On the formability, geometrical accuracy and surface quality of sheet metal parts produced by SPIF

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ABSTRACT

Conventional sheet metal forming processes are not suitable for flexible small-batch production and, therefore, are not appropriate for the growing agile manufacturing trends requiring very short life-cycles, development and production lead times. In fact, the present need for flexible sheet metal forming techniques requires the development of innovative technological solutions that are capable of reducing the fixed and capital costs of sheet metal forming to a level where small-batch production becomes economically feasible. Single point incremental forming (SPIF) is a new sheet metal forming process with a high potential economic payoff for rapid prototyping applications and for small quantity production. In general terms a typical SPIF set-up makes use of a small number of low cost active tools components; (i) a blankholder, (ii) a backing plate and (iii) a single point forming tool. The tool path is generated in a CNC machining center and during the process there is no backup die supporting the back surface of the sheet. Despite the contributions of many researchers on the development of industrial applications and better characterization of the forming limits of the process, several key topics related to the mechanics of deformation, likely mode of failure, geometric accuracy and surface quality of the formed parts remain little understood and scarcely systematized. This paper attempts to provide new contributions about the abovementioned issues by means of a comprehensive experimental investigation performed under laboratory controlled conditions.

Keywords: Single point incremental forming, Formability, Geometrical accuracy, Surface quality, Experimentation

1. INTRODUCTION

The use of incremental forming processes has the potential of solving many of the drawbacks related to conventional sheet metal forming technologies where the costs of tooling and set-up times are extremely high and usually not competitive for unitary or small batch production. The most recent developments in the domain of the incremental forming processes and in particular of SPIF (Single Point Incremental Forming), a freeform sheet metal forming process, can avoid dies and punches throughout the utilization of a spherical tool in a conventional milling machine with numerical control.[1].

The generalized use of computational systems for manufacturing lead to the development of various new sheet metal forming processes in which the deformation mechanism is localized in a small region under the forming tools. However, the majority of these processes are limited to symmetrical parts and only recent research efforts were focused on the extension to non-symmetrical [1-4].

Among the different types of incremental forming processes the SPIF represents the most suitable choice from an economic point of view [1]. In this process no conventional tool set-ups and presses are needed.

The sheet is clamped all around with a special chuck and the tool movement is controlled by a computer program, which defines the trajectory along which the tool should move. This trajectory must be defined from the CAD model and will lead to the desired shape by deepening the rotated tool in to the sheet metal [5].

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The basic components of the process are; (i) the sheet metal blank, (ii) the blankholder, (iii) the backing plate and (iv) the rotating single point forming tool.

Up to now most research efforts in the field of SPIF have been focused on the industrial applicability and feasibility of the process. Relevant applications can be found elsewhere [6,7]. However, SPIF is far from being a mature and consolidated technology and therefore gaps of knowledge can be found in the following issues: i) deformation mechanics, ii) formability of complex shapes and iii) tribological and material issues.

Experimental and theoretical investigations reported in the literature have been showing a significant enhancement of material formability associated to incremental forming operations when compared with traditional stamping and deep drawing processes. In fact, SPIF allows very high values of plastic strain before the occurrence of ductile fracture. Typical strain paths limits in SPIF are remarkably larger those currently obtained in current stamping and deep drawing [8-10].

This paper presents a closed-form analysis of fundamentals of SPIF by means of a comprehensive experimental investigation performed under laboratory controlled conditions explaining some experimental results available in the literature for the past couple of years. New versions of SPIF based on the utilization of dummy sheets inserted between the workpiece and the tool are also addressed.

2. EXPERIMENTAL BACKGROUND

2.1 Mechanical and Tribological Conditions

The experimental set was carried out through the use of two different methods: a) traditional SPIF of a single sheet and b) SPIF with a dummy sheet with lubrication between the two sheets.

The experimental apparatus using a dummy sheet implies forming two sheets together and it is presented in Figure 1. The utilization of a top sheet (the dummy) that can be discarded after forming differs from the traditional SPIF where the workpiece surface will be affected by the sliding of the forming tool. Further detail can be found in [11]. The use of the dummy sheet can represent an additional cost to the process. However the application of the process to small batches or prototypes production allows neglecting the dummy sheet cost when compared with the initial costs and the production costs.

