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EXPERIMENTAL ANALYSIS OF SINGLE POINT INCREMENTAL FORMING OF TRUNCATED CONES IN DC04 STEEL SHEET

ABSTRACT

Experimental tests to form truncated cones were carried out on a 3-axis milling machine. 0.8-mm thick low-alloy DC04 steel sheets were used as test material. The profile tool-path trajectory was generated using the EDGECAM software. The slope angle and diameter of the base of the conical shaped drawpieces were 70°-72° and 65 mm, respectively. The drawpiece heights were up to 75 mm. The full synthetic lubricant 75W85 was used to reduce the frictional resistance. The effect of selected incremental forming parameters on the formability of the DC04 sheet and the susceptibility to crack formation have been analysed and discussed. It was found that the surface roughness of the workpiece is strongly influenced by step depth. By controlling the feed rate, it is possible to prevent failure of the material.

Keywords: *FEM; incremental forming; numerical modeling; SPIF; truncated cone*

INTRODUCTION

The main advantages of single point incremental forming (SPIF), which is a very flexible sheet forming process, are [1, 2]: no need to manufacture the dies, the ability to shape elements on a conventional numerically-controlled milling machine, a much lower forming force compared to conventional deep drawing, flexibility of production, a higher value of sheet deformation in relation to die forming, and that constructional changes in the formed elements can be quickly and easily taken into consideration [3-5]. Incremental forming technology is characterised by a few limitations compared to the conventional sheet forming methods, like a low geometric accuracy of elements, significant springback of the drawpieces, longer duration of forming times and the economic justification for it when using it in small-lot production [6].

In SPIF the rotatable tool, which can be attached to a computer numerical control (CNC) machine, indents into the sheet by depth steps and follows a contour for the desired part. It then indents further and continues to draw the next contour until the desired shape is formed. The following are some of the important process parameters in SPIF: forming angle, tool geometry, step size, tool rotational speed, feed rate and lubrication.

Many studies have been conducted to study the incremental sheet forming (ISF) process. Kurra and Nasih [7] and Powers et al. [8] analysed the influence of several process parameters, such as type of lubricant, step size, feed rate, tool diameter and spindle speed on surface roughness. They observed a decrease in surface roughness and tool diameter with decreasing step size, but the type of lubricant and feed rate had no significant effect on surface roughness. Liu et al. [9] found that the thickness of the sheet affected the roughness of the surface the most, followed by tool diameter and feed rate. Li et al. [10] studied the effects of process variables on the power, forming time, and energy required for the SPIF process. The calculated powers used for sheet deformation during the forming process increase significantly with increase in step-down size and feed rate. Moreover, variation in sheet thickness and tool diameter have limited influence on the processing power consumed by the milling machine. Slota et al. [11] applied an X-ray diffraction method to achieve an understanding of the residual stress formation caused by the SPIF process of deep drawing a quality steel sheet drawpiece. It was found that the inner and outer surfaces, characterized by their average roughness values, was not significantly affected by step size. In the case of the outer surface, only a small increase in the S_a parameter is observed along the generating line of the cone. Schmitz et al. [12] investigated the effect of tool path as well as intrusion depth of the forming tool into the sheet material on the geometrical accuracy. They found that changes in the range of a tenth millimeter of the intrusion depth with a consistent tool path lead to different resulting part geometries.

A detailed review of the current state-of-the-art of ISF processes in terms of its technological capabilities and discussions on the ISF process parameters and their effects on ISF processes may be found in the works of Gatea et al. [13] and Behera et al. [14]. Maqbool and Bambach [15] quantified the respective contribution of each forming mechanism (i.e., bending, membrane stretching, through-thickness shear) involved in the SPIF process and the dependence of geometrical accuracy on the dominant deformation mechanism. Li et al. [16] presented a detailed literature review on the current research of ISF relating to deformation mechanism, modelling techniques and forming force prediction. Moreover, several potential hybrid incremental sheet-forming strategies have been discussed. There have been numerous investigations related to incremental sheet forming processes to improve the dimensional accuracy of the parts thus formed. Göttmann et al. [17] improved the geometric accuracy of formed parts by locally heating the workpiece by a laser beam. Fu et al. [18] developed a closed-loop toolpath correction algorithm for a part in the form of a truncated pyramid. The results show that the tool path correction algorithm is reasonable and the means using a finite element-based numerical simulation are effective. Bambach et al. [19] proposed a multi-stage forming strategy that reduced local springback in the final forming step.

