MATHEMATICAL MODEL FOR DETERMINING THE FORCES IN SINGLE POINT INCREMENTAL FORMING

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ABSTRACT: Incremental forming of sheet metal is a flexible technology to produce metal parts by moving a punch with the help of CNC systems. This process is slow, but has lower costs because there are not necessary dedicated punches and dies, thus making it very suitable for the production of small series and single parts. The purpose of this study was to investigate the influence of geometrical parameters on the forces on two directions during the single point incremental forming process and to elaborate mathematical models for determining the forces. For this purpose, the authors have chosen a pyramid frustum-shaped part. The parameters taken into account are the punch diameter and the step. The authors have carried out tests on two different materials: DC04 steel and AA6016 aluminium. To determine the forces, a dynamometer was used. Conclusions regarding the influence of geometrical parameters on the forces are also presented.

KEY WORDS: single point incremental forming, experimental research, sheet metal, force measurement

1. INTRODUCTION

Usually, in sheet metal forming, punches and dies are manufactured to be close to the desired part's geometry. In the last years, some new sheet metal forming processes have been studied, such as laser forming (Cheng, 2005), water jet assisted forming (Jurisevic, 2006), hammering with robots (Schafer, 2005) or incremental sheet forming with a small indenter. With these processes, it is possible to form sheet metal parts without manufacturing specialized dies and punches. The most studied process is incremental sheet forming (ISF) with a small indenter. There are two types of incremental sheet forming with a small punch, single point incremental forming (SPIF), which use a single punch and two points incremental forming (TPIF which uses besides the small punch a male or female die, a support post or a second indenter. In both cases, the tool follows a 3D path described by a CNC program. In this metal forming process the tool produces small localized plastic deformations in the area under the punch. This process is very flexible because for a new part it is enough to change the CAM program. It is suitable for small-batch production and for rapid prototyping applications.

The latest research in the area includes studies investigating the possibility to form new materials through ISF, like sandwich panels, which have ductile and largely incompressible cores (Jackson, 2008), tailored blanks produced by friction stir welding (Silva, 2009). Other research directions are the optimization of tool path in two single-point incremental forming (Attanasio, 2006), to increase the geometrical accuracy of the parts by using an offline model derived from an online sensors-based strategy (Meier, 2009) or to investigate suitable tools and lubricants for processing a pure titanium sheet (Hussain, 2008). There are also researches that use multi-step tool paths to obtain parts with vertical walls (Duflou, 2008) or to investigate hybrid processes, combinations of ISF with stretch forming.

This paper intends to determine the influence of geometrical parameters on the forces and to elaborate mathematical models that would allow the determining of forces in the process.

2. EXPERIMENTAL EQUIPMENT

Due the process complexity and to the inexistence of a specialized machine for this metal forming process, the authors conducted the experiments on a DMG Veco 635 CNC milling machine. The experimental testing installation is composed of the CNC milling machine, the dynamometer and the forming equipment. The data acquisition system is composed of four modules: the transducers (a force transducer for the z direction and a force transducer for the x direction, consisting of HBM 350XY11 tensometric devices) placed on the two rings of the dynamometer, the signal conditioning modules, the analogous-digital conversion device (KPCI 3108, Keithley Instruments Inc.) and a
software package that controls the acquisition system and processes the collected data (Matlab).

The forming equipment was installed on the CNC. It is composed of a bottom plate on which there are two brackets that support the die, a die and a blankholder ring.

Dies have various shapes such as circular, square, triangular and other. In order to measure forces on two directions (the vertical advance direction z and a direction in the sheet's plane, x), a dynamometer was installed under the forming equipment. To produce the pyramid frustum parts, a square die with an inside side length of 60 mm and 6 mm fillet radius was used. To move the punch, a feed rate of 240 mm / min with a horizontal punch rotation speed of 180 rpm was used.

To reduce friction at the contact between the punch and the material, forming lubricant was used. The materials chosen for the production of parts are DC04 steel of 0.9 mm thickness and AA6016 aluminium of 0.8 mm thickness, cut into squares of 120 mm side length. The mechanical characteristics of the two types of sheets were determined on a tensile test machine Roell RKM & Korthaus 100/20. The obtained data are presented in table 1.

<table>
<thead>
<tr>
<th>Thickness [mm]</th>
<th>K [Mpa]</th>
<th>n</th>
<th>εu [%]</th>
<th>R00</th>
<th>R45</th>
<th>R90</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>447</td>
<td>0.21</td>
<td>27.3</td>
<td>0.71</td>
<td>0.46</td>
<td>0.47</td>
</tr>
<tr>
<td>0.9</td>
<td>524</td>
<td>0.18</td>
<td>47.4</td>
<td>1.34</td>
<td>1.02</td>
<td>1.58</td>
</tr>
</tbody>
</table>

3. EXPERIMENTAL RESEARCHES

The object of this study was to determine the force during the single point incremental forming process, on two components: a vertical one and a horizontal one. For this, the authors selected a pyramid frustum-shaped part.

