Preliminary Studies on Single Point Incremental Forming for Thermoplastic Materials

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ABSTRACT: This paper presents some preliminary investigations on applicability of Single Point Incremental Forming techniques (SPIF) to thermoplastic materials. A 2^{4-1} fractional factorial design of experiments with three replications was performed to investigate the effects of forming parameters on material formability. To study the formability of the thermoplastic sheets, a cone-shaped part with circular generatrix with varying wall angles with respect to depth was considered. The formability of SPIF to the thermoplastic sheets can be defined in terms of the maximum wall angle reached without tearing and/or failure. This angle was measured at position where the mechanical failure of the deformed sheet occurred such as wrinkling, crushing and tearing. It is concluded that the existing knowledge and know-how of sheet metal on SPIF process can be applied to thermoplastic sheets that has potential and preeminent benefits.

Key words: Incremental forming, Single Point Incremental Forming (SPIF), Polymer, Thermoplastic Sheet

1 INTRODUCTION

In recent years, sheet thermoplastic materials have gained increasing interest for applications in many civil and industrial sectors, due to their preeminent characteristics differing from metal sheets. In fact, the structural and thermal properties (i.e. resistance to impact and to temperature, bearing capabilities, etc.) make them particularly suitable to all the applications in which a high strength/mass ratio and a good formability is required such as in medical, aerospace and automotive sectors.

Injection moulding technology has traditionally received extensive attention for the production of polymers parts [7,8]. Although the high flexibility in the design of components shapes, the economical competitiveness of the process requires large production batches to amortize the costs of dies and tooling. Otherwise, flat components can be obtained by deforming sheet polymers in thermoforming processes as combination of drawing and stretching mechanisms [3]. However, these processes present strong limitations, particularly with respect to the forming of small to medium batch production. Thermoforming requires expensive and dedicated plants equipped with complex dies.

In case of shapes, in which the stretching mechanism prevails, a review of the literature points out a lack in controlling the uniformity of large deformations before necking and/or rupture [3]. Additionally, the material squeezing realized by the simultaneous contact of the two dies causes relatively large localized tensile loads, which tends to tear the polymer sheet. Therefore, the improvement of the material forming limits and the manufacturing processes, especially for the small to medium production of complex shape components, is required.

Single Point Incremental Forming (SPIF) technology has been introduced in the recent past to manufacture sheet metal products by using Computer Numerical Control machines (CNC). The major advantage of incremental forming is represented by the possibility to manufacture sheet metal parts difficult to form with traditional processes in a rapid and economic way without expensive dies and long set-up times. In SPIF the tooling is usually a simple frame for the sheet metal clamping, while the deformation is realized by using a tool that is moved along a predefined path by a robot or a CNC machine. Although the process can be rather slow compared to the traditional stamping or drawing processes, single point incremental forming process of metal sheets represents the best way to manufacture prototypes and complex

components produced in small batches for aeronautical, automotive and medical applications. At the present time, researchers have obtained feasible results and potential applications on sheet metal products [1, 2, 5].
With the target of realizing advantages similar to SPIF of sheet metals, this paper presents some preliminary investigations on applicability of SPIF techniques to thermoplastic materials. The maximum wall angle is also considered as index of maximum formability of thermoplastic sheet. To reduce the amount of tests and, consequently, the duration of experimental campaign, Design Of Experiment techniques (DOE) were applied to the design of the experimental plan. In order to evaluate the formability, the variation of the wall angle with respect to the depth of the formed part was considered. A cone-shape part with a circular arc as generatrix was selected. In order to obtain accurate results, a 2^{4-1} factorial plan of experiments with three replications was designed.

2 EXPERIMENTS

2.1 *Design model for experiment*

A cone-shaped part with a circular arc as generatrix was selected to test the formability in the experiments. The part geometry was designed in order to enable investigating all of the wall angles from 0 to 90 degrees. Since the thickness of the part changes according to the cosine's law and the slope of part increases with its depth, the analyzed region is limited to an angle minor than 90 degrees (see Fig. 1).