In this paper experimental investigations have been carried out on truncated cones produced by single point incremental forming of DC04 steel sheet. The slope angle of the truncated cones and diameter of the base of the conical shaped drawpieces were 70° - 72° and 65 mm, respectively. The effect of the selected SPIF parameters on the formability of the DC04 sheet and the susceptibility to crack formation have been analysed and discussed.

EXPERIMENTAL

Material

Deep drawing DC04 quality steel sheets (acc. to EN 10130:2009) with a thickness of $t_0 = 0.8$ mm were used in the investigations. A chemical composition of DC04 steel sheet is listed in Table 1. Due to their specifically designed surface structure and excellent formability, DC04 cold rolled steel sheets are well-suited to the fabrication of complex, formed body parts like floor panels, spare wheel wells and auto bodies [20]. The mechanical properties of the sheets tested were determined according to the EN ISO 6892-1:2016. The selected mechanical parameters are listed in the Table 2.

Table 1. Chemical composition of examined DC04 steel sheet (in wt. %)

C, max	Mn, max	P	S
0.08	0.40	0.030	0.030

Table 2. Selected mechanical parameters of the sheets tested

Parameter	Specimen orientation		
	0°	45°	90°
Yield stress, MPa	185	194	176
Ultimate tensile stress, MPa	304	315	296
Elongation, %	23	22	23
Strengthening coefficient, MPa	490	490	466
Strain hardening exponent	0.21	0.16	0.17

Surface roughness of the as-received sheets and drawpieces were characterised by 2D main surface roughness parameters: roughness average Ra , maximum profile peak height Rp , root mean square roughness Rq , maximum height of the profile Rt , maximum profile valley depth Rv and average maximum height of the profile Rz . Measurement of the surface roughness parameters was carried out using a Surtronic 3+ profilometer. The failure characteristics and surface of the samples after the forming process were examined using the Phenon desktop scanning electron microscope (SEM).

Methodology

In the experiments, a rotational forming tool (high-speed steel) with a rounded tip gradually forms the sheet by performing an integrated movement around the blocked edge of the shaped object (Fig. 1). Workpieces of size 120 mm x 120 mm were placed in the stamping tool and were clamped along the edges (Fig. 2). The essence of the process is to form the element by the integration of two tool movements: the horizontal one along the closed trajectory; and the inward transition to the next horizontal forming path. Experimental tests were carried out on a 3-axis HAAS milling machine. The truncated cones with the wall angles of 70-72° were formed.

Fig. 1. Geometry of the forming tool

Fig. 2. View of the forming tool

Due to the complexity of the tool path (Fig. 3), the SPIF of metallic sheets is carried out on CNC machines that permit the use of a control program in order to fabricate any desired shape of part using the appropriate interpolation of tool movements. The profile tool-path trajectory was generated using the EDGE CAM software.

Fig. 3. (a) forming tool (a) and the tool path

During machining, the following processing conditions were applied: the incremental depths: 0.3, 0.5 and 0.7 mm, feed rates: 1100, 1500 and 1950 mm·min⁻¹, tool tip radius 3.5 mm, the tool rotational speed of the tool 87 rpm. Fully synthetic gear oil 75W-85 was used to reduce friction forces.

RESULTS AND DISCUSSION

The step size has little effect on the character of material deformation during one pass. In the case of truncated cones formed with feed rates 1100 and 1500 mm·min⁻¹, the same results were obtained. No defects have been observed (Table 3a, 3b). In the case of the feed rate of 1900 mm·min⁻¹, increasing the step size from 0.3 to 0.5 mm limited the possibility of forming the drawpiece with a slope angle of 71.5 (Table. 3c). For the smallest step size of 0.3 mm, cracking of the drawpiece at the edge of the cone apex was observed in the range of a slope angle of 71°-72° (Table. 3). Table 3 demonstrates very high angle sensitivity since for angle 70 degrees no fracture at none conditions and for angle 72 degrees fracture at all conditions - angles in the range from 70 to 72 sensitive to the forming conditions. All problem with forming conditions can be easily solved with 70 degrees or lower angle. Forming of the drawpieces in the ISF process with low feed rates increases the duration of treatment and is economically disadvantageous. In the case of the drawpieces formed with a step size 0.7 (Fig. 4a,b), clear scarring corresponding to the moving of the tool tip along the tool trajectory is clearly visible. Reduction of the step size, with constant rest parameters, caused elimination of the linear grooves (Fig. 5a,b).