Figure 2 summarizes the punch trajectories to achieve a pyramid frustum-shaped part through single point incremental forming. Penetration into the material was done in the same place, in a corner. After the punch entered with a step on z direction, it performed a rectangular move on the xOy plane. The pyramid frustum has a height of 10 mm and a base side length of 46 mm.

For this test, the authors selected as influence factors the punch diameter and punch penetration depth on vertical direction. The selected independent variables, the variation domain and their variations levels are presented in table 2.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Natural units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical step (mm) pz</td>
<td>0.25 0.5 1</td>
</tr>
<tr>
<td>Punch diameter (mm) dp</td>
<td>6 8 10</td>
</tr>
</tbody>
</table>

Following objective functions of the single point incremental forming process were taken into account: the maximal forming force on the z direction – perpendicularly to the sheet metal and the maximal forming force on x direction – a direction in the sheet's plane.

For determining the two forces, the authors used a $3^2$ factorial program with the help of response surfaces method in which the independent variables have been modified at three variation levels. A polynomial model has been chosen, because of the mathematical processing facilities which it implies.

Following the parts' measuring, it was noticed that, for the variation domains of the two independent variables, the value of the considered parameters vary within the limits: $F_{z\text{max}}=180.3-439.1$ N and $F_{x\text{max}}=922-1708$ N for the DC04 sheet and $F_{x\text{max}}=177.3-420.8$ N and $F_{z\text{max}}=555.4-1106$ N for the AA6016 sheet.

The mathematical models resulted for the two measured forces for both materials are:

- DC04 sheet
  
  \[ F_{x\text{max}} = 162.711 - 17.554dp + 339.476pz + 2.204dp^2 - 29.893dppz + 147.644pz^2 \]
\( F_{x_{\text{max}}} = 913.211 - 60.642 dp + 455.676 pz + 2.379 dp^2 - 72.657 dppz + 209.9 pz^2 \)  
(2)

- AA6016 sheet

\( F_{x_{\text{max}}} = 108.744 - 1.604 dp + 498.562 pz + 1.029 dp^2 - 53.179 dppz + 109.244 pz^2 \)  
(3)

\( F_{z_{\text{max}}} = 839.644 - 122.058 dp + 273.18 pz + 8.783 dp^2 - 51.786 dppz + 182.4 pz^2 \)  
(4)

Figure 3. Forces on x direction for 0.9mm DC04 sheet for a 10mm punch diameter and 1 mm vertical step

Figure 4. Forces on z direction for 0.9mm DC04 sheet for a 10mm punch diameter and 1 mm vertical step

The graphic spatial display of the connections between each influence factor and the two response functions \( F_{x_{\text{max}}} \) and \( F_{z_{\text{max}}} \) is given in figure 5 for the DC04 sheet and in figure 6 for the AA6016 sheet. We can observe that with an increasing vertical step, forces increase on both directions for both materials types. The reason for this increase is that the punch has a higher contact area in the local deformation area at higher punch steps. With an increasing punch diameter the forces on z direction increase for both material types, but on x direction, for lower punch steps, as the punch diameter increases, forces increase as well, while at higher punch steps, as the punch diameter increases, forces decrease. This phenomenon can be explained by the fact that a small punch penetrates the material deeper than a big punch at higher vertical steps and on x direction the contact is larger for a small punch and at lower vertical steps on vertical direction both punches have a small contact area on x direction and the forces on x direction are larger for the bigger punch because of its larger contact area.
4. FEM ANALYSES

In addition to the experimental researches, the authors conducted two finite element analyses, one for each material type. Both analyses were made with a very fine mesh. For this we used the general-purpose finite element software LS-DYNA. LS-DYNA has eleven different formulations available for the Shell 163 element used in this numerical simulation. The authors selected in this case the Belytschko-Lin-Tsay formulation because it is fast and uses the reduced integration method. For the material model, the authors used an anisotropic elasto-plastic model definition: Barlat's 3rd parameter. The part, discretized as a shell, deformable body, is composed of 57600 thin-shell-163-type elements. The material associated with the part’s elements is presented in table 2, the mechanical characteristics being introduced like pairs of points true stress - true strain. The modelled forming system is composed of the punch, a die and a blankholder ring modelled as rigid bodies and a rectangular material blank. The movement of the punch is the same as that shown in figure 3.

Figure 7 presents the forces for a DC04 sheet, formed with a 10 mm punch and 1 mm vertical step. The results are in very good agreement with those obtained experimentally.

5. CONCLUSIONS

In the case of determining the forces, the most influential factor to consider is the step on z direction. The larger the step, the larger the forces are too. The punch diameter has a smaller influence on the forces' size and as in the step's case, the higher it is, the larger the forces are on z direction, while on x direction a small punch produces larger forces at higher vertical steps and a big punch produces larger forces at lower vertical steps.

The FEM analyses are in very good agreement with the experimental researches.

6. ACKNOWLEDGEMENTS

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7. REFERENCES