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An Experimental Investigation on Thinning and Formability in Hybrid Incremental Sheet Forming Process

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Abstract

Single point incremental forming (SPIF) has several advantages over conventional sheet forming process, but due to its inherent drawbacks such as localized thinning, poor formability of parts having steep walls and long processing time make it unsuitable in many industrial applications. In present experimental investigation, two-step hybrid incremental sheet forming (HISF) process is proposed which combines stretch forming (SF) and SPIF process. Stretch forming or preforming is done in order to get intermediate shape and desired thickness distribution. On the same setup final part shape is obtained using SPIF process. From the literature review it is found that sophisticated tooling is used for stretching process. In present experimental investigation simple tooling comprising wooden preforming tool is used for stretching followed by SPIF process to form final part shape. Full factorial design of experiments is used to quantify influence of wall angle, preforming and preform tool radius on minimum thickness. From the experimental results it is observed that wall angle has significant influence on thinning which is in good agreement with the previous literature. Further, from the same set of experiments, the influence of preforming depth and preform tool radius on minimum thickness is studied keeping wall angle as constant. It is found that preforming has significant influence on minimum thickness and formability. For conical frustum of 30° and 50° wall angle, 70 mm preform tool radius and 10 mm preforming results in minimum thinning. Also, improvement of 18% in minimum thickness is observed while forming parts with 50° wall angle. Using preform tool radius 70 mm and preforming depth 18 mm, an improvement of around 40 % in forming depth of part having 70° wall angle is achieved in HISF process as compared to SPIF process.

Keywords: Hybrid incremental sheet forming; Stretch forming; Single point incremental forming; Thinning; Formability.

1. Introduction

Incremental sheet forming (ISF) has several advantages over conventional sheet metal stamping processes such as less forming forces, increase in material formability, die-less forming and flexibility [1,2]. Despite these advantages, some major limitations such as localized thinning, poor geometric accuracy and uneven thickness distribution make ISF process unacceptable in many industrial applications. Aforementioned limitations motivated researchers to develop different process combinations such as ISF combined with laser heating or ISF combined with electric hot forming process. The process combinations are found to be

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viable options for improving thickness distribution, localized thinning, and geometric accuracy along with reduced forming time as compared to ISF process.

Hybrid incremental sheet forming (HISF) process is a novel methodology which is capable to overcome the limitations of ISF process by combining ISF with some allied process such as stretch forming combined with ISF process. Fig. 1 depicts the schematic representation of HISF process comprising stretch forming and single point incremental forming (SPIF) process. Preforming or stretch forming is done in first stage to get intermediate shape and desired thickness distribution. SPIF process is then used to form the final part shape. Preforming process is carried out using hemispherical shaped wooden preforming tools. On the same setup, preforming tool is replaced with ISF tool which is also hemispherical in shape.

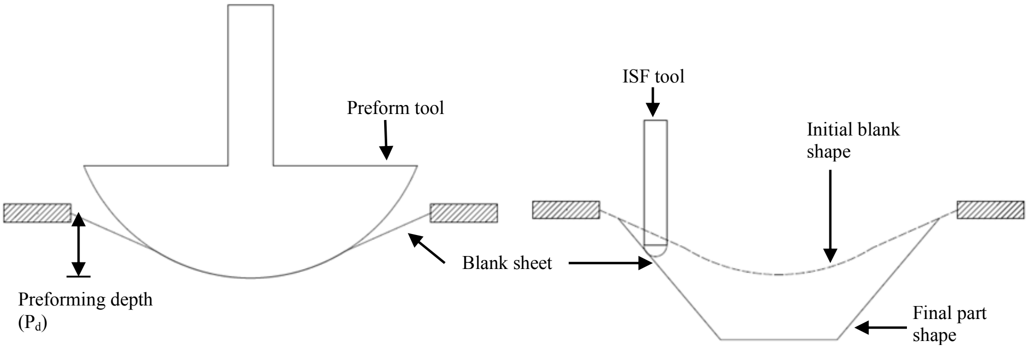


Fig. 1 Schematic representation of two-step hybrid incremental sheet forming (HISF) process

