

Study On The Single Point Incremental Sheet Forming of AISI 321 Variable Wall Angle Geometry

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Abstract

For rapid prototyping, design validation and small batch productions process with low tooling cost is preferred. Single Point Incremental Forming (SPIF) is a die-less sheet metal forming process which requires only low cost forming tool driven by CNC machine in a toolpath to form required geometry at room temperature from sheet blank clamped in a low cost and low stiffness clamping system. In this study, effect of process parameters such as tool radius, feed rate and lubrication are considered on the formability of the truncated profile of AISI 321 Variable Wall Geometry (VWA). Set parameters conditions with 2 level layers are optimized using numerical and statistical approach. Experimentation on the same setup is carried out by selecting the most, least and mid favorable solutions optimized on the basis of forming forces and stresses in the sheet. Geometrical accuracy, sheet thinning, and forming forces are compared analytically, numerically and experimentally addressing the inadequacy of analytically models for Variable Wall Angle Geometries.

Introduction

Sheet metal work is everywhere from travelling by various transportation means, getting treated in hospitals with medical equipment, using modern gadgets like mobile and laptop, while shopping with currency coins to eating with cutlery. Dies and punches used for most of the sheet metal working are expensive without mass production. Storage of dies is a challenging task specifically in automobile sector in which components are large with more product life time. With the advancement and increased demand of sheet metal products for various fields, there is a need for advanced and rapid techniques in sheet metal working. Incremental sheet forming is rapid, agile and highly flexible process for small batch productions. Designed products can be rapid prototype and tested via this process before rolling out the final design and product. New tailored design requirements can also be met via Incremental Sheet Forming (ISF). ISF makes variety of 3D shapes using a simple forming tool in low cost, high quality and smaller lead time due to which it has gained the attention of both industry and academia during last two decades.

ISF is the technological advancement of spinning process. During ISF, sheet metal is formed into 3D shape using a simple specialized tool, path guided and force applied by Computer Numeric Controlled (CNC) machining center. Tool is usually in contact with the sheet metal at the point of contact only which generates local area deformation and stresses that allows greater formability limits. ISF is widely adopted for small batch and customized products compared to stamping and deep drawing process [1, 2] because with minimum specialized tool forming can be performed by simply importing CAD data into CNC compiler.

In Single Point Incremental Sheet Forming (SPIF), a single tool is in contact with sheet with a defined toolpath without any die for sheet metal. Tool moves incrementally in set trajectory of toolpath to form the sheet. Only clamping plates and backup supports are used owing to tool forces.

Edward Leszak [3] patent the ISF in 1967 by developing the die-less sheet forming axis symmetric products with inexpensive tool attached on turntable in 1964. ISF development history may be grouped into 3 periods [4]. Until 1996 researchers mostly worked on the SPIF process which includes major contributions from researchers like Leszak, Berghan and Mason. Mason in 1978 [5] used the rollers progressively in passes to produce desired shape using backing material as a support which later on discovered not to be necessary.

While from 1993 to 2000 major scope of the researchers in Japan was on Two Point Incremental Forming (TPIF) specifically by Iseki et al. [6] During this era Iseki revolutionized the processes of ISF by starting his experiments with turn table [6] and later on developed 3 dimensional Incremental forming machine in 1996 [7]. During this period giant automotive Japanese companies such as Hitachi, Toyota and Honda developed the process of ISF for manufacturing embossed wall panels with different variants of ISF [4].

Later in 2000, researchers expanded their scope of work on ISF from all over the world. Filice et al [8] and Jesweit et al [9] during early 2000's studied the capability of using CNC milling centers for ISF. Most of the patents were from Automotive Industry, Honda in 2002 patented the ISF process in which body is formed incrementally into convex and concave parts using female die. Honda applied ISF in collaboration with Amino [10] to make replacement parts of Honda S800 sports car. Dimensions of original parts is taken with measuring machines and parts is then reproduced using generated coordinates. In 2004, BMW make individual parts from standardized part by using a mandrel type forming tool. Daimler used conventional TPIF to form a full die from interlocked pieces of sheet.

