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Influences of process and material parameters on quality of small-sized thin sheet-metal parts drawn with multipoint tooling

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Abstract

Multi-point tooling forming is one of the special categories of sheet metal forming techniques with good operational flexibilities due to using two sets of adjustable pins along the machine ram direction (vertical direction usually), which represent the acting points of desired forming-tool surface contours. Nevertheless, some defects may develop during forming under different process and machine-set conditions, such as wrinkles and undesired surface indents. This paper presents a study of the influences of possible process variations by adjusting the tooling as well as associated quality control when thin sheet-metals were drawn into the cap-type parts, being focused on the small-sized components. Effects of the curvatures to be formed, sheet material and geometry, holding force, lubrication condition and use of rubber as cushions on the formed component-geometry and surface quality have been investigated. The formed parts were measured with a Co-ordinate Measuring Machine and observed on the indentation with a high resolution Camera. The results showed that careful control of the process parameters and machine setup for the forming of thin sheet-metals for a particular type of the material and geometry is needed prior to the forming production uses with multi-point tooling forming, and use of rubber cushions and proper design of blank-holding are extremely important for successfully forming thin, small sized sheet-metal components with discrete pin-tools.

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1. Introduction

Sheet metal forming plays an important role in various fields of applications, e.g., producing complex three dimensional shape parts, good surface finish and lightweight structures. Nevertheless, for some processes where the shaped die-surfaces will have to be provided, these forming dies are often fixed to specific die-surface shapes, lacking certain flexibility for reuses and re-configurations. Multi-point forming technology is regarded as a flexible-tooling technology for sheet forming with high flexibilities through adjusting its two sets of movable pins (upper and lower set in vertical direction usually) to desired heights, forming a continuous three-dimensional tooling contour. The idea was first presented by Nakajima [1] in 1969, using a die with height adjustable wires on a numerical control milling machine. Following this concept, Nishioka [2] improved the concept by introducing a universal press with two sets of multiple piston heads in vertical upper and lower direction, giving a discussion on the surface quality of large sheets of metal, based on local heating methods. Since 1990, reconfigurable discrete dies of sheet metal forming were developed by Hardt and co-workers [3, 4], these dies being configured to desired forming surfaces under the control by a numerical control machine. At the same time, the concept of “multi-point forming” was first presented in 1992 [5], and the first automated system using multi-point forming based on repeated forming principles was proposed in 1999 [6]. Generally the multi-point forming process is known as multi-point die forming and prescribed deformation path forming, depending on whether the positions of pins are varied or not during the forming process [7]. In this study the heights of pins were adjusted prior to the tests, based on the design shape, i.e. multi-point die forming.

Usually each set of pins consist of matrices of dome-like punches which must be packed as tightly as possible, only with very little clearance. The pin size should be selected carefully as it has been proven that the occurrence of defects has a negative relationship with the surface area of contact spots [7]. Indentations can be reduced by the use of cushions and wrinkle can be suppressed to some extent by applying blank holders since an in-plane tensile bias can be produced by binding the material at the edges [8]. However, during the forming process, some undesired defects including wrinkles and indents could be an unavoidable phenomenon. Abosaf et al. determined some of the optimum process parameters, using finite element modelling and analysis [9].

Since many studies have been conducted on the superiority of multi-point forming, the focus of this study was examination of a multi-point forming process for the forming of miniature sized components with thin aluminum and steel sheets, when it is applied to deep drawing. In this work, a simple variable method was used to study the influences under different variable conditions, i.e. variations of the depth of curvatures, sheet material selection, holding force, surface lubrication, and use of rubber as cushions. A deep drawing with multi-point tooling test machine was developed for this study. Both the sheet wrinkles and indentations were observed and a relationship to the process variables was established. In this paper, process of the experiment is described and the results presented, being followed by describing the measurement method and the analysis carried out. Finally, the conclusions are drawn from the results and discussion.