Some researchers have investigated HISF process. For example, Araghi et al. [3] proposed a new hybrid forming process which combines ISF with stretch forming process. A spherical cap with groove was formed using a partial die in HISF process. Spherical dome of the part was formed by stretching and the groove was formed by SPIF process. Improvement in thinning and thickness distribution was observed along with reduced forming time using proposed HISF process. Araghi et al. [4] presented a detailed review of HISF process mainly comprising stretch forming combined with ISF process and laser assisted ISF process. Authors concluded that stretch forming combined with ISF improves thinning and forming time whereas laser assisted ISF is mainly useful for forming difficult to form materials such as magnesium alloys. Lu et al. [5] proposed two-stage HISF process comprising stretch forming followed by SPIF process. A multi-point tool which forms the initial preform shape is used for stretching process to obtain intermediate shape and thickness distribution. SPIF process is then used to form final part shape of part. An aerospace cowling as a test specimen was formed using this process and it was observed that the process combination results in slight reduction in thinning compared to SPIF process. They further optimized the preform shape which resulted in considerable improvement in thinning along with reduced forming time. Tandon and Sharma [6] proposed three-stage incremental stretch drawing process to minimize thinning and to improve thickness distribution along the formed part. Three different tools were used for drawing and incremental forming process. A large sized tool was used for drawing process followed by a medium sized tool which is used for drawing as well as partial incremental forming process. Finally a small tool incrementally forms the final part shape using inside out forming tool path. Authors have reported an improvement of 290% in the sheet thinning using proposed HISF process. Liu et al. [7] used a multipoint forming tool for hydroforming of curved shell components. They found that geometric shape error can be compensated by reconfiguration of multipoint punch resulting in fairly accurate part shapes. Zha et al. [8] formed sheet metal parts using fastened pre tensioning of blank metal sheet over a preform tool. Considerable reduction in spring back in the formed part was observed along with improved thickness distribution because of the presence of secondary support. Panjwani et al. [9] used multipoint flexible bolt support (FBS) to form non-axisymmetric parts such as “M” and “L” shape. From the experimental results it was observed that considerable amount of unwanted geometric deviation was restricted using flexible support. The process can form accurate part shapes which cannot be formed using SPIF process. It was reported that configuration of FBS in terms of bolt diameter, number of supports, thickness of bolts, and clearance (distance between the supports and cavity formed) greatly influence the geometric accuracy of formed parts. Shamsari et al. [10] used a two-step hybrid forming process to improve the formability of parts. A hydraulic system was used for primary bulging process and SPIF was then used to form final part shape. Bulging was done at different oil pressures and it was observed that maximum forming depth achieved using hybrid forming process is more compared to SPIF process. One of the major limitations of this hybrid forming process is bulging of the truncated cones at the bottom because of the preliminary bulging process.

From the literature review, it is found that the process combinations of stretch forming followed by SPIF process can improve thickness distribution, thinning, and formability (in terms of maximum forming depth) along with reduced forming time. Further, it is also observed that sophisticated tooling is used by earlier researchers such as partial die, multipoint stretching tool and hydraulic system [3,5,10] for forming parts using HISF process. Also shape function has not been defined which is one of the major parameter responsible for material flow in addition to thickness distribution and thinning. In present experimental investigation the influence of wall angle, preforming depth and preform tool radius on minimum thickness of formed parts and formability in terms of maximum forming depth using HISF is studied. A simple tooling setup comprising wooden preforming tool is used for stretch forming followed by SPIF process to form final part shape. Rest of the paper is structured in sections including experimental setup and methodology, results and discussion, and conclusion.

2. Experimental Setup and Methodology

In the present study experiments are performed on a 3-axis CNC milling machine (model – M/s Batliboi DART with Siemens controller 802D). To generate the part program, a C++ program is developed. Wall angle, major diameter of cone, pitch or vertical step depth and maximum forming depth are inputs given to the C++ program which writes tool path in form of G-code and M-code and is stored in a ".txt" file. Accuracy of tool path program is checked using simulation software CNC simulator pro and on the simulation platform available on CNC milling machine (Fig. 2). Tools used for preforming process are made of wood and are hemispherical in shape. Low cost, easy availability and easy to form in desired shape makes wood as most suitable material for preforming tools. ISF tools are made of high speed steel (HSS M5) grade.Fixture used for present work is made of L-shaped iron angles welded together to form a rig. Backing plate is used to support the blank sheet and to avoid unwanted bending near the clamped edges and to firmly hold the blank sheet in place. Aluminum alloy Al-1050 of 200 mm × 300 mm having thickness of 1.22 mm is used as a blank sheet. Conical frustums having major diameter of 90 mm and wall angle ranging from 30^o to 70^o are formed using the proposed HISF process as depicted in Fig. 3.