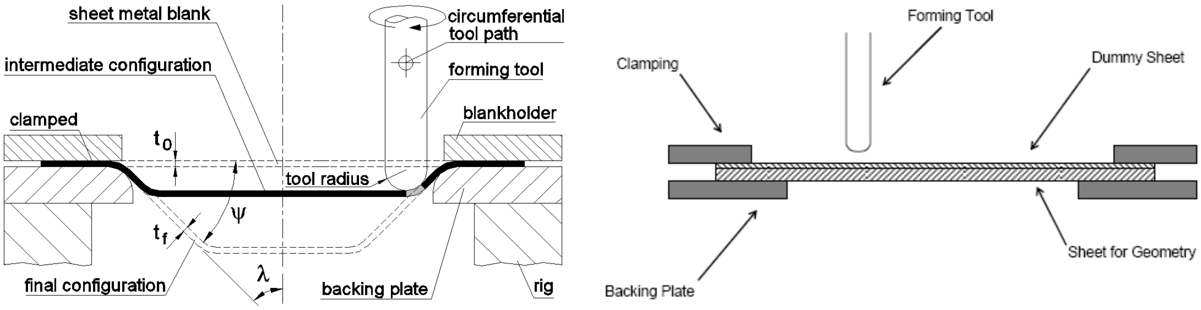


Fig. 1 – Schematic representation of SPIF process (left) and using a dummy sheet (right).

All experiments in the main investigation were carried out using aluminium AA1050-H111 with 1 mm, 1.5 mm and 2.0 mm of thickness. The dummy sheet material was the DC01 deep drawing steel 0.63 mm thick. The lubricant applied between the forming tool and the top sheet (dummy or workpiece) is diluted cutting fluid. The tool path used in the material deformation was generated in a CAM software (Mastercam) with the parameters presented in the table 1.

Table 1- Tool and operation parameters used in the SPIF experiments.

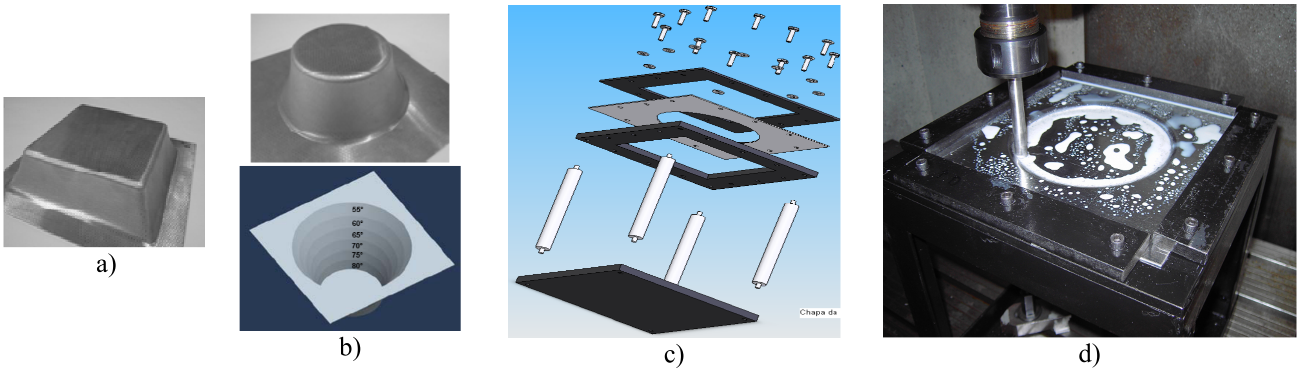
Step size per revolution	Forming tool diameter	Tool shape	Rotation Speed	Feed rate
0.5 mm	ø12 mm	Hemispherical tip	35 rpm	1000 mm/min

2.2 Experimental Procedure

To perform the experiments two different geometries were used: i) a truncated pyramid with increasing wall angle in vertical 15 mm sections, 55 mm deep and 196x196 mm; ii) a hyperboloid with increasing wall angle in vertical 15 mm sections and an initial diameter of 162 mm.

The pyramidal geometry is chosen to investigate whether the dummy may suppress the problem of bulging of the four planar sides, which has been shown experimentally and by modelling [12,13]. The hyperboloid is used to compare formability with and without the dummy sheet. The increasing wall angle ensures a fracture before the tool reaches the bottom. In the present investigation the maximum depth before fracture is used as a measure of formability, but this depth also indicates the maximum wall angle for geometries similar to a cone.