2. Material, equipment and design of experiment

Fig. 1 shows a multi-point forming test rig which is newly developed in the University of Strathclyde to study possible material and process variations and associated quality and control when thin sheet-metals are drawn into various shapes, being focused on the small-sized components and thin sheets. The multi-point tooling system consists of 23 tightly packed adjustable dome-like pins for each punch-set. Four blank holders were used to control the sliding of the sheet metal along the surface of the die-plate. Effects of the curvatures to be formed, sheet material and geometry, holding force, lubrication condition, and thickness of rubber cushions, on the formed component-geometry and surface quality, have been investigated, to quantify their influences on the final finished sheet-metal parts. For the experiment, aluminum alloy 1050 and low carbon steel sheets with the thicknesses of 1.0 mm were used as the raw materials, each being cut into the size 200.0 mm x 200.0 mm. Sheet metal cap parts with two different dome-like finish-curvatures were formed the depth of which at the center were 8.0 mm and 16.0 mm respectively.

In order to make pre-adjustment the height of pins more conveniently, 3D printed sample parts with identical curved surfaces were used as reference surfaces to align the pin heights. This approach represents an economic and fast way to pre-set the pin heights to match representing surface contours.



Fig. 1. Multi-point forming test rig used for experiment reported.

Table 1. Main material/process/tool variables

Blank Material	Lubrication	Rubber thickness	Spring strength	Curved surface depth formed
[+] Aluminum	[+] Applied	[+] 8 mm	[+] 8.79 daN/mm	[+] 16 mm
[-] Steel	[-] Not applied	[-] 4 mm	[-] 3.8 daN/mm	[-] 8 mm

The holding force was varied by varying holding springs, with the spring strength of 8.79 daN/mm and 3.8 daN/mm respectively used. The holding springs were pressed and holding force increased during the process. A type of multi-purposes cutting oil was applied to the interfaces between the blank and the die-plate for the lubrication purpose. Polyurethane with thickness of 2.0 mm and 4.0 mm were chosen as the elastic cushions with good hyper-elastic property. During the tests, both sides of the sheet plate were covered with the cushions. The main variables are given in Table.1, with plus and minus for a contrast.

Before the tests, the machine was set to the pre-defined stroke ensuring that depth of the curved surface to be controlled to enable the specific finish curvature to be achieved. Lubricating oil was cleaned after each test to ensure the similar surface contact condition to be used for a following test.

3. Results and discussion

The formed sheet metal parts were measured with a Co-ordinate Measuring Machine and the indentations on the surfaces were observed with high resolution camera. 19 x 19 evenly distributed points were measured consecutively and the co-ordinates of on specific lines were plotted to illustrate the surface curvatures. Wrinkles and indentations were observed from the photos taken by high resolution camera, indicating the relationship of these to the influences from different process and material parameters.

Since there were two different combinations for each of the five kinds of material, tooling and processing parameters, a combination of 16.0 mm curved surface depth aluminum sheet with lubrication applied, a total thickness of 8.0 mm rubber cushion, under a spring stiffness of 8.79 daN/mm for holding force, was used as the base model for each comparison group, i.e. all process variations with plus remarks. A total of 6 test sheets have been measured and the Z-axis co-ordinates across the center line profile of X-axis and Y-axis have been plotted to

investigate the finish surface deformations. Taking the ideal 3D printed dome-like surface in Fig. 2 as a reference surface, in each group the shape error z_{error} was used to determine the difference at every contact point of the center line contour, integrating the average shape error E_{error} for each metal sheet. These parameters are defined as follows, being similar to that reported in [10-12]:

$$z_{error} = z_{3Dtest} - z_{exp} . \quad (1)$$

By calculating the root mean square value of error above between the 3D-printed dome-value and the test piece surface with different thicknesses, the average shape value, E_{error} , can be given as:

$$E_{error} = \sqrt{\frac{1}{N} * \sum_{i=1}^N (z_{i3Dtest} - z_{iexp})^2} , \quad (2)$$

where N represents the total number of the measured points. It should be noticed since the shape error can be affected by the wrinkles, only the values of the deformed surface were calculated.

