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ANALYSIS OF FORCES, ACCURACY AND FORMABILITY IN POSITIVE DIE SHEET INCREMENTAL FORMING

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ABSTRACT: Sheet Incremental Forming (IF) is a forming technology which consists of a sheet clamped along its edges by a suitable blank-holder while an hemispherical head punch is moved along a defined path and locally deforms the sheet. To improve the part geometrical accuracy, a die (which can be positive or negative) is placed behind the sheet with respect to the punch position. In this case, the process is called Two Point Incremental Forming (TPIF). In the present paper TPIF with positive die was studied through an experimental tests campaign using deep drawing steel sheets. The die geometry used in this research was chosen so to be representative of the process and it was tested using different tool paths. Forming forces were measured using self designed instrumented punch and table while the final workpiece geometry was detected using a coordinate measuring machine (CMM). The collected data allowed to study the effects of the different tool paths on the maximum forming forces, the geometry errors, the maximum reachable wall angle and the drawing depth during forming and after springback. The results were also compared with a previously performed experimental campaign where similar tests with negative die were conducted.

KEYWORDS: Sheet incremental forming, forces, formability, accuracy.

1 INTRODUCTION

With respect to other sheet forming technologies, sheet incremental forming (IF) [1-2] results to be competitive in prototyping or pre-series manufacturing thanks to its high flexibility and its lower development times and costs when dealing with small batches productions. Moreover, sheets formed with IF techniques show a higher formability; in particular, deformations which lead to sheet rupture in traditional drawing, can be widely overcome using this technology [1,3]. For this reason, the interests in this forming technique keep growing. IF consists of a sheet clamped along its edges by a suitable blank-holder (BH); a punch with an hemispherical head is moved along a defined path and deforms the sheet. Due to the local deformation of the sheet and to the clamping system that does not prevent the sheet bending under the action of the punch, the geometrical accuracy of the produced parts is generally poor [4]. This process setup is called Single Point Incremental Forming (SPIF). Two Point Incremental Forming (TPIF) is a particular type of IF in which the sheets are formed in presence of a die placed behind the sheet with respect to the punch position; the die can have either a positive or a negative shape of the part. As a consequence, TPIF technique shows a geometrical accuracy enhancement [5]. The present paper describes the results of an analysis conducted on forming forces, geometrical accuracy and sheet formability in TPIF with positive die. TPIF was studied through an experimental tests campaign using FeP04 deep drawing steel sheets 0.8 mm thick. The die geometry used in this research is characterized by a variable wall angle so to be the most representative of the process and it was tested using different tool paths. Forming forces were measured using self designed instrumented punch and table [6] while the final workpiece geometry was detected using a coordinate measuring machine (CMM). The collected data allowed to study the effects of the different tool paths on the maximum forming forces, the geometrical errors, the maximum reachable wall angle and drawing depth during forming and after springback. The results were also compared with a previously performed experimental campaign [6] where similar tests were conducted using a negative die. The comparison allowed to identify alikeness and differences when using a positive or negative die in two point incremental forming in terms of forces, geometrical accuracy and sheet formability.

2 EXPERIMENTAL TESTS

2.1 EQUIPMENT

The test campaign was using a self designed IF device mounted on a CNC milling machine [6]. The device is

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composed by a table and a punch (Figure 1). The table is mounted on the CNC table and is held by load cells whose position and assembly allow to measure the force along an orthogonal reference system. Moreover the table is equipped with a movable blank holder and with a frame which can hold a die (Figure 1). The punch is mounted on the machine mandrel and is instrumented with strain gages. In this way, by means of a data acquisition system which was self-designed for this application, it is possible to measure the forming forces acting both on the workpiece and on the punch.

