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Forming force in Single Point Incremental Forming under different bending conditions

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Abstract

Estimation of incremental sheet forming force is required in order to design dedicated equipment, utilize adapted machinery or develop online process control strategies. In the present work, forces on Single Point Incremental Forming (SPIF) of variable wall angle geometry were studied under different bending conditions. The effect of several process parameters was analyzed. The results demonstrated that the maximum forming force increases with the tool diameter and the step down while for higher spindle speeds the forming force decreases. The last effect is due to the higher friction between the tool and the blank when using a fixed spindle speed, which causes an increase of the forming temperature. The forming force evolution, which varies with the bending conditions, could be used as an indicator to prevent the sheet failure.

Keywords: Single Point Incremental Forming; forming force.

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1. Introduction

Designers of sheet metal components, face the lack of techniques allowing them to rapidly manufacture full or scale size prototypes. On the other hand, providers of small batch components or, in the extreme case, one-of-a-kind products, must rely on manual processes that yield lengthy and costly results.

Incremental Sheet Forming (ISF) is a relatively novel technique able to solve the previously mentioned problems. Components obtained by ISF may be totally functional and have a geometric complexity not attainable

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by other sheet metal forming processes. Furthermore, the technology is potentially available for any manufacturing facility owning CNC machine tools coupled to CAD/CAM profile generators.

ISF allows an important reduction of the tooling costs in comparison with the conventional manufacturing process of sheet metal, such as deep drawing, in which there is a need to build expensive dies for each series of products.

Prediction of forming forces in ISF is especially important in the case of using adapted machinery not designed for the process like milling centers and robots. It has been demonstrated by Durante et al. (2009) that the predominant force in ISF is developed in the axial direction of the tool while this, in general, is not the case in milling. As a consequence, an accurate estimation of the maximum axial force developed during the forming process is required in order to ensure the safe utilization of the hardware.

Forming forces are also linked to the quality of the formed component. Duflou et al. (2007) identified the main factors as well as their type of influence on the forming forces of uniform wall angle cones.

Another reason to study forming forces is their direct relationship with the stress level of the workpiece. In turn, stress can be related to the evolution of the plastic strain, which determines the structural integrity of the formed component. Following this idea, Filice et al. (2006) identified the differences in the force curves corresponding to successful and failed SPIF (Single Point Incremental Forming) components with a constant wall angle.

In several sheet metal forming processes, the failure mode depends on the parameter t/R, ratio of the sheet thickness t to the radius of the forming tool R, as pointed out for instance by Vallellano et al. (2010) and Stoughton and Yoon (2011) in stretch-bending, and by Silva et al. (2011) in the case of SPIF. In this sense, the authors suggested in the work done by Centeno et al. (2012) the importance of quantifying the enhancement of formability in ISF due to the bending effect by means of this t/R ratio.

In the present work, cones of circular generatrix have been manufactured in SPIF varying some process parameters under different bending conditions. The sheet thickness is kept constant in the experimental campaign while the tool diameter is varied. Thus, different bending states are achieved. The effect of the variable process parameters in the maximum force achieved during the forming process is analyzed.

2. Methodology

The experimentation was carried out on a Kondia® HS1000 3-axis milling machine equipped with a Fidia numerical control. As seen in Fig. 1 the experimental setup for SPIF testing included a clamping plate, a backing plate with a circular hole of 75 mm diameter, four supports and a bottom plate. A table-type dynamometer Kistler 9257B was mounted in the work-table in order to measure the forming forces that occur during the SPIF process. The forces were acquired using a DaqBoard 505 data acquisition card and the DaqView 9.0.0 software.

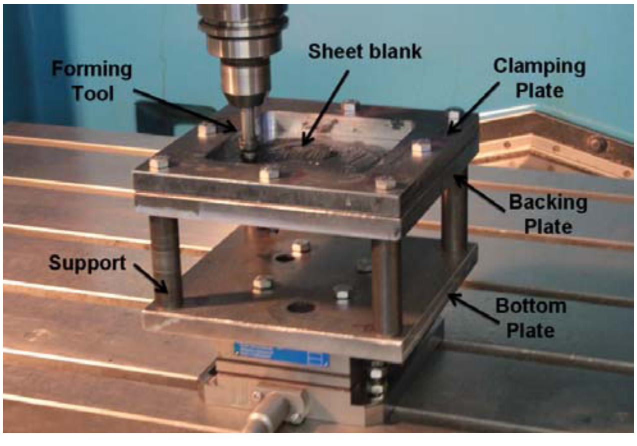


Fig. 1. SPIF experimental setup mounted on a Kondia CNC milling machine.

