Optimisation of Tool Path for Improved Formability of Commercial Pure Aluminium Sheets during the Incremental Forming Process

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Abstract. An axisymmetric dome of 70 mm in diameter and 35 mm in depth was formed using the ISF process using varying proportions (25, 50 and 75%) of spiral (S) and helical (H) tool path combinations as a single tool path strategy, on a 2 mm thickness commercially pure aluminium sheets. A maximum forming depth of ~30 mm was observed on all the components, irrespective of the different tool path combinations employed. None of the components were fractured for the different tool path combinations used. The springback was also same and uniform for all the tool path combinations employed, except for the 75S25H which showed slightly larger springback. The wall thickness reduced drastically up to a certain forming depth and increased with the increase in forming depth for all the tool path combinations. The maximum thinning occurred near the maximum wall angle region for all the components. The wall thickness improved significantly (around 10-15%) near the maximum wall angle region for the 25S75H combination than that of the complete spiral and other tool path strategies. It is speculated that this improvement in wall thickness may be mainly due to the combined contribution of the simple shear and uniaxial dilatation deformation modes of the helical tool path strategy in the 25S75H combination. This increase in wall thickness will greatly help in reducing the plastic instability and postpone the early failure of the component.

KEYWORDS

Incremental Sheet Forming; Helical and Spiral Tool Path; Combined Tool Path; Forming Depth; Wall Thinning; Springback.

INTRODUCTION

Incremental sheet forming (ISF) is a novel, dieless forming technique for producing sheet metal components with the application of small amounts of incremental deformations. This process is well-suited for small batch type production of components at very low cost and lead time. ISF process is conventionally carried out on a 3-axis CNC milling machine using a hemispherical tool. While executing the process, the tool follows the computer generated tool paths developed using the CAD geometry of the product. The formability of the material is influenced by the process parameters such as the tool rotation speed, feed rate, tool diameter and step size used for the experimentation, and affect the maximum forming depth, wall thickness, spring back and surface finish of the final product[1-3]. However, the type of tool path employed is most important than the process parameters, as it greatly influences the formability and dimensional accuracy of the sheet metal[4-7]. The basic tool paths often used are either a spiral or contoured one, and in recent times, complex tool path generation becomes a very important topic associated to ISF[8-10]. Previous studies[6, 7] have shown that the helical tool path strategy provided better formability and less thinning than the spiral tool path strategy for the same process parameter values and vice versa, however the springback was more for the helical tool path strategy. Few other studies suggest that it is better to run the tool path from the edge of the part to the center, in order to improve the accuracy of the final product[10-13]. Another study[14] formulated a tool path for extended geometry with higher wall angle than the required one, in order to compensate for springback, and obtained better accuracy on the final component. All of the works that were carried out till date related to tool path involved either the application of feature-based tool paths or modification of tool path strategies (ex: out-to-in, multi-step forming etc.) using the predictive approach. None of the authors have attempted to combine two different tool path strategies as a single one and analyse the results of such a combination yet. This approach may be useful in exploiting the advantages of both the tool path strategies and improve the dimensional accuracy of the final product.

Hence, the present study is aimed to combine the spiral (S) and helical (H) tool path strategies as a single tool path and study the influence of varying the proportions of individual tool paths in the combination on the forming depth, amount of thinning and springback of a CP-Al sheet during the ISF process. Spiral and helical tool paths, at different proportions (25, 50 and 75%) are combined together, with helical tool path always following the spiral tool path strategy, and the dimensional accuracy and formability of the aluminium sheet is evaluated.

EXPERIMENTAL DETAILS

Material

Commercially pure (CP) aluminum sheets of 2 mm thickness and 250 x 250 mm dimensions was used as the starting blank material for the ISF experiments. CP-Al sheets were used for the experiments in order to avoid the interaction of second phases on the formability of the sheet material and its influence on the tool path designed.

ISF Setup

A special fixture, as shown in Fig. 1, for holding the sheet material was designed for the current ISF experiments. The aluminium sheet was placed over the fixture and the whole setup was fixed firmly with the CNC milling machine bed using the supporting ring and external C-clamps.