The experimental apparatus used to perform the experiments can be seen on figure 2.



a)

b)

c)

d)

Fig. 2 - Geometry of the parts obtain by SPIF used in the formability limits characterization and experimental apparatus: a) Truncated pyramid; b) Hyperboloid in steps; c) Virtual model of the support structure (blankholder and backing plate); d) Experimental apparatus.

2.3 Surface roughness analysis

The application of the parts obtained by SPIF is known to highly depend on the surface quality. Consequently, a great attention is paid to three parameters that are usually proposed to describe surface condition: (i) a geometrical parameter: surface roughness, (ii) a mechanical parameter: residual stress and (iii) a metallurgical parameter: microstructure. These parameters can vary according to the forming conditions.

Since the SPIF is clearly a technology where the experimentation have a fundamental role the effects of these parameters are commonly accounted empirically.

In particular the surface roughness is usually characterized through average geometric parameters such as R_a (average roughness), R_{max} (peak-to-valley height roughness) or R_z (10-point roughness). These parameters are defined in terms of the profile height distribution (z) recorded, in respect to the mean line, over an assessment length (L) according to,

$$R_a = \frac{1}{l}\int_0^l |z(x)|dx\,, \quad R_{\max} = |z_{\max} - z_{\min}|\,, \quad R_z = \frac{1}{5}\left[\sum_{i=1}^{5}(z_i)_{\max} + \sum_{j=1}^{5}(z_j)_{\min}\right] \tag{1}$$

where $(z_i)_{max}$ and $(z_j)_{min}$ are the five higher local maxima and lower local minima, respectively, of the profile height distribution (z).

The roughness measurements were carried out in a Surface Finish Analyser Mahr, Marsurf M2 model and the procedure of measurement of the above mentioned parameters followed the DIN EN ISO 4287:1998 and DIN 4768:1990.

This kind of standard roughness parameters constitutes a simple and useful way of quantifying profile height distributions.

2.4 Geometrical Accuracy

One of the main factors that influence the SPIF parts geometrical accuracy is the spring-back effect resulting from the elastic deformation of the material that after the local deformation tends to turn his primitive form.

The study of the geometrical accuracy of the parts obtained in laboratory controlled conditions has to take into account this factor. In order to reach this goal a comparison between the theoretical and experimental profile was carried out.

The profile measurement required the cut of the parts along two perpendicular directions, the rolling direction and normal to this direction. The cuts were polished and the profiles were digitalized. The theoretical profile was obtain through the known sine-law which relates the final thickness to the slope of the formed surface, $t = t_0 \sin\alpha = t_0 \cos\theta$, where t is the thickness of a formed part, t0 is the thickness of a blank, α is the half-apex angle of a part and θ is the wall/slope angle of a part.

3. RESULTS AND DISCUSSION

Since the incremental sheet forming of aluminium AA1050-H111 with thickness above 1.5 mm leads to final pieces with serious problems of surface quality, new innovative technological solutions based on the use of dummy sheets allow to successfully overcome this type of problems and to obtain parts with high levels of surface quality. The use of dummy sheets with larger thicknesses increases significantly the pressure and the tool penetration in the material surface leading to a situation where is more favourable to deform and remove small chips of material then only locally deform the material [11].

The use of dummy sheets between the tool and the aluminium sheet allows resolving the problem of the low surface quality and avoiding the eventual formation of chips. The figure 4 depict a detail of the surface quality of a part obtain by SPIF with and without the use of dummy sheet. As it can be observed the quality differences are very significant.

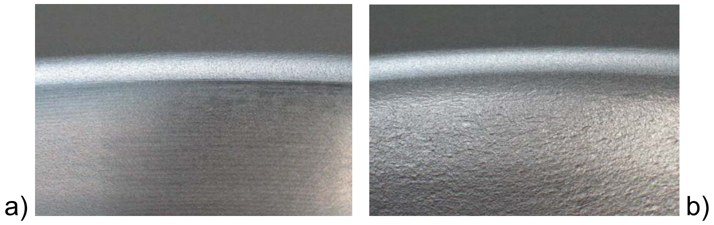


Fig. 4 – Surface of hyperboloid formed with traditional SPIF (a) and using a dummy sheet (b).

The surface roughness analysis of the parts was carried out at the failure point and along different directions: perpendicular to rolling direction (A), parallel to rolling direction (B) and with 45º to the rolling direction (C).