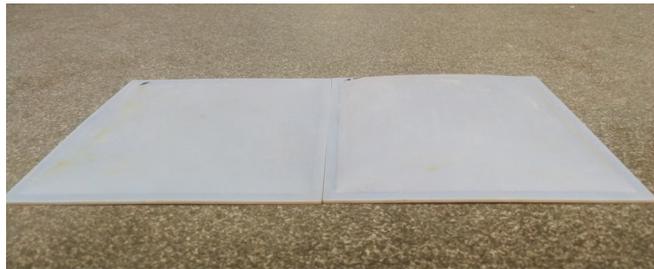
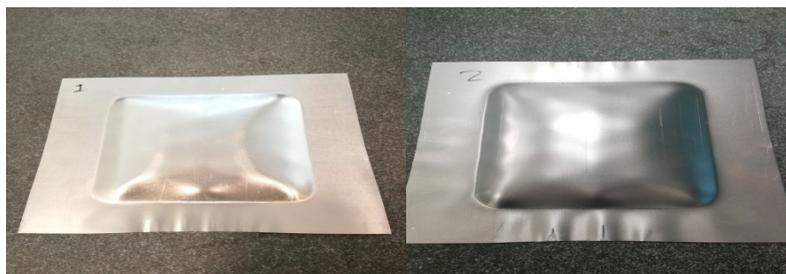


Fig. 2. 3D printed dome-like surfaces (8.0 mm and 16.0 mm depth).

3.1. Effect of blank material selection

To study the effect of the material property, the experiment was conducted using aluminium alloy and steel sheets with the thickness of 1.0 mm, under the similar conditions. Two formed metal sheet parts are shown in Fig. 3. More wrinkles and indentations were found in steel sheets as seen in Fig. 3(b), while aluminium sheets perform smoother surfaces, and these may be related to the differences of the material's plasticity, yield strength, etc., and hence, the drawing ability of those two materials.

Fig. 4 presents the surface profiles drawn based on the points measured in the vertical direction along the centre line of X-axis and Y-axis respectively. The two profiles are similar, due to the similar plastic deformation was enabled during the experiment, which followed the profiles set by the pins. The calculated average shape error for aluminium sheets along of central line are 1.085 mm and 0.775 mm along X-axis and Y-axis respectively, while these were 1.105 mm and 1.005 mm for steel sheets. In general, these are similar, with the steel parts have slightly more shape errors, which may be counted for combined effects from the materials' yield strength, Young's modulus as well as deflection amount of the tooling due to the forming force difference, etc.



(a)

(b)

Fig. 3. Two parts formed: (a) aluminum part and (b) steel part.

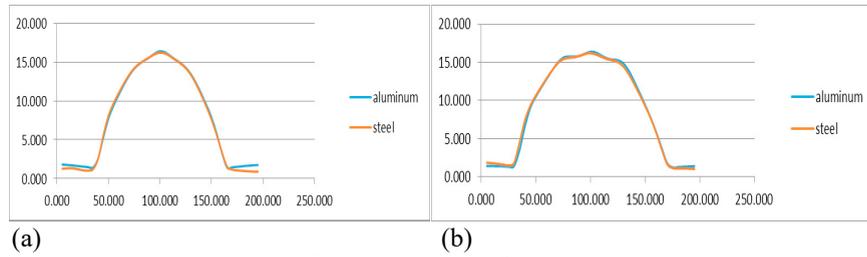


Fig.4. Z-axis direction measured profile of Aluminum and Steel parts: (a) along X-axis (b) along Y-axis.