Increasing the feed rate can lead to the wrinkling of the sheet in the area of deformation and may cause an accelerated susceptibility to cracking. It also has a very significant impact on the total processing time. Additionally, at high feed rates close to 2000 mm/min., surface scarring was observed as a result of the failure to transmit signals to the machine's actuators due to insufficient transfer capacity.

In the range of feed rates applied (1100-1950 rpm), this parameter was not observed to have any significant influence on the possibility of forming non-defective drawpieces. For each value of the feed rate (Table 3), fracture was mostly occurring at the corner of the part (Fig. 6a-c) due to the equi-biaxial stretching of sheet metal. The depth of the drawpiece h at which the failure of the wall of the truncated cone occurred was also similar for specific step sizes (3), i.e. 14-18 mm at a step size 0.3 mm and approximately 20 mm at step size 0.7 mm.

A test forming of the drawpiece in conditions of dry friction was carried out in order to study the effect of lubrication on the formability of the sheet material. While a truncated cone with a height of 75 mm was obtained in the lubrication conditions, in the absence of lubrication, the drawpiece failed at a tool depth of 41 mm (Fig. 6a). So, lubrication conditions clearly affect the formability of DC04 sheet. The effect of friction conditions on the surface finish is not studied in this paper.

The slope angle of the conical truncated drawpiece is a very important geometric parameter which permits the sheet metal to be formed correctly. Too large a slope angle causes the truncated cone to fail before reaching the desired depth $h = 75$ mm.

Table 3. Results of experimental tests realised at feed rates: (a) 1100 mm·min⁻¹, (b) 1500 mm·min⁻¹ and (c) 1950 mm·min⁻¹

(a)		Step size a_p , mm		
		0.3	0.5	0.7
Slope angle α , °	70	formed	formed	formed
	71	Fractured at $h = 16$ mm	formed	formed
	71.5	Fractured at $h = 18$ mm	formed	formed
	72	Fractured at $h = 15$ mm	Fractured at $h = 17$ mm	Fractured at $h = 20$ mm

(b)		Step size a_p , mm		
		0.3	0.5	0.7
Slope angle α , °	70	formed	formed	formed
	71	Fractured at $h = 16$ mm	formed	formed
	71.5	Fractured at $h = 16$ mm	formed	formed
	72	Fractured at $h = 16$ mm	Fractured at $h = 19$ mm	Fractured at $h = 20$ mm

(c)		Step size a_p , mm		
		0.3	0.5	0.7
Slope angle α , °	70	formed	formed	formed
	71	Fractured at $h = 16$ mm	formed	formed
	71.5	Fractured at $h = 14$ mm	Fractured at $h = 19$ mm	formed
	72	Fractured at $h = 14$ mm	Fractured at $h = 18$ mm	Fractured at $h = 20$ mm

Fig. 4. SEM micrographs of the surface finish of the (a) external and (b) internal surfaces of a truncated cone fabricated at $a_p = 0.7$ mm, $\alpha = 70^\circ$, $f = 1500$ mm·min⁻¹

Fig. 5. SEM micrographs of the surface finish of the (a) external and (b) internal surfaces of a truncated cone fabricated at $a_p = 0.3$ mm, $\alpha = 70^\circ$, $f = 1500$ mm·min⁻¹

Fig. 6. SEM micrographs of the fracture surface of drawpieces formed at: (a) $a_p = 0.5$ mm, $\alpha = 71^\circ$, $f = 1500$ mm·min⁻¹, dry friction; (b) $a_p = 0.5$ mm, $\alpha = 72^\circ$, $f = 1500$ mm·min⁻¹; (c) $a_p = 0.3$ mm, $\alpha = 71^\circ$, $f = 1500$ mm·min⁻¹

The selected parameters of the surface roughness of the internal and external surfaces of truncated cones formed at two step sizes are listed in Table 4. Surface roughness parameters were measured along generating line of truncated cones. The forming process increased the values of all surface roughness parameters on the outer surface of the drawpieces. The lowest values of main roughness parameters were observed for truncated cones formed at the lowest incremental depth $a_p = 0.3$ mm. In the case of the drawpieces formed at $a_p = 0.7$ mm a clear decrease in the main roughness parameters was observed on the inner surface of drawpieces. For the drawpieces formed at the incremental depths of 0.7 mm a clear linear grooves were observed on the surface as a result of the interaction of the tool tip with the workpiece. This phenomenon applies to both sides of drawpieces.