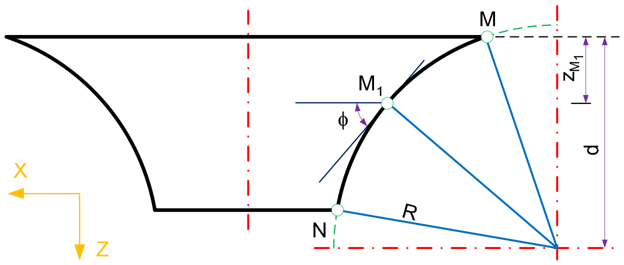

Fig. 1. Geometric illustration of part profile

Fig. 1 shows the generatrix of a part studied during in the experiments. The analyzed area is outlined by the arc of *MN*. The wall angle ϕ of a generic point on the generatrix, defined by the tangent to the profile, can be calculated as follows:

$$\phi = \arccos\left(\frac{x}{R}\right) \quad (1)$$

where *R* is the radius of the circular arc and x the vertical coordinate given by:

$$x = d - z_{M_1} \quad (2)$$

The value of *d* is the maximum height of the cone and z_{M1} the vertical coordinate of the tool when the failure appears. This value is recorded by the CNC-controller interface and verified by using a Coordinate Measuring Machine (CMM).

2.2 *Experimental equipments*

In the experiments, square polypropylene sheets (400x400x3 mm) were used. They were clamped on the frame and put on the machine table (see Fig. 2). The forming zone was a circle of 300 mm diameter.
The tools were manufactured in stainless steel with ball-shaped top. The whole experimental campaign was carried out on a Cielle 30x35-β CNC. The part model was modelled in Pro Engineer Wildfire 2.0. This model was used to generate tool-path and to output numerical control codes.

Fig. 2. Setting of experimental equipment

Due to the friction between the surface of thermoplastic sheet and the tool, local heating can exceed the softening temperature of the thermoplastic polymer. In this case, the material formability increases but the deformation is not stable during the process. In order to avoid this effect, water-miscible metalworking fluid was used in the percentage of 25% (Blasocut™ 2000).

2.3 *Testing procedure*

Fig. 3. Mechanical failures on formed part

The square thermoplastic sheet was clamped on the support frame. A constant lubrication is granted by a hydraulic system during the experiments (see Fig. 2). The sheets were deformed until either wrinkling or tearing occurred. If the tool is not stopped after the wrinkling appears, the material deforms in a non-uniform way and the wrinkling shown in Fig. 3 appears.

The wall angle at which either wrinkling or tearing occurred was considered as the index of the maximum material formability. It was calculated by formula (1). Each experiment was performed three times to verify the repeatability.

3 DESIGN OF EXPERIMENTS

As introduced above, this work is a preliminary investigation of SPIF applied to thermoplastic materials. Thus, it is necessary to comprehend preliminarily effects of forming parameters on these materials. The objective of this experiment is to determine which forming parameters influence the formability of thermoplastic sheet and to understand the interacting effects.

Table 1. The levels of factors for experiments

Source	Low level	High level
Step size (mm)	0.2	1
Tool size (mm)	6	12
Feed rate (mm/min)	1000	3000
Spindle speed (rpm)	200	700

Table 2. Design of Experiments

Run Oder	Step size	Tool size	Feed rate	S. speed
1	-	+	-	+
2	+	+	+	+
3	-	-	+	+
4	+	-	+	-
5	-	-	-	-
6	+	+	-	-
7	-	+	-	+
8	-	-	-	-
9	-	-	-	-
10	+	-	-	+
11	+	+	-	-
12	-	-	+	+
13	-	+	+	-
14	+	+	-	-
15	+	+	+	+
16	-	+	-	+
17	+	-	-	+
18	+	-	+	-
19	-	+	+	-
20	-	-	+	+
21	+	-	+	-
22	+	+	+	+
23	+	-	-	+
24	-	+	+	-

On the basis of the main parameters affecting the SPIF of sheet metals analyzed in the literature [5], four forming parameters (factors) were considered in the single point incremental forming experiments on thermoplastic sheets: (i) step size, (ii) tool size, (iii) feed rate and (iv) spindle speed. Low level and high level of factors are shown on Table 1 and were chosen on the basis of a preliminary sensitivity analysis. The wall angle is the response of experiments. The maximum wall angle is defined as maximum index of formability achieved before failure.

A 2^{4-1} factorial design of experiment was prepared in twenty-four runs, with three replications for each experiment (see Table 2). The 2-level fractional factorial design presents clear advantages in terms of reduction of costs, time, and resources needed to make the runs. The proposed plan did not consider effects of other parameters such as: type of material, thickness of polymer sheets, shape and local heating.

