IOP Conf. Series: Materials Science and Engineering **314** (2018) 012026 doi:10.1088/1757-899X/314/1/012026

Formability behavior studies on CP-Al sheets processed through the helical tool path of incremental forming process

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Abstract. Incremental sheet forming (ISF) is a novel die-less sheet metal forming process, which can produce components directly from the CAD geometry using a CNC milling machine at less production time and cost. The formability of the sheet material used is greatly affected by the process parameters involved and tool path adopted, and the present study is aimed to investigate the influence of different process parameter values using the helical tool path strategy on the formability of a commercial pure Al and to achieve maximum formability in the material. ISF experiments for producing an 80 mm diameter axisymmetric dome were carried out on 2 mm thickness commercially pure Al sheets for different tool speeds and feed rates in a CNC milling machine with a 10 mm hemispherical forming tool. The obtained parts were analyzed for springback, amount of thinning and maximum forming depth. The results showed that when the tool speed was increased by keeping the feed rate constant, the forming depth and thinning were also increased. On contrary, when the feed rate was increased by keeping the tool speed constant, the forming depth and thinning were decreased. Springback was found to be higher when the feed rate was increased rather than the tool speed was increased.
Keywords: Incremental sheet forming; CP-Al; Helical tool path; Thinning; Springback.

1. Introduction

The use of computers made huge revolution in the manufacturing sector and enabled several older sheet metal forming techniques to take lesser time and cost for manufacturing, besides maintaining better accuracy. However, the frequent necessity for the change in design of the components demanded by the end users is pushing backwards all the conventional forming processes due to significant raise in the cost of redesigning the toolings associated with the process and hence promoting novel forming processes, which incur less production cost and lead time. Incremental Sheet Forming (ISF) is a novel, die-less computer-aided manufacturing process, which uses computer numerically controlled (CNC) machines to produce components with very less lead time and production cost.

The idea of dieless forming technique with the use of single point forming tool using CNC machines was patented long before its commercial use [1]. The process uses a predefined tool path, created in CAM software using the CAD geometry of the product, to form the sheet metals in a CNC milling machine with the use of a hemispherical tool. The tool is in continuous contact with the sheet metal, thereby creating a narrow deformation region just beneath the tool area. A series of such narrow and incremental deformations form the final product. Due to these narrow deformation zones, the whole sheet is not under continuous state of stress and hence the formability of the sheet metal is increased largely, when compared with the conventional sheet metal forming process [2-4].

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The formability of the material is largely affected by the process parameters used for experimentation [5-6]. Combinations of different process parameters like the tool speed, feed rate, tool diameter, and step size define the amount of thinning, forming depth, springback and surface finish obtained in the process [7-8].

Springback is a huge concern in metal forming process as it reduces the dimensional accuracy of the products. When the applied load is removed after plastic deformation or the product is taken out from the fixtures, the metal tends to deviate from the designed geometry, due to elastic recovery, which creates springback. It was found out that the springback is reduced in ISF process compared with the conventional sheet forming processes due to the localised plastic deformation and the ISF process using the fixture support aided in reducing the springback of the material further [2, 9-11].

Research on ISF has been initiated in the last decade and is still on the preliminary stage of investigation. ISF process parameters like tool speed, feed rate, tool diameter, wall angle, tool path plays an important role in determining the formability of the material and researchers are still trying to overcome issues like springback, dimensional inaccuracy, surface quality etc. Proper designing of tool path is a challenge in ISF process, which adversely affects the process parameters and the formability of the material [12-13]. The objectives of the present study are to analyse the formability behaviour of commercially pure aluminium (CP-Al) sheets formed incrementally using the helical tool path strategy for different process parameter combinations of tool speed (S) and feed rate (F), and study the influence of tool parameters on the springback and thinning of the formed components.

2. Experimental Procedure

The experimental set up employed for the ISF experiments is shown in figure 1(a) and (b). CP-Al sheet of dimension 250 × 240 × 2 mm^3 was mounted over the fixture and it was rigidly held using a supporting ring fastened with two clamps on both the sides. The whole setup was fixed to the bed of the CNC milling machine. An 80 mm axisymmetric dome geometry was created using the CAD software and the corresponding G-codes of the geometry to feed into the CNC milling machine was created in a CAM software using the helical tool path strategy. A hemispherical forming tool of 10 mm diameter was used for the experiments and coolant oil was used to reduce the frictional force between the tool and sheet.



Figure 1. (a) Experimental set up of the ISF process (b) Forming trial of the ISF experiment.