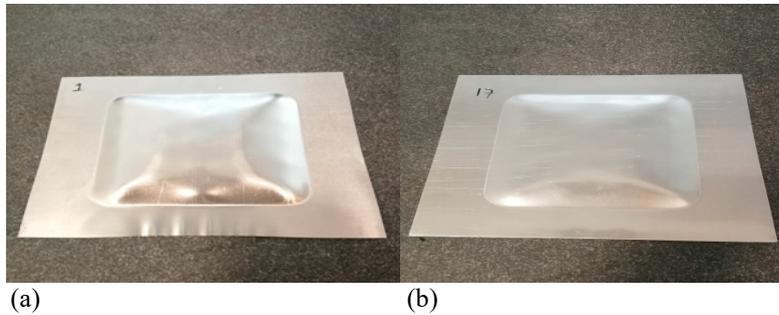


Fig.5. MPF formed aluminum parts with: (a) 16.0 mm depth curvature, and (b) 8.0 mm depth curvature.

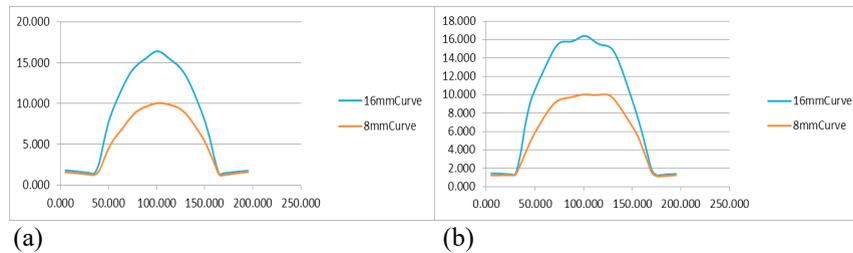


Fig.6. Z-axis direction measured profile with different curvature depths: (a) along X-axis and (b) along Y-axis.

3.2. Effect of depth of curvature formed

Fig. 5 shows the formed Aluminium sheet parts with a curvature depth of 16.0 mm and 8.0 mm respectively. The one with 8.0 mm depth shown in Fig. 5(b) has a better finish surface, regarding both wrinkles as well as indents, because more forces and deformations were applied to the sheet with the deeper curvature. The average shape error value confirmed this by giving 0.804 mm and 0.400 mm at the central line in the x direction and y direction respectively for the part (b), where these are 1.085 mm and 0.775 mm for the part (a) respectively, as illustrated in Fig. 6. Careful attention should be paid when deeper and steeper surfaces are to be formed in multi-point tooling forming while an error compensation should be considered when the pin heights are pre-set initially.

3.3. Effect of thickness of elastic rubber cushion

During the multi-point forming process, elastic rubbers have been used between the pin tools and the sheets to reduce the dimples and indentations. More indentations can be observed for the sheet part with a total of 4.0 mm thick cushions, as shown in Fig.7(b), comparing to that with 8.0mm thick cushion (shown in Fig. 7(a)), this showing that increasing the thickness of the cushion could reduce the occurrence of surface indents. Nevertheless, shallow wrinkles were still found on the both sheet parts, since the cushions did not cover the blank-holding areas. Fig.8 also illustrate that the center profile corresponding to the 8.0 mm cushion is slightly larger in off-line than that with 4.0 mm, this may be due to a larger forming force applied to achieve a similar shape while the cushion is thicker and the tools were deflected more.

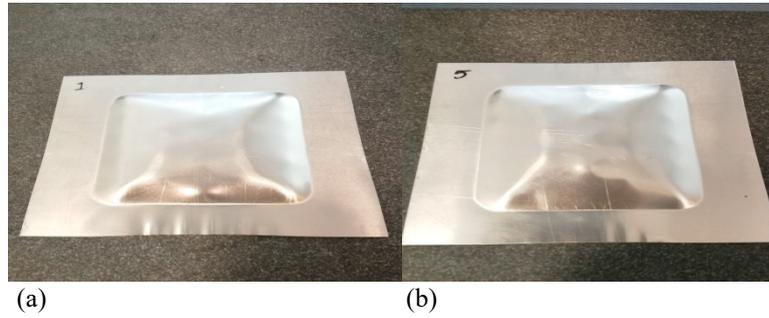


Fig.7. Part formed using: (a) 8.0 mm thick rubber and (b) 4.0 mm thick rubber.

