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Experimental and analytical evaluation of Incremental Sheet Hydro-Forming strategies to produce high forming angle sheets

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ABSTRACT

Incremental Sheet Hydro-Forming (ISHF) is a hybrid process of Incremental Sheet Forming (ISF) and Sheet Hydro-Forming (SHF). In the ISHF process, a single ball tool moves over one side of the surface of the sheet and hydraulic support is provided in another by using the pressurized hydraulic fluid. In the current research, an attempt has been made to achieve high forming angles using ISHF. The forming strategy, multi-stage & multi-step (MSMS), has been proposed to improve the formability in ISHF. The MSMS has resulted in the improvement in the formability and forming angle achieved is 78.75^o. The primary issue, identified in MSMS forming strategy, is the failure of the product due to thinning of the sheet. To address the failure of the sheet due to thinning, a modified version of MSMS was proposed. This modified version of MSMS has shown tremendous improvement in the formability of the ISHF. The forming angle upto 90^o has been successfully achieved using the modified version of MSMS. Analytical models have been developed for MSMS forming strategy and for the modified version of MSMS forming strategy. The experimental results are closely the same as predicted by analytical models.

1. Introduction and motivation

Incremental sheet forming (ISF) is a flexible process for producing 3D complex sheet metal parts. The formability of ISF is much higher than traditional sheet forming processes (Malhotra et al., 2012). The manufacturing industries focus on developing methods, which can meet the demand of producing highly customized products with a reasonable manufacturing cost. Kumar and Kumar (2016) identified one of such hybrid incremental sheet forming which meets such requirement of the industry known as an Incremental Sheet Hydro-Forming (ISHF). In the ISHF process, a single tool moves over one side of the surface of the sheet metals, and the pressurized hydraulic fluid supports another side of the surface of the Sheet metals. A CNC machine controls the tool path.

The key discussion points in the area of ISF are formability, surface quality, geometric accuracy, forming forces & sheet thinning. Many researchers are working in the field of ISF. Malhotra et al. (2012) found that the nature of deformation is local and is primarily responsible for increased formability in SPIF. Ai et al. (2017) found that bending plays a significant role in ISF deformation stability. Cheng et al. (2017) found a significant increase in formability, in electro-hydraulic die forming, is associated with the high-velocity impact against the die wall and the consequent high effective strain rate. Park and Kim (2003) assessed the formability of an aluminium sheet under various forming conditions, and difficult-to-form shapes were produced successfully. Attanasio et al. (2008) optimized the tool path in two-point sheet incremental forming with the full die to reproduce an automotive component with best dimensional accuracy, best surface quality and lowest sheet thinning. Kumar and Kumar (2018a) carried out the analysis of incremental sheet forming process through simulation to predict the forming forces, energy requirements, effective stresses, and total forming forces on the sheet.

Baruah et al. (2017) found that lubrication is the highest contributing factor in ISF for all the three directions – rolling, transverse & angular and feed rate as the least. Vertical step down and speed were the second & third contributing parameters. Durante et al. (2018) proposed an alternate toolpath which enabled the highest formability and minimum twisting, as compared to that observed when the uni-directional toolpath was used. Hussain et al. (2007) investigated that in single point incremental forming (SPIF), the final thickness of a deformed sheet can be predicted by the sine law.

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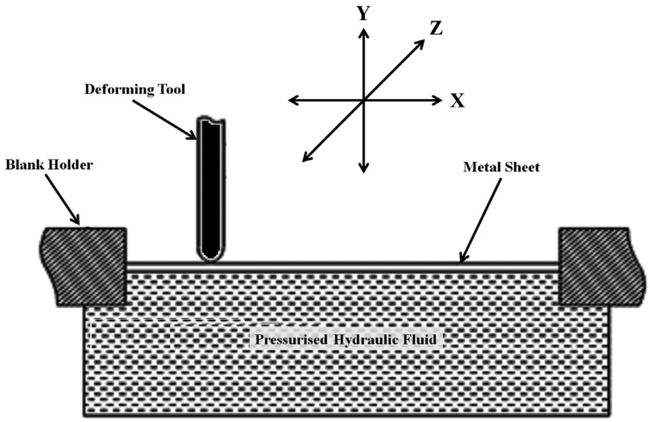

Fig. 1. Incremental Sheet Hydroforming (Kumar and Kumar, 2015).

Duflou et al. (2007) developed an innovative platform, which was capable of measuring forces in the process during incremental forming. Li et al. (2017) investigated the effect of ultrasonic vibration applied to SPIF (single point incremental forming) process. Forming force during forming process induced fracture and affect the accuracy of the sheet metal.