Different feed rate and tool speed combinations, as shown in table 1, were used in order to study the effect of these parameters on the formability of the material. The components were formed either up to the full forming depth of the designed geometry or until fracture. After the completion of

forming process, the formed domes were scanned using a FAROARM 3D laser scanning profilometer, which rebuilt the whole profile as surface-by-surface. The scanned profile was then exported to Solid Works software and the thickness profile, springback and forming depth were analysed.

Table 1. Different combinations of tool speed (S) and feed rate (F) used for ISF experiments

Experiment No.	Tool Speed (rpm)	Feed Rate (mm/min.)
1	50	50
2	500	50
3	3000	50
4	500	1000
5	1000	1000

For thinning analysis, one-quarter of the dome through the centre was considered and the wall thickness values were measured at every 4 mm depth from the top surface, i.e. mouth, of the dome. Figure 2 shows the methodology of the thickness measurement for the S3000F50 profile. The maximum forming depth was estimated as the centre distance between the top surface, i.e. mouth, of the dome to the bottommost inner surface of the dome (Length AB in figure 2). Similarly, the springback on the formed profile was calculated by comparing the designed profile (obtained from CAD geometry) with the actual scanned 3D profile (obtained using the FAROARM laser scanner).

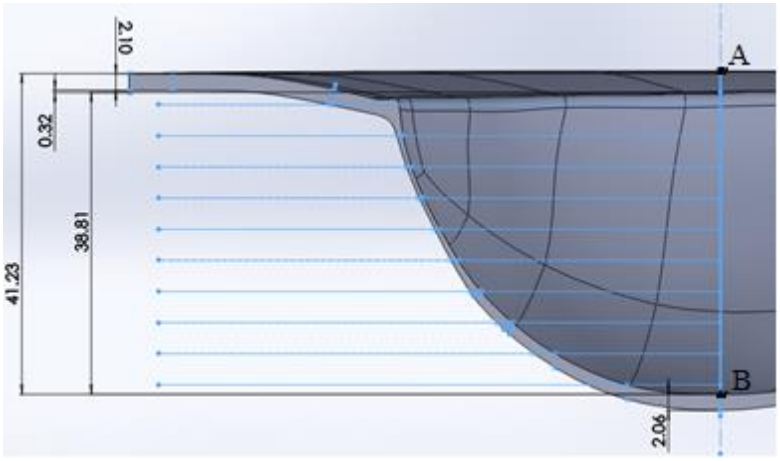


Figure 2. Methodology of thickness measurement of the formed profile.

3. Results and Discussion

3.1 Forming depth analysis.

Figure 3(a) shows the helical tool path followed for the ISF experiments. In helical tool path, the tool initially moves in a circular path, then steps down vertically at a constant value and proceeds again in the circular movement. For the present experiments, a constant vertical stepdown value of 0.5 mm was used, which constituted nearly 30,000 co-ordinate points for the whole tool path. Figure 3(b) shows the photograph of the incrementally formed component. The dimple line in the component denoted the tool movement during the stepdown. Table 2 shows the maximum forming depth achieved on different ISF parts formed using different process parameter combinations. All the samples were formed up to

the full forming depth and no cracking was observed in any of the components. At constant feed rate, when the tool speed was increased, the forming depth also increased. On contrary, when the feed rate was increased by keeping the tool speed constant, the forming depth was decreased. The increase in feed rate greatly reduced the forming time, whereas no change in forming time was observed for the increase in tool speed**.**

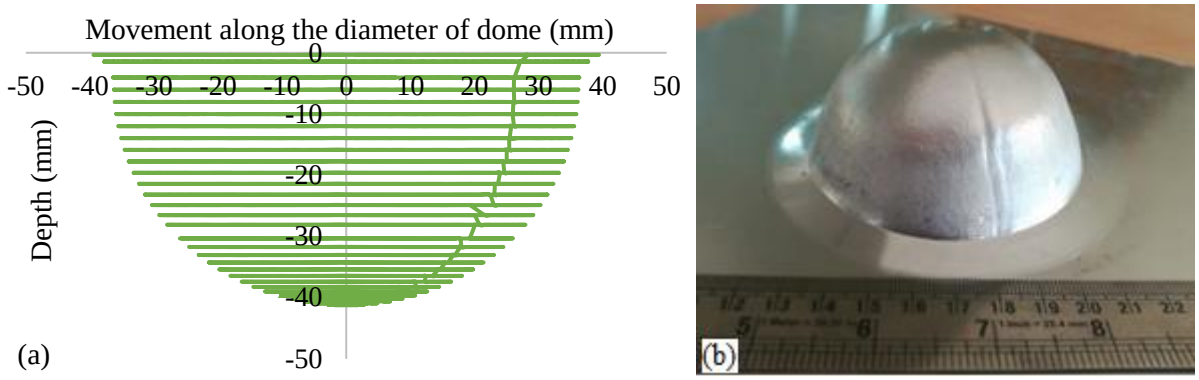


Figure 3. (a) Helical tool path followed for the ISF experiments **(b)** Formed dome after ISF.