In the present experimental work, influence of three process parameters namely wall angle, perform tool radius (P_rad) and amount of stretching or performing depth (P_d) on minimum thickness (T_{min}) is studied. Experiments are designed according to the full factorial design of experiments (DOE) plan. Total 27 experiments are performed according to the parameters and levels specified in

Table 1.The values of constant parameters are listed in Table 2. Further, investigation on formability in terms of maximum forming depth of parts having 70^o wall angle using HISF and SPIF is also done.

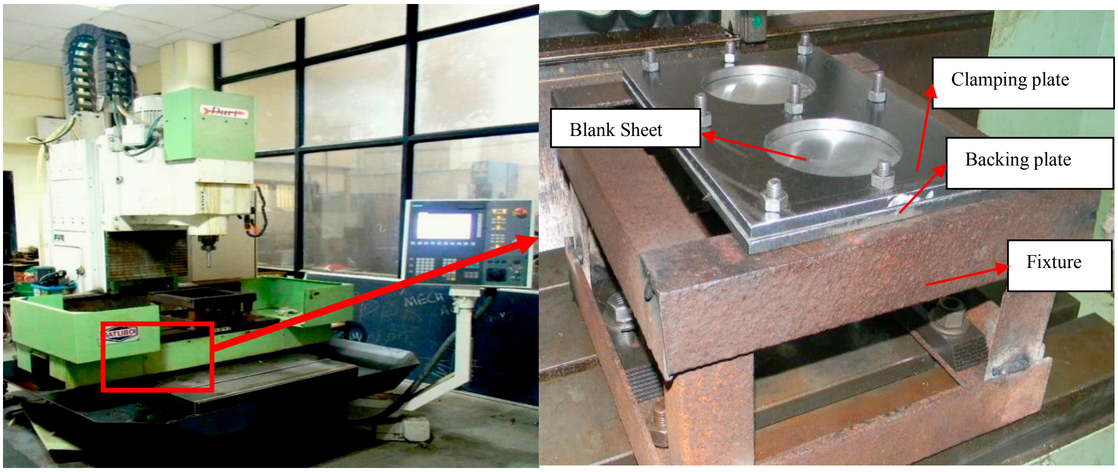


Fig. 2 CNC milling machine along with fixture

Table 1 Process parameters and their levels

Parameter	Unit	Level 1	Level 2	Level 3
Preform tool radius (P_rad)	mm	50	70	90
Preforming depth (P_d)	mm	10	14	18
Wall angle (ϕ)	Degrees	30	50	70

Table 2 Constant parameters and their values

Parameter	Unit	Level 1
ISF tool diameter	mm	10
Pitch or vertical step depth	mm	0.6
Feed	mm/min	1200
Spindle speed	rpm	0

Fig. 3 Conical frustums having wall angle of 30°, 50° and 70° formed using HISF process

Thickness is measured along formed surface at six different locations starting from the clamped edge using Mitutoyo's digital point micrometer. Minimum thickness (T_{min}) is used as response for further analysis. Analysis of variance (ANOVA) is performed to identify the significance of wall angle, preforming depth and preform tool radius on minimum thickness (T_{min}).

3. Result and Discussion

The analysis of variance (ANOVA) is performed to identify the significant variables and to quantify their influence on the response characteristic. The ANOVA table (Table 3) decomposes the variability of response characteristics into contribution due to various factors. Here the contribution of each factor is measured having removed effects of all other factors. The "Predicted R-Squared" of 98.63% is in reasonable agreement with the "Adj R-Squared" of 99.61%.

Table 3 ANOVA table for T_{min}

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A – Wall angle (ϕ)	2	2.06904	2.06904	1.03452	3283.91	0.000
B – P_rad	2	0.00798	0.00798	0.00399	12.67	0.003
C – P_d	2	0.00297	0.00297	0.00148	4.71	0.045
AB	4	0.00146	0.00146	0.00036	1.16	0.397
AC	4	0.00549	0.00549	0.00137	4.36	0.037
BC	4	0.00205	0.00205	0.00051	1.63	0.259
Error	8	0.00252	0.00252	0.00032		
Total	26	2.09151				
				R^2	99.88%	
				Adj R^2	99.61%	