Ambrogio et al. (2007) investigated the influence of process parameters on accuracy through a reliable statistical analysis. Min et al. (2018) tried to improve the poor geometric accuracy of workpieces plagues in single-point incremental forming (SPIF) due to lack of support and unwanted plastic deformation. Bansal et al. (2017) tried to improve geometric accuracy, accurate prediction of sheet thickness, tool-sheet contact area and forming forces are important. Thyssen et al. (2017) presented approach as well as first experimental results to compensate inaccuracies in incremental sheet forming caused by local heating. Valoppi et al. (2017) investigated the characteristics of fracture arising in Ti6Al4V sheets deformed using the Double-Sided Incremental Forming (DSIF) strategy. Kumar and Kumar (2018b) did a comparative analysis of ISF & pressure assisted ISF process through CAE simulation. They found that the pressure-induced ductility helps in reduction of forming forces with pressure assisted ISF, energy requirements in pressure assisted ISF is slightly higher than the ISF process.

2. Multi-Stage & Multi-Step forming strategy for ISHF

A laboratory setup, of incremental sheet hydro-forming Kumar and Kumar (2016), was developed and has been used to carrying out experiments [Fig. 1].

The main elements, of the Incremental Sheet Hydro-Forming machine, are identified as:

(1) Sheet Metal Blank
(2) Hydraulic Blank Holder
(3) Ball Point Forming Tool or Deforming Tool
(4) CNC Machine
(5) Hydraulic System.

ISHF process may be termed as multi-stage forming, if multiple stages are required for producing the final product. The metal sheet is deformed into the final shape gradually in each stage of forming as seen in Fig. 2. Similarly, the step size is varied as each stage for successful deformation of the sheet. Therefore, in order to achieve high forming angle in Incremental Sheet Hydro-Forming, Multi-Stage & Multi-Step (MSMS) forming strategy is proposed. In the current work, analysis and experiments have been carried out for Multi-Stage & Multi-Step forming strategies.

2.1. Preliminary analysis

The preliminary analysis has been done for the successful implementation of ISHF. The part geometry selected for the experiment is $2l_0 \times 2l_0 \times l_0$.

From Fig. 2, let

l_0 = Initial length of sheet under forming
l_1 = Length of sheet under forming after first step
x_1 = Total increment in X direction in 1st step
l_n = Length of sheet under forming after n steps
X_n = Total increment in X direction in nth step
Z_n = Total increment in Z direction in nth step

From the right angled triangle A_0OA_1

$$l_1 = \frac{l_0}{cos\phi_1}$$
$$X_1 = l_1 cos\phi_1$$
$$Z_1 = l_1 sin\phi_1$$

Similarly the Z_n, X_n have been calculated n number of steps as shown in Table 1. The forming angle needs also to be varied at each stage. In the proposed forming methodology the maximum forming angle to be achieved is $\frac{\pi}{2}$. Therefore, it is proposed to achieve 50% for the target forming angle. Similarly, the forming angle has been varied at each stage.

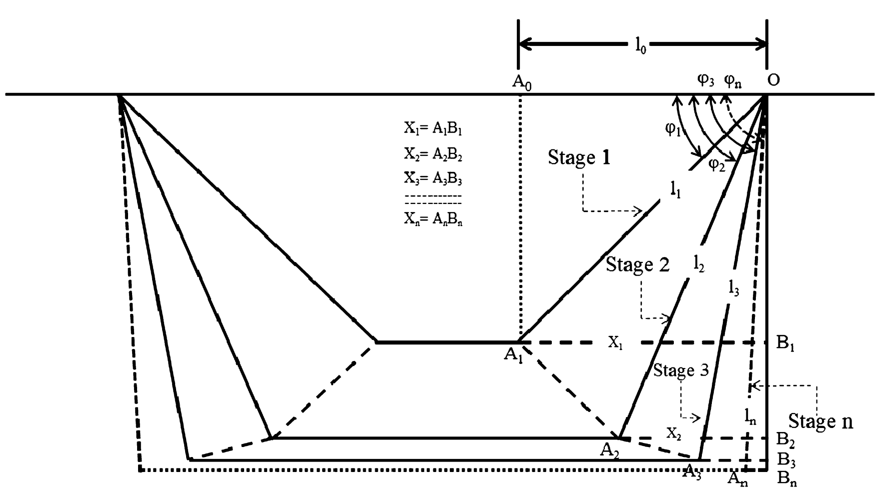

Fig. 2. Multi-Stage & Multi-Step forming strategy.