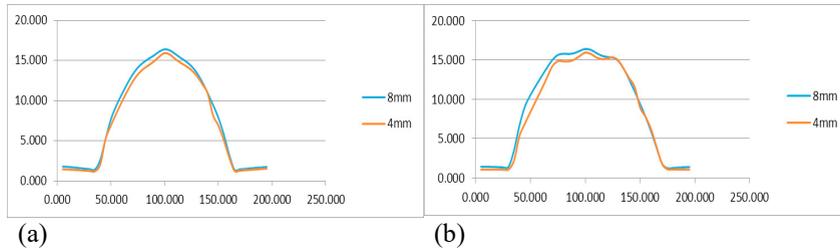


Fig.8. Z-axis direction measured profiles for two different rubber thicknesses: (a) along X-axis and (b) along Y-axis.

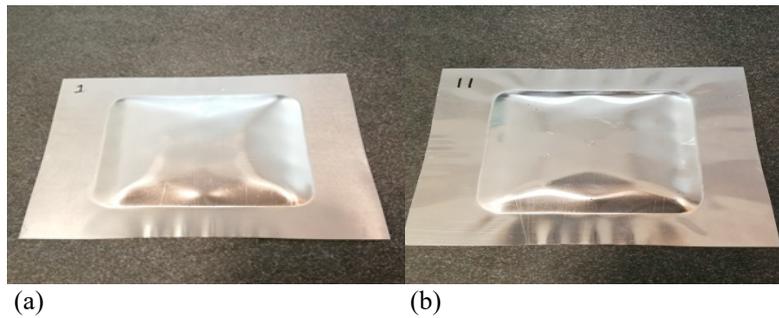


Fig.9. Parts formed with different spring stiffness values: (a) 8.79 daN/mm and (b) 3.8 daN/mm.

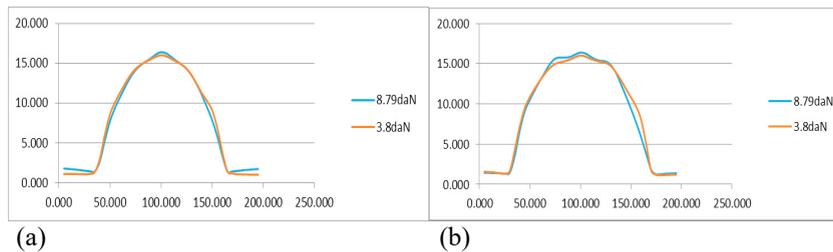


Fig.10. Z-axis direction measured profiles with different spring stiffness values (a) 8.79 daN/mm (b) 3.8 daN/mm.

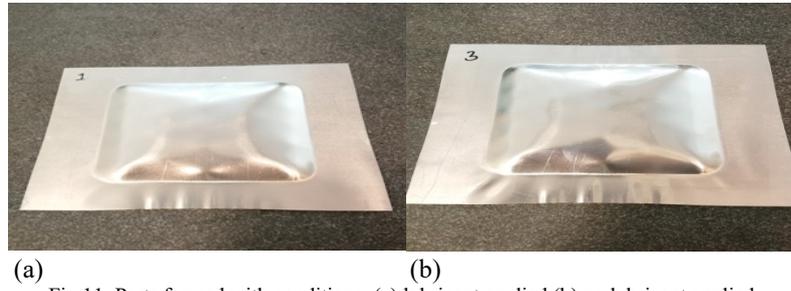


Fig.11. Parts formed with conditions: (a) lubricant applied (b) no lubricant applied.

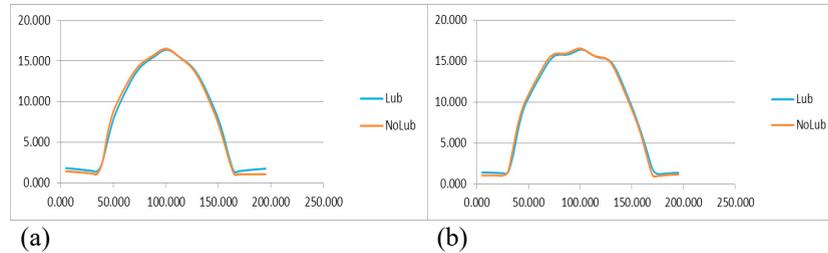


Fig.12. Z-axis direction measured profile with and without lubrication: (a) along X-axis and (b) along Y-axis.