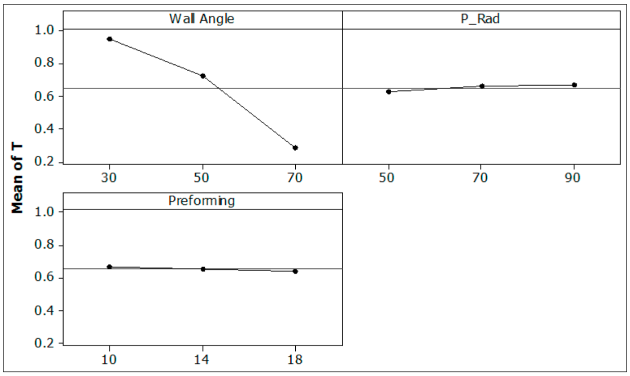


Fig. 4 Main effects plot for minimum thickness (T_{min})

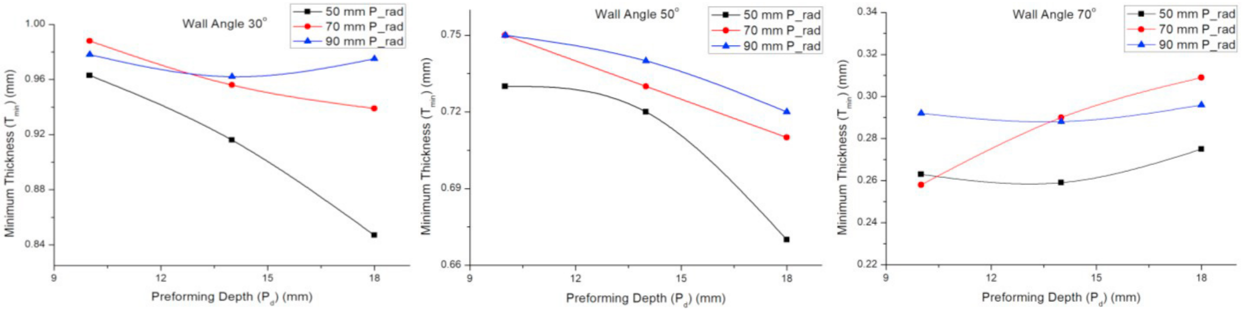
From the ANOVA table, it is found that all three parameters i.e. wall angle (ϕ), preform tool radius (P_rad) and preforming depth (P_d) are significant model terms as p-value of these parameters is less than 0.05. It can be observed from the main effects plot (Fig. 4) that as wall angle increases, considerable reduction in thickness takes place which is in agreement with the sine law of thinning [11,12]. The influence of wall angle on minimum thickness is very large as compared to other two process parameters namely preforming depth and preform tool radius. Hence following analysis is done considering wall angle as constant parameter.

Thickness distribution is function of preform tool shape in HISF process [5]. As observed from main effects plot, change in preform tool radius and preforming depth results in considerable change in the thinning of fomed component. Hence in present experimental investigation, preform tool radius and preforming depth are considered as shape functions. It is observed from hemispherical bulging test that more thinning takes place in the blank sheet at the center of hemispherical bulge. Thinning decreases from center to periphery [13–15]. Also, certain amount of bending takes place near the clapmed edges. As discussed by Young and Jeswiet [16] more thinning resulting in thinning band near clamped edges is observed in parts formed by ISF process.

Preforming or stretching is a plastic deformation process which leads to thickness reduction. Fig. 5 depicts thinning with respect to preforming depth and P_rad for parts with wall angle 30°, 50° and 70°. As preforming depth increases, more plastic deformation takes place resulting in increased thinining as depicted in main effects plot.

It is observed from the Fig. 5 (a) and (b) that for preform tool radius of 50 mm and 70 mm, as preforming increases from 10 mm to 18 mm, there is a considerable reduction in minimum thickness. This reduction in thickness is observed because increase in preforming depth results in more plastic deformation and thinning. As preform tool radius increases, plastic deformation is spread over large area resulting in comparatively reduced thinning. Thinning trends for 90 mm preform tool radius are different while forming parts with 30°wall angle. When large preform tool size is combined with increased preforming,it results in overforming. Because of the overforming SPIF further cannot form desired part shape and considerable distortion is observed. Hence no further thickness reduction takes place and less thinning is observed. The distortion of part shaperesults in large amount of geometric inaccuracy in final part shape.