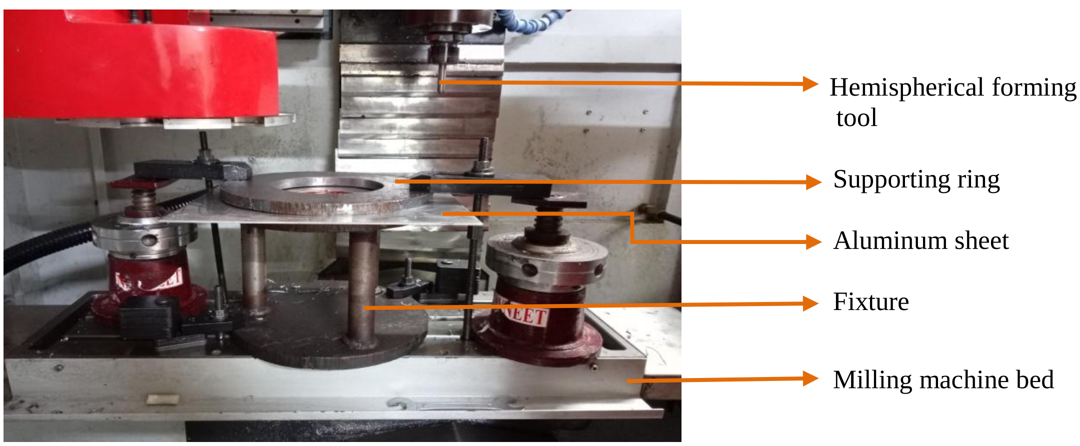

FIGURE 1. ISF experimental setup.

Tool and Tool Paths

An axisymmetric dome of 70 mm in diameter and 35 mm in depth was created using the CAD software. Different tool path combinations, as mentioned below, were created for the full depth using the MASTERCAM software with a vertical step down of 0.5 mm.

a) Complete spiral
b) 75% spiral followed by 25% helical (75S25H)
c) 50% spiral followed by 50% helical (50S50H)
d) 25% spiral followed by 75% helical (25S75H)

Spiral tool path: In this particular tool path, the X, Y, and Z co-ordinates change continuously at every point of the trajectory and the tool descends gradually according to the constant vertical step down value.
Helical tool path: In this tool path, the X and Y co-ordinates alone change (Z is constant) at every point of the trajectory, when the tool moves along the diameter of the component. After one full revolution along the diameter, the tool steps down, i.e. Z co-ordinate changes, and then again the X and Y co-ordinates alone change during the next revolution and so on. Table 1 shows the distance covered by the individual tool paths along the depth of the dome for the different tool path combinations used.

TABLE 1. Designed depth of tool path for the different tool path combinations used.

Tool path combinations	Distance of tool path along the depth of the dome (mm)	
	Spiral	Helical
Complete spiral	35	0
75S25H	26.25	8.75
50S50H	17.5	17.5
25S75H	8.75	26.25

The corresponding G-codes of these tool paths were fed into the CNC milling machine and a hemispherical forming tool of 9 mm in diameter, made of high speed steel (HSS), was used for the ISF experiments. The optimum feed rate and spindle speed were selected as 50 mm/ min and 3000 RPM, respectively, based on our earlier experimental observations[6, 7]. Standard engine oil was used as a coolant for the experiments. All the ISF experiments were carried out either up to full forming depth or until fracture was initiated.

The formed domes were scanned using a FAROARM 3D laser scanning profilometer and the scanned profiles were analyzed in the Solid Works software for the measurement of forming depth, springback and dome wall thickness.

RESULTS AND DISCUSSION

Forming Depth

All the ISF experiments using different tool path combinations were carried out to the full forming depth, as no fracture was observed while forming any of the components. Fig. 2 shows the photograph of the ISF component formed using the complete spiral tool path strategy. A hump formation was observed near the maximum wall angle region for all of the components. The maximum forming depth values obtained for the different tool path combinations were given in Table 1. The maximum forming depth was almost same, approximately 30 mm, for all the different tool path strategies employed. This implies that the proportions in the combination of individual tool paths does not have an effect on the improvement of the forming depth, even though different stretching effects were imparted by different tool path combinations.