Table 2. Maximum forming depth achieved on different ISF parts formed using different process parameter combinations.

Experiment no.	Parameters	Maximum forming depth (mm)
1	S50F50	40.67
2	S500F50	41.02
3	S3000F50	41.23
4	S500F1000	40.84
5	S1000F1000	40.33

When the tool speed was increased, the friction between the tool and sheet was increased, which eventually increased the temperature of the sheet metal under the tool region. As a result, the forming stresses were lowered and the formability of the material was increased. This holds true only for the lower feed rate. At higher feed rate, even though the frictional heating generated was high as a result of increased tool speed, the formability was decreased. It is speculated that the higher feed rate made the tool to reach the next deformation zone quicker than before the frictional heat dissipates to the subsequent deformation zone [14] and the frictional heat does not aid the forming process at higher feed rate, which eventually reduced the formability. The same argument applies to the increase in feed rate at constant tool speed also.

3.2 Thickness analysis.

Wall thinning is one of the important aspects to be considered in sheet metal forming, as plastic instability originates from this region. Figure 4 shows the thickness values at various points along the forming depth of the dome. At constant feed rate, when the tool speed was increased, the amount of thinning increased due to increased amount of deformation and subsequent increase in forming depth. Similarly, at constant tool speed, when the feed rate was increased, the amount of thinning decreased due to decreased amount of deformation and lower forming depth.

The thickness analysis showed that the thinning is always predominant on the sidewalls of the dome for all the process parameter combinations. The wall thickness of the formed part reduced drastically up to certain forming depth and increased afterwards for further forming depth. Maximum thinning was observed around 16 mm of the forming depth for all the process parameter combinations and it was found to be highest, i.e. ~80%, for the S1000F1000 combination. The reason behind the occurrence of maximum thinning at the same sidewall region for all the samples is that this is the region at which maximum wall angle of the formed part was achieved. This region is termed as "thinning band" in figure 5, and the wall angle of the part was reduced beyond this point. Similar observations were made by others during the ISF process [15]. Overall, the combined action of uniaxial stretching and shearing deformation modes, due to the vertical step down and circumferential movement of the tool, respectively, contributed to such a non-uniform thinning on the part.

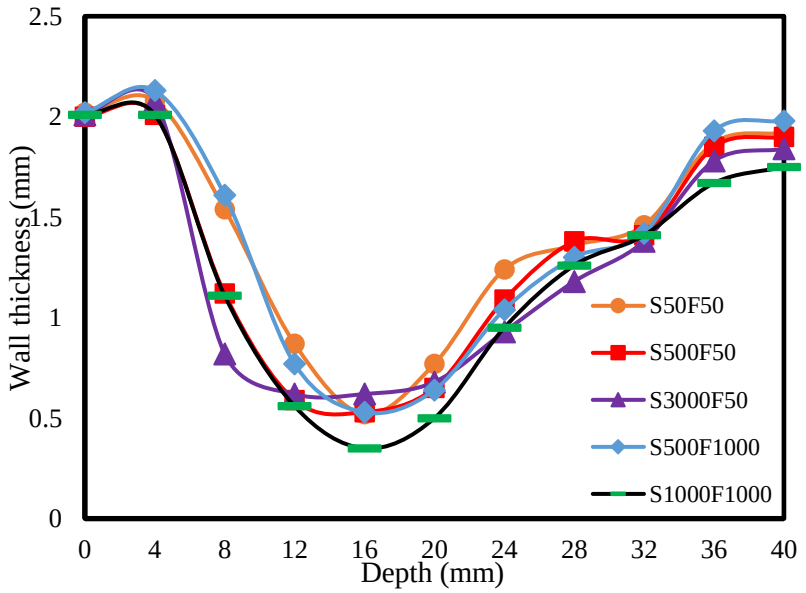


Figure 4. Thickness profile of ISF parts formed using different process parameter combinations.