Table 4. The surface roughness of the internal and external surfaces of truncated cones

Type of surface	Source	$Ra, \mu\text{m}$	$Rp, \mu\text{m}$	$Rq, \mu\text{m}$	$Rt, \mu\text{m}$	$Rv, \mu\text{m}$	$Rz, \mu\text{m}$
external	As-received sheet surface	0.351	1.06	0.433	2.02	0.604	1.67
	Surface after forming at $a_p = 0.7$ mm, $\alpha = 70^\circ$, $f = 1500$ mm·min ⁻¹	3.05	7.02	3.87	22.1	10.6	17.6
	Surface after forming at $a_p = 0.3$ mm, $\alpha = 70^\circ$, $f = 1500$ mm·min ⁻¹	2.44	5.51	2.96	14.6	6.67	12.2
internal	As-received sheet surface	1.04	2.63	1.25	6.62	2.33	4.96
	Surface after forming at $a_p = 0.7$ mm, $\alpha = 70^\circ$, $f = 1500$ mm·min ⁻¹	0.83	2.13	1.04	5.85	2.52	4.65
	Surface after forming at $a_p = 0.3$ mm, $\alpha = 70^\circ$, $f = 1500$ mm·min ⁻¹	0.922	2.74	1.16	7.91	3.10	5.84

The radius of the tool tip affects the formability of the sheet; a small tip radius results in less contact of the working part of tool with the sheet surface, which generates less forming forces. Using a constant value of a_p and small values of the tool tip radius causes an increase in the surface finish (Fig. 7). Surface roughness of the sheet change due to change of wall angle and the springback behaviour of the metallic sheet material [13]. Moreover, the values of roughness depending on whether the tool was rotating or not [21, 22].

Fig. 7. Representation of the tool tip radius on the surface of a deformed sheet: (a) small value of the tool tip radius, (b) high value of the tool tip radius

The variation of drawpiece thickness is a very important piece of information when analysing the susceptibility of material to deformation in ISF. The variation in thickness was observed for drawpieces formed without defects and with a height of 35, 50 and 75 mm (Fig. 8). Along the profile of drawpieces, three characteristic areas can be distinguished in terms of deformation values. In the area close to the area of blankholder action, the material is bent and the wall thickness of the drawpiece is continuously decreasing (Fig. 9a) until a certain thickness t is obtained, which in practice does not change in the next area of the sidewall (Fig. 9b). At the edge of the bottom of the drawpiece, the wall thickness changes rapidly (Fig. 9c). As the drawpiece height increases, the side wall area and bottom area are subject to thinning. In the side wall area, the material thickness is almost constant (steady-state region) [21]. The thinning of the sheet material in this region is the limiting factor determining the maximum allowable height of the drawpiece. The thickness thinning ratio is the ratio of the thickness of sheet t in a steady state region to the initial sheet thickness t_0 . The values of the thickness thinning ratios for the drawpieces with a height of 35 mm, 50 mm, and 75 mm are 0.387, 0.325 and 0.387, respectively. So, this indicates that it was possible to form a drawpiece with a height of 75 mm in which the side wall thinning was 71% without risk of damage.

Fig. 8. Conical drawpieces with heights (from left-hand side) 75, 50, 35, 20 mm

Fig. 9. Distribution of drawpiece wall thickness for a drawpiece with a height of 75 mm at: (a) the vicinity of the region of blankholder action, (b) the sidewall of the drawpiece, (c) the edge of the bottom of the drawpiece

SUMMARY AND CONCLUSIONS

The formability of the sheet in SPIF is defined in terms of a few parameters: the radius of the tip of the forming tool, the feed rate, the tool rotation speed, and the size of the vertical step down. The lubricant type directly influences the surface quality of the surface and tool wear. The following conclusions are drawn from the research:

- a greater step size can lead to lower surface quality,
- both step size and tool rotation speed have an effect on surface quality,
- fracturing occurs at the corner of the part where near equi-biaxial stretching exists,
- increasing the feed rate can lead to the wrinkling of the sheet in the area of deformation and may cause an accelerated susceptibility to cracking,
- lubrication conditions clearly affect the formability of DC04 sheet,
- the maximum thickness reduction which did not cause material damage was approximately 71%.

ACKNOWLEDGEMENT

The research has been supported by Grant Agency of the Ministry of Education, Science, Research, and Sport of the Slovak Republic (VEGA 1/0259/19).

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