Table 1
Multi-Stage & Multi-Step forming strategy.

Step no. (n)	Forming angle (ϕ_n)	Forming length (l_n)	X_n	Z_n	ΔZ_n
1	$\phi_1 = \frac{\pi}{4}$	$l_1 = \frac{l_0}{cos\phi_1}$	$x_1 = l_1 cos\phi_1$	$z_1 = l_1 sin\phi_1$	$\Delta Z_1 = t_0$
2	$\phi_2 = \frac{3\pi}{8}$	$l_2 = \frac{l_1}{cos(\phi_2 - \phi_1)}$	$x_2 = l_2 cos\phi_2$	$z_2 = l_2 sin\phi_2$	$\Delta Z_2 = \Delta Z_1/2$
3	$\phi_3 = \frac{7\pi}{16}$	$l_3 = \frac{l_2}{cos(\phi_3 - \phi_2)}$	$x_3 = l_3 cos\phi_3$	$z_3 = l_3 sin\phi_3$	$\Delta Z_3 = \Delta Z_2/2$
.	.	.	.	.	.
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n	$\phi_n = \frac{\pi}{2}(1 - \frac{1}{2^n})$	$l_n = \frac{l_{n-1}}{cos(\phi_n - \phi_{(n-1)})}$	$x_n = l_n cos\phi_n$	$z_n = l_n sin\phi_n$	$\Delta Z_n = \Delta Z_{n-1}/2$

Table 2
Material properties: Aluminum-1080A.

Physical properties	
Density	2.70 g/cc
Mechanical properties	
Brinell Hardness	18
Elastic Modulus	68 GPa
Fatigue Strength	21 MPa
Poisson's Ratio	0.33
Shear Modulus	26 GPa
Shear Strength	49 MPa
Tensile Strength (UTS)	74 MPa
Tensile Strength: Yield (Proof)	17 MPa

Table 3
Experimental details: Multi-Stage & Multi-Step forming strategy [Experiment No. 1].

Step no. (n)	Forming angle (ϕ_n)	Forming length (l_n)	X_n	Z_n	ΔZ_n
1	45^o	$l_1 = 14.14$ mm	$x_1 = 10.00$ mm	$z_1 = 10.00$ mm	0.5 mm
2	67.50^o	$l_2 = 15.31$ mm	$x_2 = 5.86$ mm	$z_2 = 14.14$ mm	0.25 mm
3	78.75^o	$l_3 = 15.61$ mm	$x_3 = 3.05$ mm	$z_3 = 15.31$ mm	0.125 mm

Table 4
Experimental details: Multi-Stage & Multi-Step forming strategy [Experiment No. 2].

Step no. (n)	Forming angle (ϕ_n)	Forming length (l_n)	X_n	Z_n	ΔZ_n
1	45^o	$l_1 = 21.21$ mm	$x_1 = 15.00$ mm	$z_1 = 15.00$ mm	0.5 mm
2	67.50^o	$l_2 = 22.96$ mm	$x_2 = 8.79$ mm	$z_2 = 21.21$ mm	0.25 mm
3	78.75^o	$l_3 = 23.43$ mm	$x_3 = 4.57$ mm	$z_3 = 22.98$ mm	0.125 mm

2.2. Experimental results

Based on the preliminary analysis experiments were carried out. The initial blank of 125 mm diameter and thickness 0.5 mm thickness of Aluminum-1080A has been chosen for carrying out the experiment. The material properties has been shown in Table 2.

For the first experiment, dimensions of the part to be produced using MSMS forming strategy, is 40 mm × 40 mm × 20 mm. The experiment details have been shown in Table 3 and for the second experiment, dimensions of the part to be produced using multi-stage & multi-step forming strategy, is 60 mm × 60 mm × 30 mm. The experiment details have been tabulated in Table 4.

The experiments were planned for 78.75^0. The final deformed product is shown in Fig. 3 for the first experiment and in Fig. 4 for the second experiment.

The deformation behavior reveals that the crack occurs in corners at large forming angle. The second experiment could run only for 67.5^0. However the crack also appeared in straight portion or along the wall toward bottom as shown in Fig. 4. The main reason for occurrence of crack is thinning of sheet. The results show that there is a need to develop an analytical model to predict sheet thinning at large forming angle, which can be generalized for all type of ISHF products.