Figure 5 a) presents the Ra (average roughness) parameter for a hyperboloid with 1.5mm of thickness formed with and without the use of a dummy sheet. Five different points of measure are presented for each directions, namely perpendicular to rolling direction (A), parallel to rolling direction (B) and with 45º to the rolling direction (C). The fifth point of measured was the nearest of failure point. Positions 1 to 4 correspond to vertical sections with 0mm (reference) 7.5mm, 12,5mm and 20mm respectively.

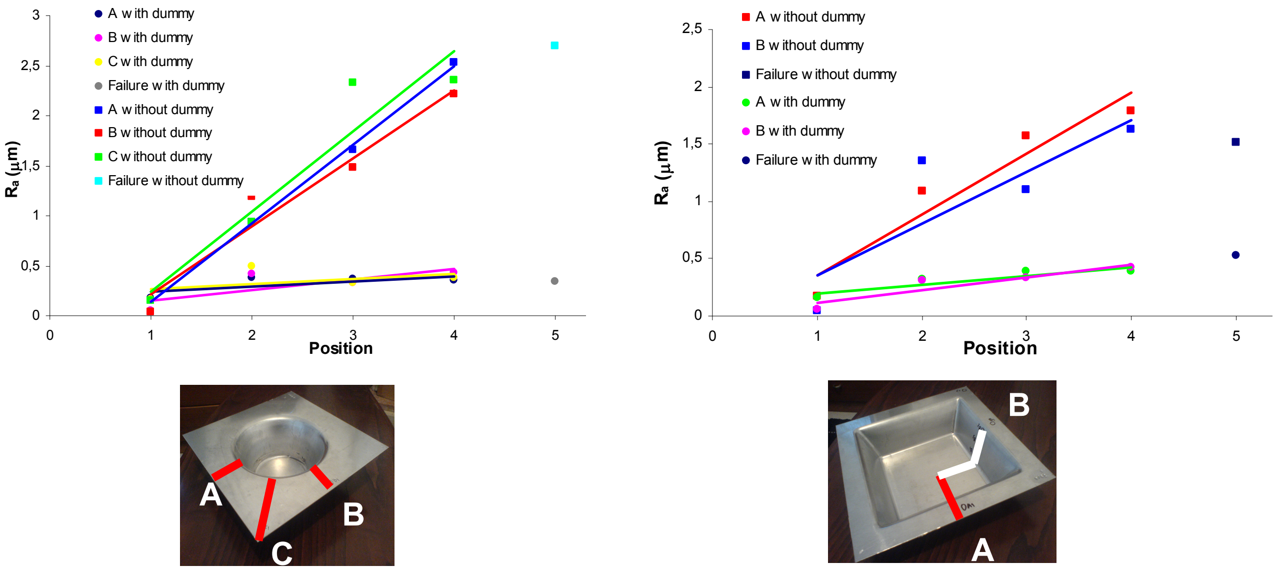
As it can be observed a significant difference occurs between the results obtained with and without the use of dummy sheet. It can be noticed an increase of the average roughness for deeper vertical section, in both situations following the reduction of thickness at the part. It is important to point out that the use of dummy sheet leads to a low variation of the average roughness with the decrease of thickness and the increase of the part deep.

Figure 5 b) presents the Ra parameter for a truncated pyramid with 1.5mm of thickness obtained with and without the use of a dummy sheet. Five different points of measure are presented for each direction, namely perpendicular to rolling direction (A) and parallel to rolling direction (B). The fifth point of measured was the nearest of failure point. Positions 1 to 4 correspond to vertical sections with 0mm (reference) 7.5mm, 12,5mm and 20mm respectively. Also for this geometry a significant difference occurs between the results obtained with and without the use of dummy sheet. It can be observed an increase of the average roughness for deeper vertical section, in both situations following the reduction of thickness at the part.

The geometrical accuracy study of the parts obtained in laboratory controlled conditions based on the comparison between the theoretical and experimental thickness and profiles variation along the final parts.

In figure 6 a) the measured thickness of a hyperboloid with 2mm of thickness and the theoretical sine law thickness are plotted for different wall angles. As can be seen in this figure, the sine law is an acceptable approximation for higher wall angles. However, for low values of wall angle the sine law presents underestimate values. The use of a dummy sheet reveals to be little influent at the final thickness.