Jesweit et al. [2] concluded that formability of ISF is defined by four major parameters: sheet thickness, drawing angle, radius of forming tool, feed rate and rotational speed. Mode of deformation is still debatable issue among different researchers. There are two different school of thoughts related to deformation mode of sheet, one of them proposed stretching while other proposed shearing as deformation mode. Allwood et al. [11] purposed combination of stretching and bending deformation mode as formability mechanism. However, Silva et al. [12] concluded that the principal mode of deformation for ISF is in-plane stretching and further they deduced the formability criterion.

Conical frustum cones shapes are being used in diverging and converging cones for throttling purposes having variable wall angle (VWA) profile. Current study will aim towards the successful forming of conical frustum shown in **Fig. 1** using single point incremental forming (SPIF) on AISI 321 sheet. Geometrical accuracy, sheet thinning, and forming forces will be analytically, numerically and experimentally compared.

Materials And Methods

Material Properties of AISI 321

Table 1 Chemical Composition of AISI 321

C	Mn	Si	P	S	Cr	Mo	Ni	N	Other
0.08	2	0.75	0.045	0.030	17 ~ 19	-	9 ~ 12	0.10	0.70

Table 2 Mechanical Properties of AISI 321

Tensile Strength MPa	Yield Strength MPa	Elongation (% in 50mm)	Rockwell B Hardness HRB	Brinell Hardness HB
515	205	40	95	217

Tensile tests

Tensile tests are required for plastic material model behavior in Finite Element (FE) simulation. Dog-bone specimens of AISI 321 sheet are prepared according to ASTM E8 standard. Tests are performed at various strain rates ranging from 0.48mm/min to 480mm/min due to strain rate sensitivity of AISI 321. Higher strain rates yield strain hardening and increases the yield strength of material. Hence for ISF relatively low strain rate 48mm/min will induce strength in the material while forming

Experimental Setup

Two 190x190 mm square mild steel plates of 6mm thickness having through pocket 140x140mm used as grabbing and backing plate. Eight Ø8 through holes drilled for M8 Hex bolts. For axial load and sheet clearance during forming two C channels are welded at base. Incremental load is applied via hardened D2 hemispherical tool of radius 6mm and 8mm attached on CNC milling head on the sheet blank which transform it into the desired shape. Experimental fixture consist of different components as shown in **Fig. 3**

DMG Mori 1035 V ecoline vertical machining center is used as machine tool having SINUMERIK 840D HMI capable of displaying spindle load forces while machining/forming with max feed force of 5 KN. Toolpath is generated using Siemens NX 1872 CAD/CAM.

Numerical Simulation Of Isf

Explicit dynamics module of ANSYS is used for numerical simulation in this study because of non-linearity and localized nature of plastic deformation of SPIF.

Table 3 Interaction & Material Definition

Part	Material	Stiffness Behavior	Surface	Contact
Sheet	AISI 321	Flexible	Slave	Frictional with Tool
Tool	D2 Tool Steel	Rigid	Master	Frictional with Sheet

Frictional interaction between tool & sheet surfaces is defined by assigning the numerical value of coefficient of friction (COF). Sheet is divided into flexible and fix sheet regions and meshed with quad elements of 4mm element size. Whereas tool is full body meshed with tri elements. Adaptive meshing is selected because it gives better results compared to FE Analysis results without it. Complexity of meshing elements and smaller element size increases the simulation time without any significant effect on the results. Orthogonality is selected as mesh metric.

Sheet is assumed to have no pre-stress prior to forming. Simulation is performed in a single step and virtual forming speed is 100 times scaled up than the original time taken by the tool to form the sheet which ultimately decreases simulation time and performs effectively. To ensure quasi-static forming simulation, kinetic energy is kept less compared to total internal energy and dynamic effects are not included as simulated by Li et al [13] and Kurra et al [14].

Displacement of tool is approximated by defining its coordinates in x , y and z directions using damped simple harmonic motion for truncated cone of major diameter 100mm as toolpath from CAD cannot be defined directly in FEA. Helical tool path is defined for the tool with respect to time increment. A total end time of 1.8s is divided into 1800 increments defining the tool path displacement.

Material model definition & simulation benchmarking

Sheet plasticity is modeled using multilinear isotropic hardening in *ANSYS* as sheet is under monotonic loading and elastic unloading. For defining this behavior multilinear true stress values are required against the plastic strain. This model behavior is piece-wise linear stress-total strain curve. Uniaxial tensile test data of true stress and strain obtained from the tensile tests as elaborated **Fig. 2** is sufficient to define the material definition of AISI321 for sheet.