The testing blanks had a dimension of 150 x 150 mm, being the effective working area 120 x 120 mm. The geometry used in this work was a conical frustum with circular generatrix (Fig. 2). The initial diameter of the truncated cone was set to 70 mm, being the initial drawing angle 20º and the generatrix radius 40 mm. The material used was stainless steel AISI 304 with a sheet thickness of 0.8 mm. The parameters varied during the experiments were the tool diameter (6, 10 and 20 mm), the step down (0.2 and 0.5 mm) and the spindle speed (free and 1000 rpm). The feed rate used for all tests was set to 3000 mm/min. Houghton TD-52 lubricant for metal forming applications was used.

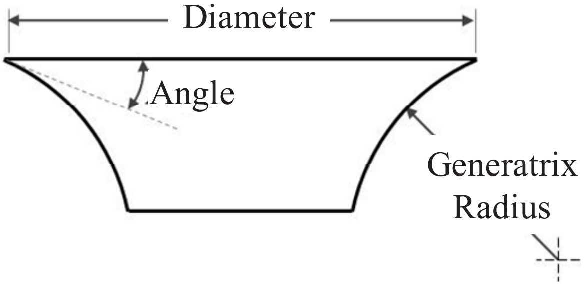


Fig. 2. Design of the conical frustum with circular generatrix.

3. Results and discussion

Table 1 represents the series of SPIF tests that were carried out within the experimental plan proposed. The maximum axial force during the SPIF process has been analyzed and is described in the following table.

Table 1. Series of SPIF tests carried out.

ID	Tool diameter TD (mm)	Step down ΔZ (mm/pass)	Spindle speed S (rpm)	Maximum axial force Fz max (N)
1	20	0.2	Free	2420.85
2	20	0.5	Free	3581.40
3	20	0.2	1000	1902.00
4	20	0.5	1000	2525.10
5	10	0.2	Free	1665.30
6	10	0.5	Free	2076.77
7	10	0.2	1000	1547.60
8	10	0.5	1000	1827.30
9	6	0.2	Free	1491.60
10	6	0.5	Free	1756.77
11	6	0.2	1000	1468.45
12	6	0.5	1000	1687.60

As it can be observed in Fig. 3, the maximum axial force increases with the tool diameter. This increase is due to a higher contact zone between the tool and the sheet when higher tool diameters are used. Although the use of higher tool diameters could allow the reduction of process time because higher step downs could be employed without compromising the surface finishing, the important increase of the forming force it is not desirable because it could be a limiting factor for the machinery used in the manufacturing process (Jeswiet et al., 2005).

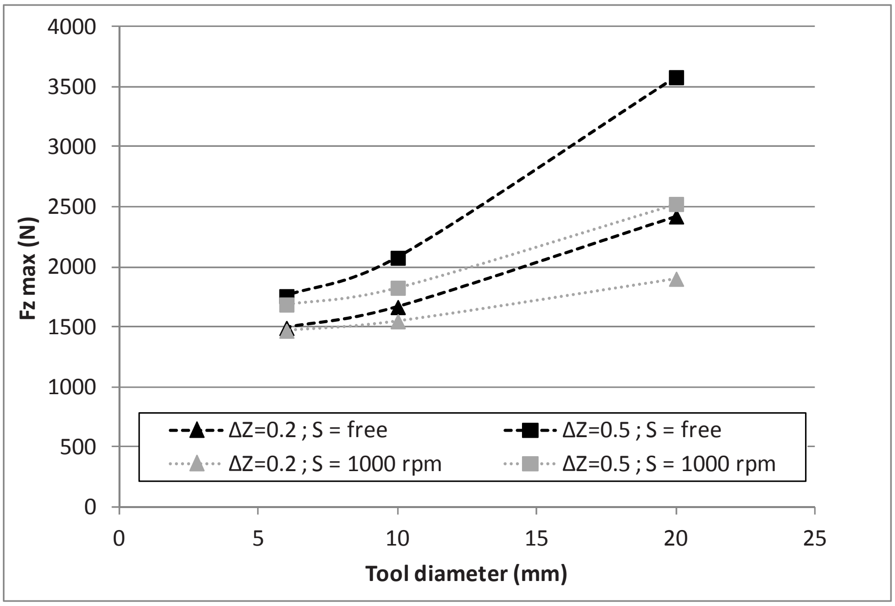


Fig. 3. Evolution of the maximum axial force.

The increase of the step down also provides an increase of the maximum force. This is because for major step downs more material has to be pushed down in order to apply the deformation.