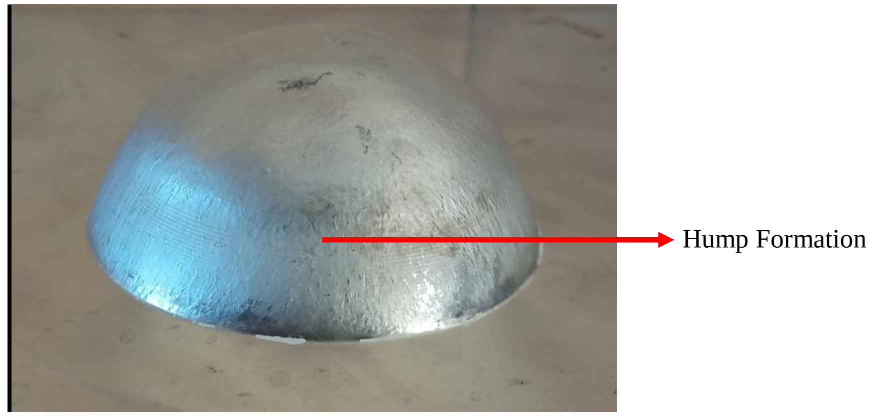

FIGURE 2. Photograph of ISF component formed using the complete spiral tool path strategy.

TABLE 2. Maximum forming depth obtained for the different tool path strategies of the present study.

Sl. No	Tool path	Forming depth (mm)
1.	Complete spiral	30.8
2.	75S 25H	29.9
3.	50S 50H	30.7
4.	25S 75H	30.5

Springback

Fig. 3 shows the springback profile of the ISF components formed using the different tool path combinations, in comparison with the designed profile. The profile showed that the springback was almost same and uniform for all the tool path combinations employed, except for the 75S25H which showed slightly larger springback. The springback was negative, i.e. less than the designed dimension, always on the forming depth direction. It is speculated that this negative springback was accommodated by the hump formation near the maximum wall angle region of the component, as seen in Fig. 2. However, the hump formation was less for the 25S75H tool path combination when compared with other tool path combinations. The springback results also revealed that the application of such combined tool path strategies with varying proportions doesn’t have much influence on reducing the springback of the components.

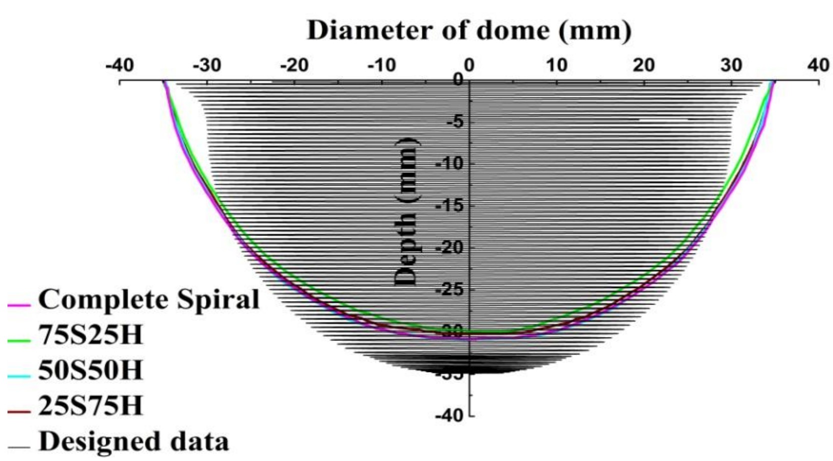

FIGURE 3. Springback profile of ISF experimental components with the designed tool path profile.

Wall Thickness

Wall thinning is one of the most important aspects to be considered in sheet metal forming, as plastic inability and subsequent cracking of the material initiates from this region. The wall thickness was measured at every 2 mm of the forming depth and Fig. 4 shows the wall thickness profile of the ISF components formed using the different tool path strategies.