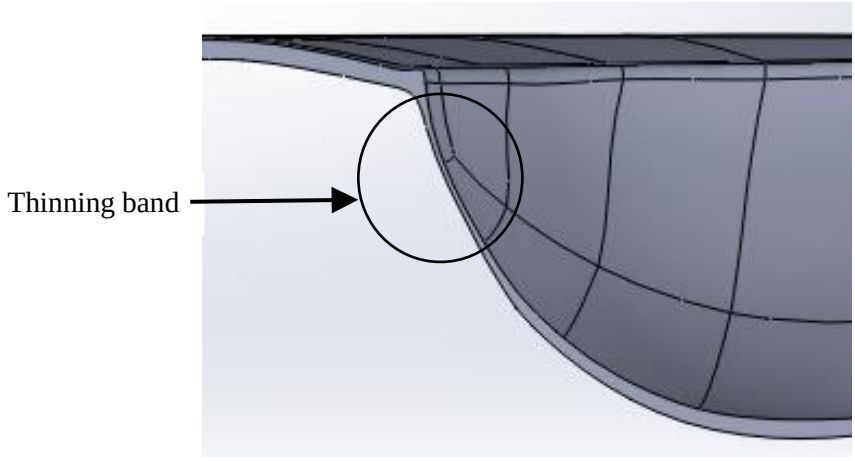


Figure 5. Thinning band depicting the region of maximum wall angle formed.

3.3 Springback analysis.

The comparison of actual 3D scanned profile of different incrementally formed parts with the designed profile is shown in figure 6. It was observed that the increase in tool speed, by keeping the feed rate constant, decreased the amount of springback in the part. On the other hand, the increase in feed rate, by keeping the tool speed constant, increased the amount of springback.

Overall, the springback was always greater near the sidewalls and mouth of the dome. Dimensional inaccuracy due to springback arises mainly because of the forming forces imparted by the tool while moving from one contact point to another and removal of clamps/ reduction in clamping forces after forming. During the ISF process, when the tool comes into contact with the sheet blank, the blank bends near the clamped edge and the huge elastic recovery at this bending region on removing the clamping forces created large springback near the mouth region of the dome. Similarly, the circumferential movement of the tool and the simultaneous increase in forming forces created springback on the sidewalls of the dome. However, the trade-off between the elastic recovery forces and frictional heating due to tool movement reduced the springback to considerable amount in this region. Microstructural investigations will be carried out in future in order to reduce the springback and thinning on the formed parts based on strain path optimisation.

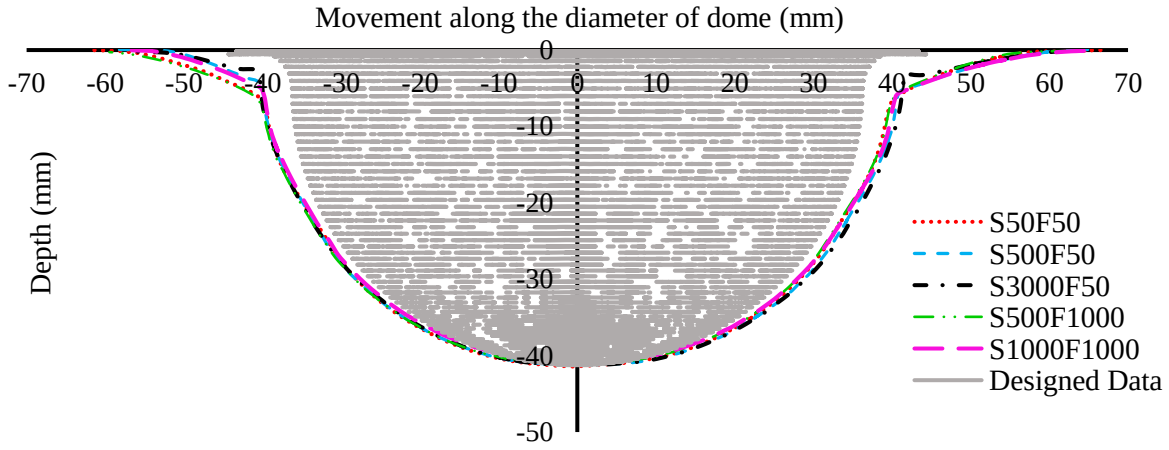


Figure 6. Springback analysis of actual ISF profiles with the designed profile.

4. Conclusions

An axisymmetric dome of 80 mm was formed using the helical tool path of the ISF process for different tool speed and feed rate combinations on commercial pure aluminium sheets, and the forming depth, amount of thinning and springback were analysed on the parts. It was found out that the forming depth and subsequently thinning were increased when the tool speed was increased by keeping the feed rate constant. On contrary, the forming depth and thinning were decreased when the feed rate was increased at constant tool speed. The springback was found to be higher when the feed rate was increased rather than the increase in tool speed, due to the higher forming forces imparted during the process.

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