4 RESULS OF EXPERIMENT

Table 3. The Analysis of Variance

Source	Seq SS	Adj SS	Adj MS	F	P
Main Effects	67,3680	67,3680	16,8420	175,66	0,00
2-Way Intera.	12,2474	12,2474	4,0825	42,58	0,00
R. Error	1,5340	1,5240	0,0959		
Pure Error	1,5340	1,5340	0,0959		
Total	81,1494				
S = 0,309641	R^2 = 98,11%		R^2_{adj} = 97,28%		

The Analysis of Variance (ANOVA) is summarized in Table 3. It describes the effects of the input parameters and of their interactions on the output variable. It is shown that all the analyzed parameters and their 2-way interactions are relevant to the process (very low P-values) and this model has a fairly good fit. Therefore, all the factors (forming parameters) have to be taken into account and used to model the response surface. Table 3 also indicates that the correlation coefficient R^2 and adjusted R^2_{adg} values (R^2 = 98,11% and R^2_{adj} = 97,28%) for accuracy of this model are very satisfactory.

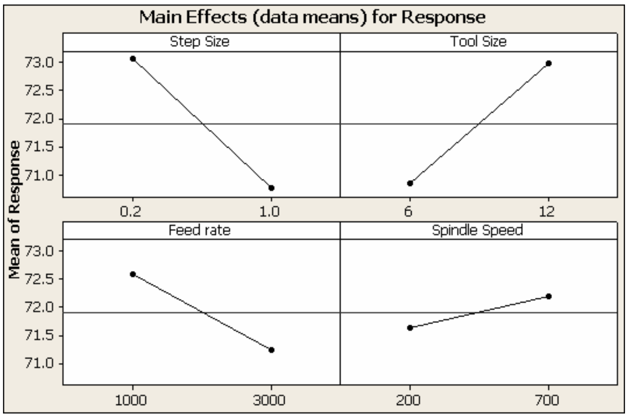

Fig. 4. Main effects for maximum wall angle

Main effects of forming parameters for maximum wall angle and their interactions are described on Fig. 4 and Fig. 5. The increase in step size and feed rate contributes to decrease ϕ_{max}, that means a decrease in formability. In particular, the step size is particularly significant for the formability when its value is larger. These results are in accordance with previous researches carried out on SPIF of metal sheets [5]. Due to the excessive vertical movement of the tool and the high friction between the polymer sheet and the tool, the deformed part is wrinkled and torn easily at larger step. The combination of smaller tool and larger step size contributes to significant decrease of formability as illustrated on Fig. 5.

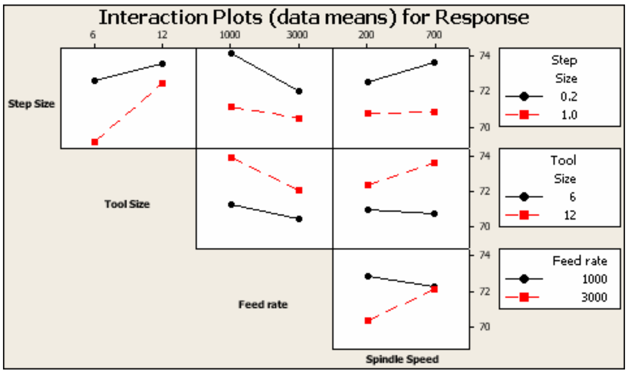

Fig. 5. Interaction among forming parameters for ϕ_{max}

When using a small radius, the tool penetrated easily into the sheet and some pieces of chip are spited out. Thus, the formability decreases significantly if the radius of the forming tool is small. The interaction plot shows that smaller radius tool and larger step size (or feed rate) contribute to decrease significantly the formability. Results obtained in similar experiments carried out on metal sheets show a different behaviour of polymers compared to metals.

Fig. 6. Some shapes were formed in thermoplastic sheet

Also the increase of spindle speed affects formability. In SPIF of metal sheet, previous researches indicated that decreasing in the spindle speed can result into a better formability. A reduction of the spindle speed can eliminate sliding friction and can retain only rolling friction. In this experiment, the increase in spindle speed contributed to increase the formability of thermoplastic sheets only with either large tool size, small step size or large feed rate. The local heating originated by higher speed is reduced by the use of coolant to proper temperature for plastic deformation. The combination between higher feed rate and higher spindle speed also improved the formability.

The interaction between tool size (or step size) and spindle speed is relative significant for larger tool size (for smaller step size). Thus, the improvement of formability in thermoplastic sheets depends on the variation of four forming parameters. Shapes used to demonstrate the abilities of forming thermoplastic sheets are shown on Fig. 6.

5 CONCLUSIONS

Design of Experiments is developed to comprehend preliminarily the Single Point Incremental Forming of thermoplastic sheets. All effects of forming parameters and their interactions are illustrated graphically as prediction of effects of parameters on formability. These experiments show that tool size has a significant effect on formability of thermoplastic sheets. Interactions between step size and tool size or tool size and feed rate have significant effects in the polymer formability. Additionally, an increase in spindle speed also contributes significantly to increase formability.

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