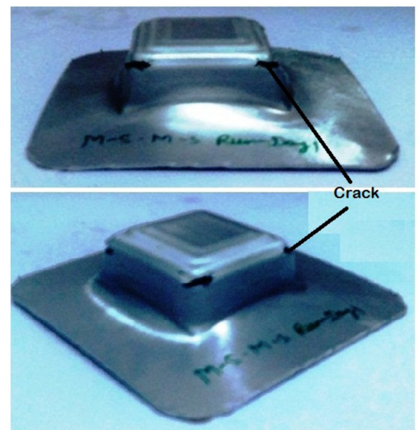

Fig. 3. Crack formation in Multi-Stage & Multi-Step forming strategy for first experiment.

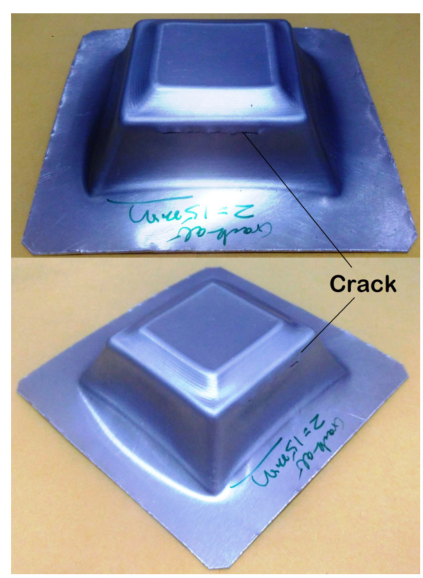

Fig. 4. Crack formation in Multi-Stage & Multi-Step forming strategy for second experiment.

3. Scope for improvement in Multi-Stage & Multi-Step forming strategy

Based on experiments carried out in the previous section, the MSMS forming strategy for ISHF has resulted in probability to achieve high

Fig. 5. Failed product in trial experiment.

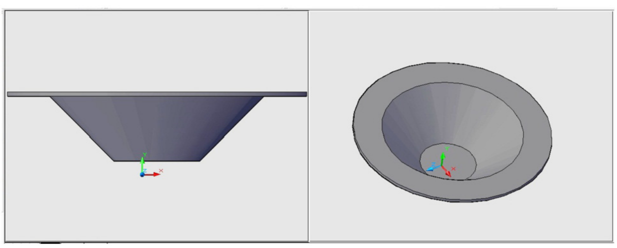

Fig. 6. Final product after implementation of Part 1 using modified MSMS forming strategy.

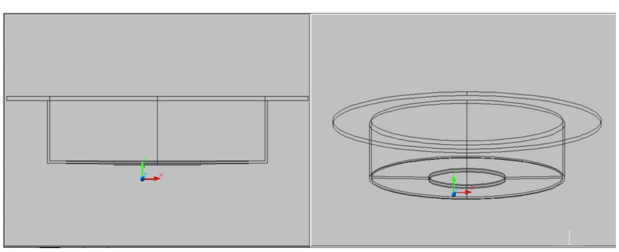

Fig. 7. Final product after implementation of Part 2 using modified MSMS forming strategy.

forming angle. The experiments have also revealed that tool-path is an important factor which governs the failure mechanism in the ISHF process. A circular cup shape as shown in Fig. 5 was chosen for carrying out the experiments to understand the fracture mechanics at forming angle of 90^o.

Based on this trial experiments there is a possibility to achieve 90^o in ISHF process using multi-stage & multi-step forming strategy. The modified version of multi-stage & multi-step forming strategy is implemented in two parts. In first part, sheet blank is deformed at 45^o as shown in Fig. 6 and in order to achieve the rest of 45^o, the deformed portion has also been deformed at forming angle 67.5^o in the 2nd stage. Similar procedure is followed for the next stage and final product as shown in Fig. 7 is expected have an forming angle of 90^o.

3.1. Analytical model for modified MSMS forming strategy

The analytical model has been discussed in current section to order understand forming mechanism in modified MSMS forming strategy. The analytical model is based on the principal of constant volume. The final deformation of the product is combined effect of bending and stretching. The forming of sheet is purely due to bending in vertical portion start point and the stretching increases gradually with depth. The same deformation behavior is followed in horizontal portion under forming.