3.4. Effect of holding force

The effect of the holding force was examined through the reaction force on the supporting springs with different stiffness values. The sliding of the blank material was restrained during the forming in order to achieve better drawn parts. The photos shown in Fig. 9 demonstrate the importance of using correct holding force to reduce or eliminate the occurrence of wrinkles along the flanges of workpiece while the surface quality of the drawn part could also be improved (Figs. 9 and 10). At the same time, overstretching the sheet metal should also be avoided in order to reduce the fractures to develop in the indented areas, if the cushion is to be used is too thin. This shows that an optimal combination of the material, tooling and process parameters is needed for a particular part to be formed. It is especially the case for forming of thinner sheet metals and with relatively large pin-tool sizes when miniature components are to be formed. The pin-size will be restrained not to be too small due to the manufacture and assembly considerations, even the part-size to be small is required.

3.5. Effect of lubrication condition

A multi-purpose cutting oil was used to perform lubrication between the blank and die-plate. It looks that the wrinkles could be slightly reduced at the edge due to using the lubricant (Fig. 11), which may be due to more uniform holding force is applied onto the blank. It may also be affected by the surface quality of the blank and the die-plate the condition of which could be improved by introducing a lubricant. The influence seems not to be too significant in the dome area formed since no lubricant was applied to the area (Fig. 12). The average shape error is similar but slightly reduced under the lubricating condition, from 1.090 mm to 1.085 mm in the x direction and 0.982 mm to 0.775 mm in the y direction, which may be due to the reduction of the forming force when the lubricant was applied.

4. Conclusions

Combining deep drawing and multi-point tooling has been tested for the forming miniature sized, thin metal parts with a view to extending merits of the multi-point tooling forming technique for sheet metal forming. The following conclusions may be drawn from the study described above:

- Combining multi-points tooling into a deep drawing process could potentially bring benefits for process and tool flexibility for deep drawing. But the quality control has to be addressed as an important issue since the sheet metal deformation mechanism becomes more complex.
- For the process configuration tested, under the similar conditions, a better surface finish was achieved for the aluminium sheets, comparing to that for the steel sheets. This may be due to that the drawing force applied through the multi-punches used for the forming of the aluminium sheets was relatively smaller than that for the steel sheets.
- The depth of the curvature to be formed has a significant effect on the surface finish, i.e. wrinkles and indents may occur where large or steep deformations take place. The average shape-error was reduced significantly from 1.085 mm and 0.775 mm in X and Y axis directions, respectively, when 16.0 mm curvature depth was formed, to 0.804 mm and 0.400 mm respectively, when 8mm depth formed.
- Using cushions is extremely important for forming thin sheet metal parts when multi-points tooling is used, which is even more important when it is used in deep drawing due to the deeper curvatures being formed, comparing to simple bending and low-level deformation stamping involving multi-point tooling.
- As a common knowledge, correct holding force is important for deep drawing. It can, nevertheless, be said to be crucial for ensuring a high quality product, considering that the contacts between the punches and the sheet metal are not uniformly distributed, even the cushions have been used, which leads to more complex stretching and local deformation mechanisms.
- Using lubrication could help to improve the material flow and to reduce the forming force requirement. The tested cases show that an average shape-error 0.108 mm and 0.31 mm reduction achieved along the two central lines for the 16.0 mm depth curved surface formed, when a lubrication oil was introduced, comparing to that with non-oil used.
- Using 3D printing to create a model sample part to help pre-setting the multi-points tooling is an efficient approach for practical uses for multi-points tooling forming.

Further tests on the different part-geometries and materials will be conducted, with focus on the thinner sheet-metals and small sized components. The aim is to produce a design and manufacturing guideline for the forming of such types of components with deep drawing with a flexible tooling configuration.

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