The effect of two previous parameters (step down and tool diameter) has been previously identified in other research works that proposed an empirical equation (Eq. 1) able to predict the forming forces for Uniform Wall Angle (UWA) components (Aerens et al., 2010). The applicability of Eq. 1 for Variable Wall Angle (VWA) geometries has been validated in a previous works (Perez-Santiago et al., 2011; Bagudanch et al., 2011) for different geometries.

$$F_{Zs} = 0.0716\ R_m\ t_0^{1.57}\ d_t^{0.41}\ \Delta h^{0.09}\ \alpha \cos\alpha \tag{1}$$

Where R_m is the ultimate tensile strength, t_0 is the initial sheet thickness, d_t is the tool diameter, α is the initial wall angle and Δh is the scallop height, for which Aerens et al. (2010) proposed the following approximation:

$$\Delta z = 2\sin(\alpha)\sqrt{\Delta h(d_t - \Delta h)} \approx 2\sin(\alpha)\sqrt{\Delta h\, d_t} \tag{2}$$

However, the effect of the spindle speed is not considered in the equation, although Fig. 3 demonstrates that the effect of this parameter is significant. For higher spindle speeds the maximum forming force is lower.

In order to determine the origin of this influence, a thermographic camera was used to record the temperature variation during the manufacturing process. Fig. 4 and Fig. 5 show the temperature distribution and the maximum temperature obtained in experiment 6 (83.20ºC) and experiment 8 (154.51ºC), respectively.

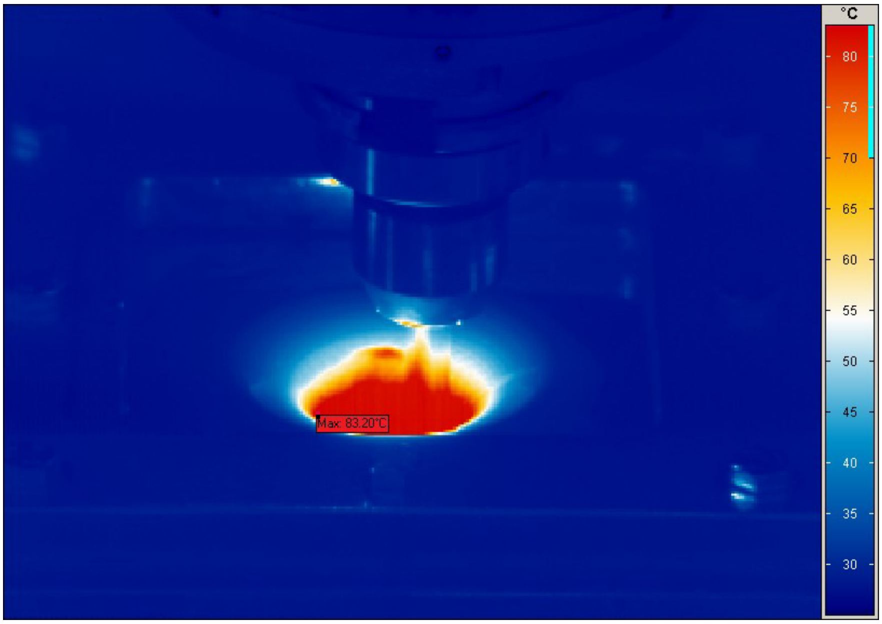


Fig. 4. Maximum temperature obtained in experiment 6.