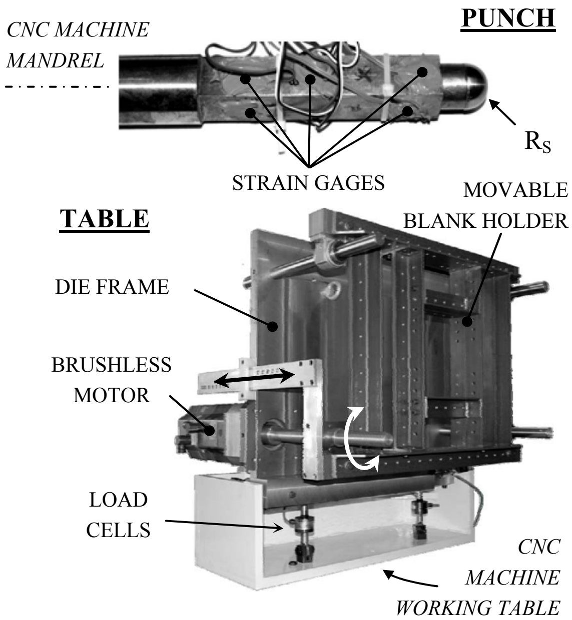

Figure 1: *Experimental device: table and punch*

2.2 DESIGN OF EXPERIMENTS

Previously conducted works [6] focused their attention on IF process parameters influence on forming forces, part formability and geometrical accuracy when reproducing a negative geometry part. The aim of the present work is to extend the research to a positive part geometry. Therefore, the same part was realized using a positive die. The geometry was chosen to be simple and representative of the process (Figure 2). The part profile starts from a horizontal plane and gradually reaches a vertical inclination. In this way it is possible to evaluate the sheet wall maximum reachable inclination (θ_{max}) as the process parameters change. Tests were conducted using tool paths with constant Δθ increment; consequently the step depth increment between two tool passes is given by (1).

$$\Delta Z(\theta) = R \cdot [\cos(\theta - \Delta\theta) - \cos(\theta)] \quad (1)$$

The choice of working with constant *Δθ* values was due to the need of minimising the scallop effect which greatly influences the sheet surface finishing [7]. To work with constant ΔZ does not allow to control the surface finishing especially for high θ values. Reminding that low ΔZ or Δθ increments give better results in terms of scallop (and surface finishing) but longer process times, optimized tool paths can be obtained combining the two strategies. Consequently, the knowledge of the process dependence from Δθ is important to determine the best tool path. To generate the tool paths, a customized self designed CAM software was used.

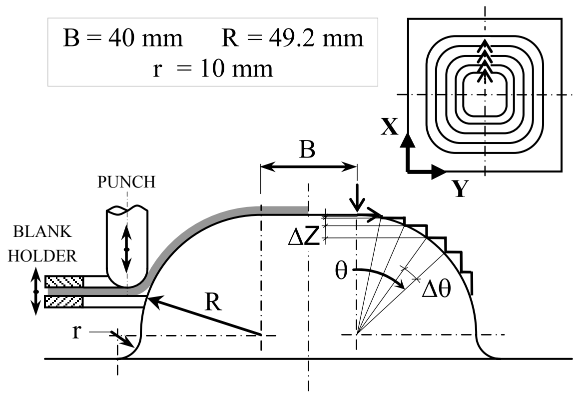

Figure 2: *Tool path, part, tool and die geometries. ΔZ and Δθ parameters*

In the above mentioned works the influence of Δθ and the die presence or absence in IF was studied [6]. In the present work, a positive geometry which can only be reproduced using a die was considered. Therefore, the experimental campaign was focused on Δθ influence (Table 1). The other parameters were kept constant during the tests, in particular the tool feed rate was set equal to 0.6 m/min, the mandrel was still, and the sheet surface was lubricated with grease. In the experiments, FeP04 deep drawing steel sheets 0.8 mm thick and a punch with a head radius $R_S = 9$ mm were used. Two repetitions were performed for each test. In each test, the sheet rupture always occurred during the *Z* depth increment, therefore the test was considered over just before the mentioned Z depth increment.