For conical frustum of 50° wall angle, as walls are steeper than that of 30° wall angle, no overforming takes place. Hence increase in prefomring depth results in increased thinning for all the preform tool sizes. Minimum thinning is observed for preform tool radius of 70 mm and 90 mm for preforming depth of 10 mm.



(a) (b) (c)

Fig. 5 Thinning with respect to preforming (P) and preform tool radius (P_rad) for conical frustum having wall angles of (a) 30° (b) 50° and (c) 70°

Table 4 Maximum forming depth achieved

P_rad (mm)	P_d (mm)	Maximum forming depth (mm)	Improved depth %
NA (SPIF)	0	12.2	NA
50	18	14.0	14.75
70	18	17.2	40.98
90	18	15.8	29.51

While forming cones having wall angle of 70°, premature failure takes place due to excessive thinning. Hence parts are not formed to designed depth. Fig. 5 (c) depicts thinning trends for 70°conical frustum under different preforming conditions. It can be observed from thinning trends that 50 mm preform tool radius results in maximum thinning compared to other preform tool sizes. As preforming depth increases, a slight improvement in thinning is observed which is opposite to that observed while forming cones having 30° and 50° wall angle. This change in behavior is observed because while preforming using small preform tool radius, plastic deformation is concentrated at a very small area. On the other hand thinning band in SPIF process mainly appears near the clamped edge [16]. When this small preform tool radius is combined with small amount of preforming depth, the amount of plastic deformation is very small and concentrated far away from the thinning band. As preforming depth increases, amount of plastic deformation increases resulting in more bulging at center of conical frustun which speads near clamped edge. This increased bulging subsequently helps in reduction in thinning. Formability in terms of maximum forming depth for SPIF and HISF process for different preforming conditions is listed in Table 4. It is found that there is about 15% improvement in maximum forming depth using 50 mm preform tool radius at 18 mm preforming depth as compared to SPIF process. But one of the major limitations of forming using 50 mm preform tool radius is large amount of bulging at the center of cone is observed [10,17]. For preform tool radius of 90 mm similar thinning trends are observed, only difference being less thinning compared to 50 mm preform tool radius. Reduction in thinning is observed due to plastic deformation spread over large surface area. It is also observed that due to its large size of 90 mm preform tool radius, more thinning near clamped edges is observed. This thinning is mainly observed after certain preforming dept and it results in fracture. An improvement of about 29.51 % is observed using 90 mm preform tool radius at 18 mm preforming depth.

While forming parts with 70 mm preform tool radius, small amount of preforming results in more thinning as depicted in Fig. 5 (c). As preforming increases from 10 mm to 18 mm, due to increased preforming depth considerable reduction in thinning is observed. The reduction in thinning is observed because of the primary preforming process which reduces the thinning band appearing near the clamped edge due to bulging. Maximum forming depth due to preforming process is also improved considerably. It is observed from Table 4 that maximum forming depth of 17.2 mm is achieved at 18 mm preforming depth which is nearly 40% more compared to SPIF process.

4. Conclusion

In the present experimental investigation influence of process parameters namely wall angle, preform tool radius and preforming depth on minimum thickness in HISF process is studied. Following conclusions are drawn from the present study –

- Wall angle has significant influence on minimum thickness compared to preforrm tool radius and preforming depth. As wall angle increases considerable reduction in minimum thickness is observed which is in good agreement with the sine law of thinning.
- Preform tool radius significantly affects minimum thickness of parts formed using HISF process. As preform tool radius increases, the contact area between preform tool and blank sheet increases resulting in improved minimum thickness.
- For parts having 30° and 50° wall angle, preform tool radius of 70 mm and preforming depth of 10 mm results in minimum thinning. An improvement of about 18 % using HISF process is observed while forming parts having 50° wall angle as compared to SPIF process. But overforming resuls in shape distortion during forming 30° wall angle. It limits the application of HISF for parts having 30° and smaller wall angles.
- For parts having 70° wall angle, 70 mm preform tool radius and 18 mm preforming depth results in improved thinning. Also, using similar parameter combination an improvement of about 40 % in maximum forming depth is observed compared to SPIF process.

Proposed HISF process is useful for forming parts having vertical walls because of its improved formability. Additionally, tooling cost for this process is minimum compared to other HISF processes as it does not need any specialized tooling setup. Further research efforts can be applied to develop proposed HISF process for forming different part shapes using variety of materials.

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