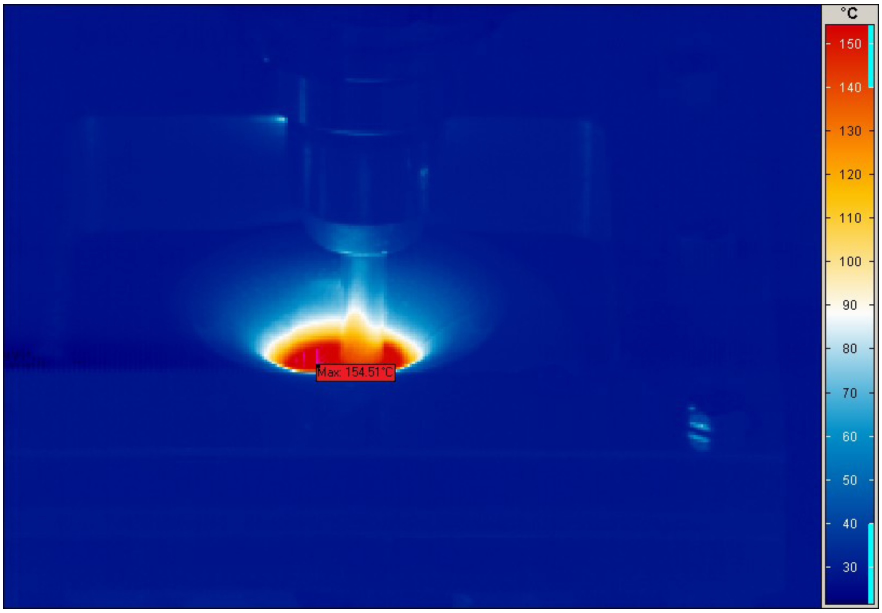
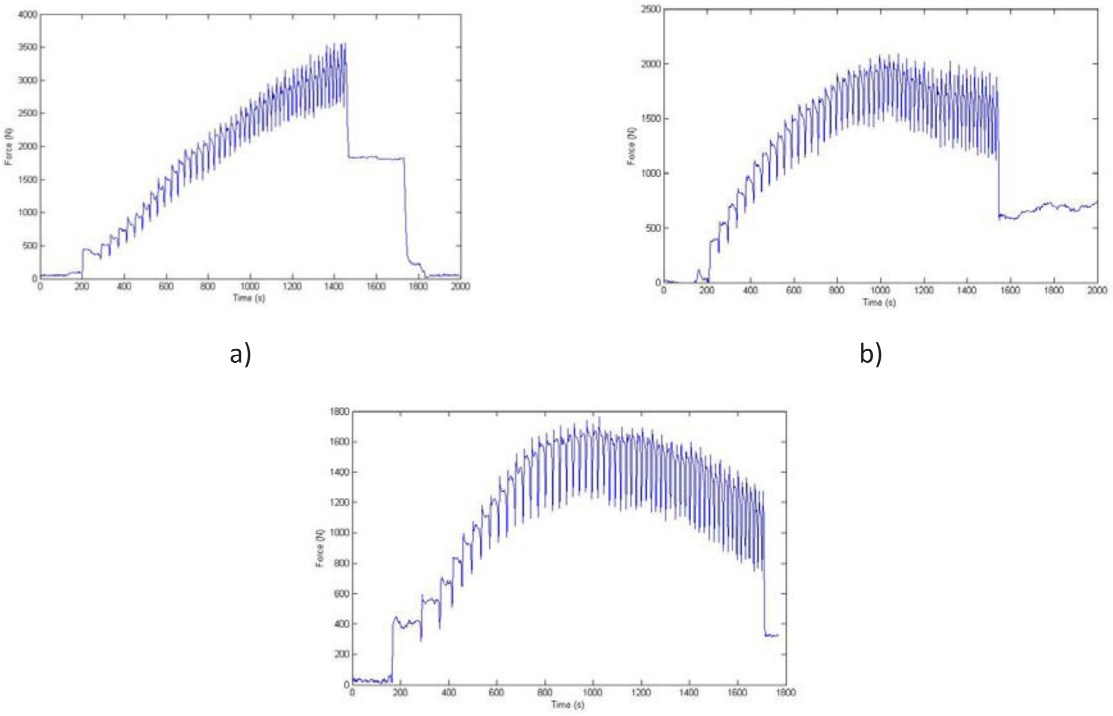


Fig. 5. Maximum temperature obtained in experiment 8.

As it can be observed, there is an important reduction of the temperature (around 70ºC) when the tool rotates freely because the friction between the tool and the sheet is highly reduced. This means that more force is needed to produce the part. Thus, the influence of the spindle speed in the maximum value of the force when producing metallic parts using ISF can be explained with the variation of the friction, which generates heat, and increases the formability of the material.

Therefore, the spindle speed can be used to control the local heat generation on the blank surface, reducing the force needed to form the sheet. This fact is important when using adapted machinery in order to not exceed the limits of safe utilization of the hardware.

Furthermore, by controlling this process parameter, a wider range of materials can be employed in ISF process: from very ductile materials (such as soft aluminum alloys) to materials with low ductility, difficult to form at room temperature (such as magnesium or titanium alloys).



a)

b)

c)

Fig. 6. Evolution of the forming force in: a) experiment 1; b) experiment 5; c) experiment 9.

As it has been explained in the introduction section, the variation of the tool radius with a fixed sheet thickness can provide different bending conditions due to the ratio t/R. This variation on the bending conditions has an effect on the force evolution, as it can be observed in Fig. 6, which represents the forming force during the experiment 1 (Fig. 6a), 5 (Fig. 6b) and 9 (Fig. 6c). The trend is considerably different for higher tool diameters.

In future work, a deeper analysis of the bending conditions will be carried out analyzing the deformation pattern of the formed sheet.

4. Conclusions

In the present paper, the effect of several process parameters (tool diameter, spindle speed and step down) on the forming force has been experimentally analyzed in SPIF for a variable wall angle geometry. It has been determined that increasing the tool diameter and the step down, the forming force increases whereas an increase of the spindle speed causes a reduction of the forming force due to the friction between the tool and the blank, which causes an increase of temperature.

The advantages of controlling the spindle speed are mainly to ensure the safe utilization of the adapted machinery and the possibility of working with materials that are difficult to form at room temperature.

The evolution of the forming force varies depending on the bending conditions. This force evolution could be used as an indicator to determine when the sheet is close to fracture and some corrective actions could be done in order to prevent failure.

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