Table 1: *Design of Experiment*

Δθ	Lubrication	Tool
2° - 4° - 6°	Grease	Feed rate: 0.6 m/min Rotation: none Rs: 9 mm

Sheet	Repetitions
FeP04 steel – 0.8 mm thick	2

3 RESULTS AND DISCUSSION

For each test, force plots were considered and the sheet formability was estimated in terms of maxima achievable depth (Z_{max}) and wall inclination (θ_{max}). Moreover, a measure of the geometrical error was performed on the final pieces. Finally, the collected data were compared with the ones obtained realizing the same part using a negative geometry with and without a die [6]. For tests nomenclature, refer to Table 2.

Table 2: Tests nomenclature

Die	Absent	Present	Present
Tool Path Geometry	Negative		Positive
Name	*SPIF Neg*	*TPIF Neg*	*TPIF Pos*
Δθ	*2° - 4° - 6°*		

3.1 DETECTED FORCES

Figure 4-left shows T_X, T_Y, T_Z profiles (respectively the working forces along X, Y and Z axes). The reported resultant force R (estimated as the vectorial sum of the other three forces), is mainly given by T_Z. Moreover, T_Z behaviour shows the presence of many force peaks. Those peaks correspond to the step depth increments, when the punch detaches and comes into contact with the sheet at the new depth (Figure 2). Therefore the force peaks derive from cinematic effects and, moreover, can be used to identify each pass characterized by a constant Z depth or, in other words, a constant wall inclination θ. The force data were then elaborated (Figure 4-right) extracting the maximum values reached by the forces in each pass (called respectively F_X, F_Y and F_Z), estimated considering the forces absolute values and excluding the force peaks. Force F_Z* was evaluated for each pass as F_Z mean value excluding the mentioned peaks.

Figure 4-right shows a sort of asymptote for the four estimated forces and when rupture occurs, their profile is nearly horizontal. More over, the force maximum behaviours show that the force along the Z axis is higher than the one acting along the X and Y axes. Moreover F_X and F_Y, expected to be equal due to the process symmetry, result to be different. This could be owed to the sheet anisotropy, therefore to compare the forces acting on the plane XY and being of more interest the working force maximum values, the highest value between F_X and F_Y (called $F_{X\text{-}Y}$) was considered. Figure 3 compares the force values obtained in the actual tests (TPIF Pos) with the previous work ones (TPIF Neg). SPIF Neg tests were not considered because the die absence makes the comparison meaningless, in fact it has been demonstrated [6] that the die influences the forming forces increasing them when it is present.