Let t_o = initial sheet thickness
R = radius of circular section
l = depth of circular section
t_{Wall} = final thickness at depth l in vertical portion of sheet at corner
t_{Bottom} = final thickness l in horizontal portion of sheet at corner

In the current analytical model, it is assumed that half of volume is stretched in vertical direction and remaining half in horizontal direction. Thus, based to the principal of contact volume t_{Wall} and t_{Bottom} may be found using the equations (1) & (2).

$$t_{Wall} = \frac{t_o}{2}\left(1 - \frac{l}{2R}\right) \tag{1}$$

$$t_{Bottom} = \frac{t_o}{2}\left[\frac{\left(1 - \frac{5l}{6R}\right)}{\left(1 - \frac{l}{3R}\right)}\right] \tag{2}$$

Let us discuss few cases:

CASE 1: $R = \infty$: $t_{Wall} = 0.5t_o$, $t_{Bottom} = 0.5t_o$.

Therefore, for the product with straight line may be deformed to any depth. The sheet thickness throughout all deformed portion either in vertical or horizontal portion is same and is equal to half of the initial sheet thickness.

CASE 2: $R = l$: $t_{Wall} = 0.25t_o$, $t_{Bottom} = 0.125t_o$.

This analytical model shows that the chances of failure in the horizontal direction (i.e. bottom plane) are more as compared to the vertical portion. The main reason behind thinning because of stretching in the bottom portion is more as compared to the vertical portion.

3.2. Experimental results

The experiments have been carried out using modified MSMS forming strategy. The aluminium sheet blank of diameter 125 mm and thickness 0.5 mm has been selected for carrying out the experiment. The first part of experiment, has been carried at step size 0.5 mm i.e. for achieving 45^o. Second part of the experiment, step size has been selected adoptively and is given by equation (3),

$$\Delta Z_h = \frac{\Delta Z_o}{2}\left(1 - \frac{h}{2R}\right) \tag{3}$$

Where, h = is depth upto which forming angle 90^o has been achieved.

The back side of the sheet is supported by hydraulic pressure. The first part of the experiment has to be performed at constant hydraulic pressure, however the second part of the experiments needs to be carried out at varying pressure. The pressure required at any depth h may be given by equation (4).

$$p_h = \frac{p_o}{2}\left[\frac{\left(1 - \frac{5h}{6R}\right)}{\left(1 - \frac{h}{3R}\right)}\right] \tag{4}$$

The experiment was successfully carried out for $l = 12$ mm and $R = 35$ mm. The final product is shown in Fig. 8. From equation (1) & (2), sheet thickness in vertical portion is $t_{Wall} = 0.207$ mm and sheet thickness in horizontal portion is $t_{Bottom} = 0.202$ mm. During experiment, sheet thickness in vertical portion is $t_{Wall} = 0.21$ mm and sheet thickness in horizontal portion is $t_{Bottom} = 0.20$ mm.

Thus, sheet thinning predicted through analytical model are closely same as obtained in experiments as shown in Fig. 9 and Table 5.

Fig. 8. Final product after implementation modified MSMS forming strategy.

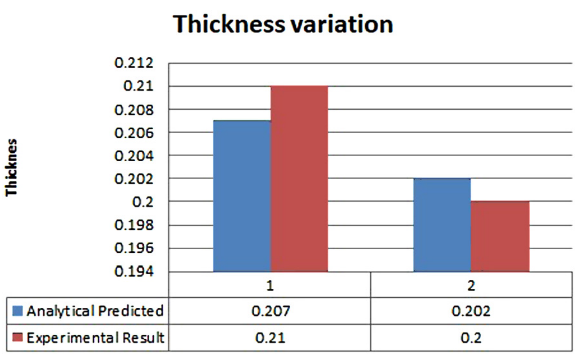

Fig. 9. Comparison of analytical model and experimental results.

Table 5
Experimental results: modified Multi-Stage & Multi-Step forming strategy.

S.No.	Parameter	Analytical predicted	Experimental result
01	t_{Wall}	0.207 mm	0.21 mm
02	t_{Bottom}	0.202 mm	0.20 mm

4. Conclusion

The outcomes current research are tremendous in the area of Incremental Sheet Forming. The multi-stage multi-step (MSMS) forming strategy has resulted in the improvement in the formability and has resulted in the possibilities to achieve forming angle up to 78.75^o. The modified version of the MSMS forming strategy has extraordinary improvement in the formability of the ISHF process. The high forming angle (up to 90^o) has been achieved using this forming strategy. The analytical model for variation of sheet thickness is in-line with experimental results. The main reason, for the improvement, is hydrostatic support provided by the hydrostatic pressure on the opposite side of the sheet surface. This forming strategy is going to open a new era in the area of incremental sheet forming. The variation of sheet thickness is independent of material properties. The result of experiments done can guide for any material.

Declarations

Author contribution statement

Yogesh Kumar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Santosh Kumar: Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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