was attached to the back end of the upper matrix of pins and the clamping force was applied using the clamping screw. The results are shown in Fig. 7(a) and Fig. 7(b) for the car model and the wiggle.

Punch Die

(a) Car model



(b) wiggle

Fig. 7. Upper pin matrix for car model and Wiggle.

The performance of the tool was investigated when it was used for carbon fibre and thermoplastic moulding and sheet metal forming. The carbon fibre cloth was spread directly over the tool which was previously coated with a de-moulding grease. Five layers of carbon fibre were applied with a resin. As shown in Fig. 8, a carbon fibre mat easily removes the scallops in the concave and convex regions of the formed shape.

Fig. 8. Carbon-fibre moulding for car model.

This result clearly demonstrates the potential of using the reconfigurable tool in the manufacture of products made of fibre-reinforced composite materials. Compared to other rapid tooling methods which consume materials and take much longer time to fabricate, the time taken for re-configuring and fabricating a component is reduced to 3 hours with the zigzag strategy and does not require special skills. Even when the pins for the car model were set manually, the accuracy of the result obtained from measurements in a cross section plane using a coordinate measuring machine (CMM) shows (Fig. 9) errors of less than 1 mm for most part of the profile. Errors of more than 1 mm occurred in the front part of the shape due to errors in laying the carbon fibre in this region.

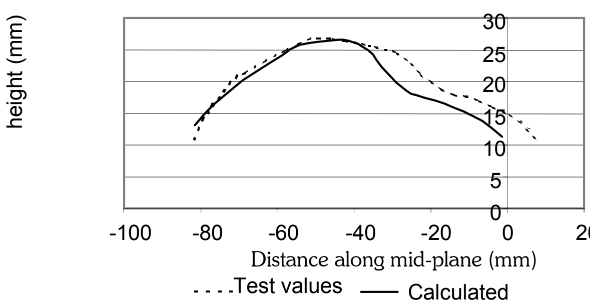


Fig. 9. Accuracy of surface in the car model.

The second part, i.e. the wiggle, was formed using an aluminium sheet, 0.5 mm thick. The tools were back-filled in order to increase the maximum load. No wrinkles or other effects were observed. This was probably because the surface of the wiggle does not have sharp changes in curvature. Spring back behaviour was observed, as can be seen in detail in Fig. 10. One way to overcome this would be to carry out a finite element analysis to predict the spring back and then adjust the pins accordingly.

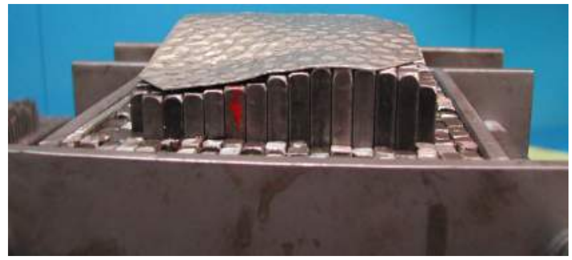


Fig. 10. Sheet metal forming for "wiggle" surface.

Two ways by which the tool can be scaled to a large size have been mentioned earlier in section 3. One of these ways which involves tiling many positioning pins sub-assemblies is demonstrated in Fig. 11. The second method in which many shapes made by the tool are glued together to obtain a larger size is illustrated in Fig. 12 for the car model when it is scaled to twice its earlier size. The shapes were made from the tool in a proprietary thermoplastic referred to as "polymorph" [5]. The polymer softens in hot water and hardens as it cools.

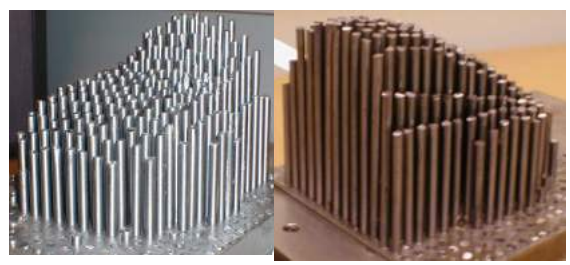


Fig. 11. Positioning pins for front and back of car model.

Fig. 12. Car model in original size and when scaled up by 2.

6. CONCLUSIONS

The paper has demonstrated the feasibility of the reconfigurable tool as a low-cost rapid tooling method. The possibility of using the reconfigurable tool for carbon fibre moulding, moulding in thermoplastics and sheet metal forming has been demonstrated. Of the tool path strategies proposed and evaluated, the pin height differential method resulted in the minimum tool path for positioning the array of pins; moreover, it is easy to implement. Experiments have also demonstrated that scalability of the tool to large size products can be achieved.

6. REFERENCES

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