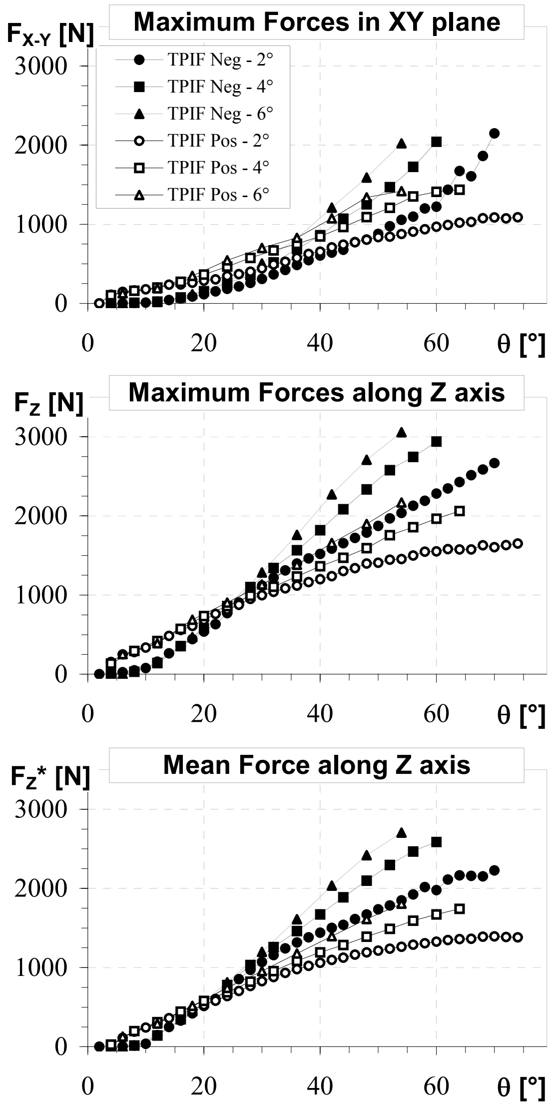

Figure 3: *Forces comparison between TPIF Pos and TPIF Neg processes*

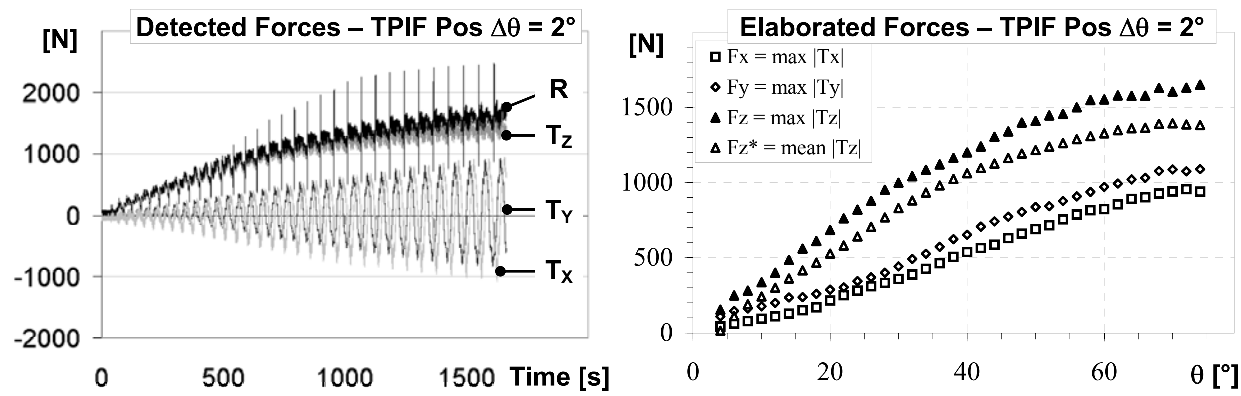

Figure 4: *Working forces behaviour during the forming process (left) and elaborated values (right). TPIF Pos - Δθ = 2°*

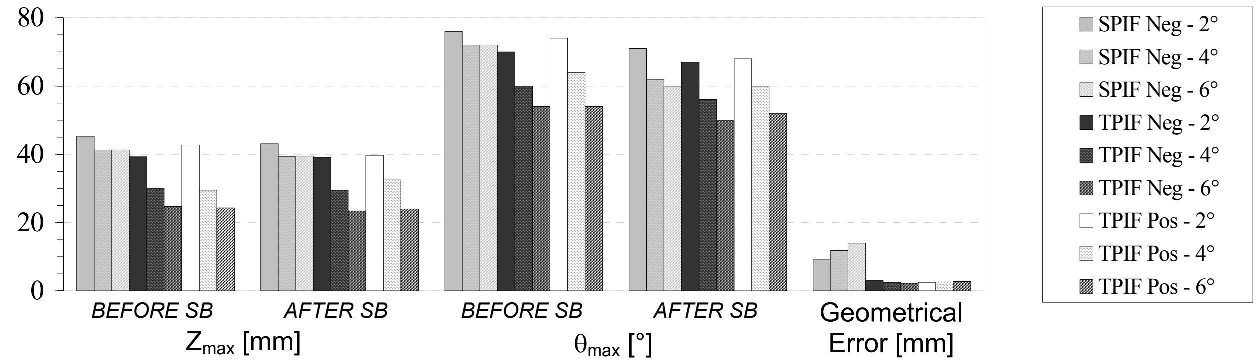

Figure 5: *Formability, springback (SB) and geometrical error comparison between TPIF Pos, TPIF Neg and SPIF Neg.*