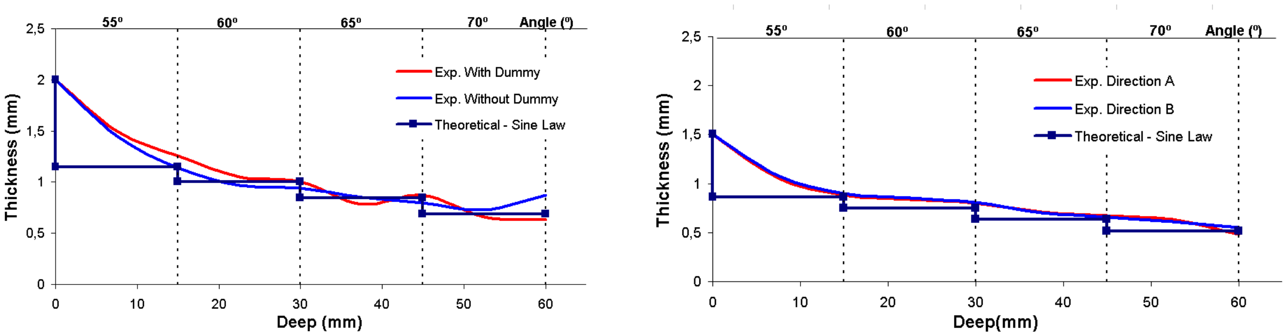
Figure 6 b) presents the experimental measured thickness of a hyperboloid with 1,5mm of thickness and the theoretical sine law thickness for different wall angles and directions. As can be seen in this figure, the influence of the rolling direction at the thickness variation is negligible.



a)

b)

Fig. 5 – Average roughness parameter for a hyperboloid with 1.5mm of thickness formed with and without the use of a dummy sheet (a) and a truncated pyramid with 1.5mm of thickness formed with and without the use of a dummy sheet (b).



a) b)

Fig. 6 – a) Experimental thickness of a hyperboloid with 2mm of thickness and theoretical sine law thickness, for different wall angles, with and without dummy sheet. b) Experimental thickness of a hyperboloid with 1,5mm of thickness and theoretical sine law thickness for different wall angles and directions.

In figure 7 the theoretical and experimental profiles variation along the final parts are compared for hyperboloid geometry with 2mm of thickness, along the rolling direction (A). At the left side of the figure the theoretical sine law thickness are plotted for different wall angles. As can be seen in this figure a good correlation occurs between the theoretical and experimental profiles.

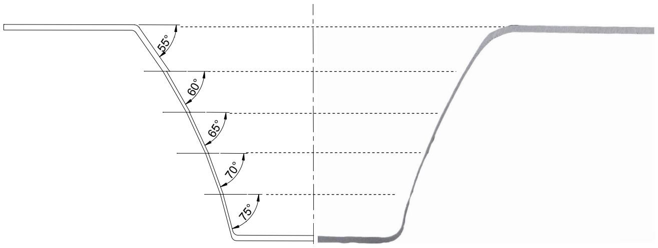


Fig. 7 – Theoretical and experimental profiles variation along a formed hyperboloid geometry with 2mm of thickness along the rolling direction (A).

4. CONCLUSIONS

The production of parts through the new sheet metal forming process single point incremental forming (SPIF) allows a very high economic payoff for rapid prototyping applications and for small quantity production. The main contributions of the present work focus on a comprehensive experimental investigation performed under laboratory controlled conditions of the geometric accuracy and surface quality of the formed parts since this issues remain little understood and scarcely systematized. The experimental work leaded to the conclusion that the formability and surface quality of the parts are clearly influenced, among others, by the follow parameters: thickness of the plate; wall angle regarding the horizontal one (α) and; the use of dummy sheet.

The experimental study allow to conclude that clear benefits exists with the use of dummy sheets between the tool and the aluminium sheet allowing to overcome problems of low surface quality. The surface roughness analysis of the parts at the failure point and perpendicular and parallel directions to rolling direction revealed a negligible influence at the final thickness. The use of the theoretical sine law thickness for different wall angles allows an acceptable approximation for higher wall angles. However, for low values of wall angle the sine law presents underestimate values. A good correlation between the theoretical and experimental profiles was achieved during the experimental work. It was also corroborated that the initial thickness is a variable that influences the surface quality of the parts improving it for small values.

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