The wall thickness reduced drastically, from the initial thickness of 2 mm, up to a certain forming depth and then increased with the increase in the forming depth. The forming depth at which the maximum thinning was observed was around 9 mm for all the components and this was the maximum wall angle region of all the components. The complete spiral tool path strategy showed a minimum thickness of 0.45 mm at this region. The modification of the spiral tool path by the inclusion of 25 and 50% helical tool path had no improvement in the wall thickness and deteriorated the wall thickness more than that of the complete spiral tool path strategy. The inclusion of 75% helical tool path in the spiral tool path (25S75H) improved the wall thickness significantly (around 10-15%), than that of the complete spiral and other tool path strategies, near the maximum wall angle region of the component. It is speculated that this improvement in wall thickness may be mainly due to the combined contribution of the simple shear and uniaxial dilatation deformation modes of the helical tool path strategy in the 25S75H combination. As the distance travelled by the tool between any two consecutive points in the trajectory is always higher for the spiral tool path strategy rather than the helical tool path strategy, this significantly not only increased the amount of deformation in the material, but also the amount of thinning of the material. Hence, the inclusion of sufficient proportion of helical tool path in spiral tool path (25S75H) is necessary for the improvement in wall thickness significantly, which in turn helps in reducing the plastic instability and postpone the early failure of the component. However, to obtain uniform wall thickness thro' out the component, it is suggested that this approach of varying the proportions of different individual tool paths should be attempted within the distance of the maximum wall angle point, as most of the plastic deformation is concentrated in this region. In the present study, the tool path is completely spiral up to the maximum wall angle region in all of the combinations attempted, and hence the mixed tool path strategy was not having much influence on improving the wall thickness of the component, except the 25S75H combination. Nevertheless, the wall thickness obtained using the different tool path combinations were always higher than that predicted using the cosine law, $t_f = t_o.\cos(\alpha)$. Such an attempt of combined tool path strategy within the maximum wall angle region is underway and will surely increase our understanding in designing an optimum tool path to avoid the plastic instability of the material. It can be concluded that the 25S75H tool path combination can be adopted instead of the complete spiral tool path strategy for better dimensional accuracy of the component.

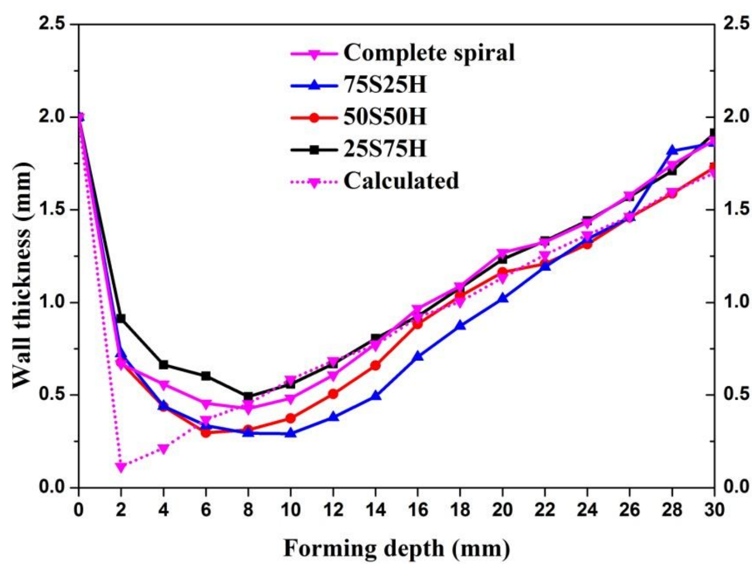

FIGURE 4. Wall thickness profile of ISF parts formed using different tool path combinations. '0' forming depth corresponds to the initial thickness of the material.

CONCLUSIONS

An attempt had been made to study the influence of varying the proportions of spiral and helical tool paths (25, 50 and 75%) in a combined tool path strategy, and the dimensional accuracy and formability of the aluminium sheet during the ISF process.

A maximum forming depth of approximately 30 mm was obtained for all the components, irrespective of different tool path strategies employed. The springback profile also showed that the springback was almost same and uniform for all the tool path combinations employed, except for the 75S25H which showed slightly larger springback. The springback was accommodated by a hump formation near the maximum wall angle region of the component.

The addition of 75% helical tool path in the spiral tool path (25S75H) improved the wall thickness significantly (around 10-15%) near the maximum wall angle region of the component, when compared with the complete spiral and other tool path strategies. Hence, it is always necessary to include sufficient proportion of helical tool path in spiral tool path (25S75H) for better dimensional accuracy of the product, which in turn helps in reducing the plastic instability and postpone the early failure of the component.

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