It is evident how some likeness and some differences are present. In fact, when considering both positive and negative tool path, forming forces depend both on θ and Δθ; in particular as those parameters raise, forces in the XY plane and along Z axis increase. Differences can be found when comparing the force values and profiles. In this case, for high θ values, the same part geometry realized with a positive tool path needs lower forces with respect to a negative path. This means lower power consuming but, more important, lower forces acting on the tool and on the die. In other words, a positive tool path allows to contain the wear of the die and the tool. When θ is low, the working forces are lower when using a negative tool path, but in this case the differences are much smaller. Moreover, the comparison shows different force curve profiles; in fact using a positive geometry, the force curves have a predominant negative curvature while a negative geometry ones do not. From this aspect derives the lower forces needed at high θ angles to form a positive geometry part.

3.2 FORMABILITY AND GEOMETRICAL ACCURACY

The part formability was estimated in terms of maxima reachable depth (Z_{max}) and wall inclination (θ_{max}). Due to the sheet springback, it was distinguished between the part geometry before and after its removal from the clamping system. Z_{max} and θ_{max} before springback were estimated respectively from the CAM tool path and through geometrical considerations (Figure 2). The values after springback were instead measured by means a CMM and a graphic software. To estimate the part geometrical accuracy, a software was designed. This software compares the tool path with part CMM detected profile and estimates the maximum distance between them. This distance is taken as maximum geometrical error. Figure 5 compares the results in the case of TPIF Pos, TPIF Neg and SPIF Neg tests. The highest formability was obtained in dieless forming (SPIF), but the very low geometrical accuracy does not make this technique widely suitable. When considering TPIF, it is possible to observe that as Δθ decreases or a positive tool path is adopted, the part formability is slightly improved while the geometrical accuracy does not significantly change. When springback is considered, it is possible to state that it acts reducing both Z_{max} and θ_{max} for all the cases. This aspect can be useful when using over-forming technique to compensate the springback.

4 CONCLUSIONS

In the present paper an experimental test campaign on TPIF was presented, in particular a simple but representative geometry part was formed using a positive tool path. The collected data (forming forces, formability and geometrical accuracy) were compared with a previous work results where the same part geometry was realized using a negative tool path. The whole campaign tested different parameters configurations. The comparison showed that, when significant force reduction and geometrical accuracy improvement are the main objectives, TPIF using low Δθ positive tool path should be successfully adopted.

REFERENCES

[1] J. Jeswiet, F. Micari, G. Hirt, A. Bramley, J. Duflou, J. Allwood. Asymmetric single point incremental forming of sheet metal. *Annals of CIRP*, 54/2,623-649, 2005.

[2] J. Jeswiet. Incremental single point forming. *SME Technical Papers MF01-246*, 2001.

[3] M.S. Shim, J.J. Park. The formability of aluminium in incremental forming. *J. of Mat. Proc. Tech.*, 113, 654-658, 2001.

[4] G. Ambrogio, L. De Napoli, L. Filice, F. Micari, M. Muzzupappa. Some Considerations on the Precision of Incrementally Formed Double-Curvature Sheet Components. In: *9th ESAFORM*, 199-202, 2006.

[5] A. Attanasio, E. Ceretti, L. Mazzoni, C. Giardini. Use of TPIF or SPIF for prototype productions: an actual case. In: *10th ESAFORM*, 163-168, 2007.

[6] A. Attanasio, A. Fiorentino, L. Mazzoni, E. Ceretti, C. Giardini. Design of an equipment for forces measurement in TPIF process. In: *9th ICTP*, 1783-1788, 2008.

[7] A. Attanasio, E. Ceretti, C. Giardini, L. Mazzoni. Asymmetric two points incremental forming: improving surface quality and geometric accuracy by tool path optimization. *J. of Mat. Proc. Tech.*, 197, 59-67, 2008.