Forming forces and simulation time are selected as FEA convergence criteria. Experimental results of forming forces obtained by Bagudanch et al [15] are compared with the simulation results of this study for convergence.

Experimental study carried out by Bagudanch et al.[15] in which AISI 304 is numerically simulated and compared with the present study for simulation validation. Results differs slightly by 5.7%, therefore simulation is a good approximation for predict the kinematics of SPIF.

Simulation Trials

Tool radius, feed rate & friction are variable process parameters for simulation. Their levels are defined and simulation trials are run as per Design of Experiment (DOE).

Table 4 Process parameters and their levels for Simulation

Process Parameters	Code	Level		Unit
		1	2	
Tool Radius	A	6	8	mm
Feed Rate	B	2400	3000	mm/min
Coefficient of Friction (COF)	C	0.25	0.3	-

Axial force Fz and von mises stress obtained from FEA simulation results are response parameters on which the success of the process based. Lower the response parameters axial force lower the required forming force and lower the von mises stress lesser will be the chance of crack in the sheet while forming. Therefore axial force Fz & von mises stresses will be minimized. Axial force Fz & Von Mises stresses of 4 DOE trails are tabulated in **Table 5**.

Table 5 Response Parameters Obtained via Simulation Trails

Simulation Trail	Process Parameter			Explanation of DOE Array			Response Parameters FEM Values	
	A	B	C	Tool Radius (mm)	Feed Rate (mm/min)	COF	Max Axial Force Fz (N)	Max Von Mises Stress (MPa)
1	1	1	1	6	2400	0.25	2215.5	446.20
2	1	2	2	6	3000	0.30	2455.2	473.45
3	2	1	2	8	2400	0.30	2421.8	457.57
4	2	2	1	8	3000	0.25	2605.0	474.51

Simulation Results Optimization for Experimentation

Linear model of statistical tool analysis of variance (ANOVA) is used to study the variance of feed rate, tool radius & COF on SPIF Response optimizer is used in Minitab to minimize both the axial force and stresses for obtaining most & least favorable solution.

Table 6 Solutions from Most Favorable to Least Favorable

Least favorable parameter condition is when tool radius is 8mm, feed rate is 3000mm/min with gentle

Solution	Tool Radius	Feed rate	COF	Von Mises Stress Fit (MPa)	Axial Forces Fit (N)	Composite Desirability
1	1	1	1	446.200	2215.50	1.00000
2	1	1	2	451.355	2243.75	0.87097
3	2	1	1	452.415	2393.55	0.65092
4	2	1	2	457.570	2421.80	0.53051
5	1	2	1	468.295	2426.95	0.31679
6	1	2	2	473.450	2455.20	0.12000
7	2	2	1	474.510	2605.00	0.00000
8	2	2	2	479.665	2633.25	0.00000

amount of lubrication while most favorable parameter condition is when tool radius is 6mm, and feed rate is 2400 mm/min with ample amount of lubrication.

Prediction of ANOVA approach is compared by performing the actual FE analysis on process parameters of solution 5 in **Table 6**. Axial forces and stresses obtained through FE analysis are predicted with values obtained by ANOVA.

Table 7 Solution 5 Comparison with FEA Results

Axial Force (N)			Von Mises Stress (MPa)		
Predicted via ANOVA	Actual FEA value	% Difference	Predicted via ANOVA	Actual FEA value	% Difference
2426.95	2433.2	0.25	468.295	469.24	0.20

Percentage difference of predicted results is not very significant which shows that ANOVA results is accurate and half array of Taguchi DOE may be implemented.

Experimentation

Experimentation Trails

Experiments are performed on the most and least optimized parameters based upon the simulation results. Each experimental set is tested by keeping the step down 0.5mm with constant spindle speed of 1000rpm.

Experiment: Most Favorable Condition: Tool R6, Feed 2400 mm/min and COF 0.25

Experimentation is performed by generating the CAM program of the most optimized parameters. Grease is initially applied as a lubricant and during the process the interaction between sheet and tool is avoided by pouring a small amount of viscous slideway oil K220. Part in desired shape is formed successfully with a better surface finish without any crack.

Experiment: Least Favorable Condition: Tool R8, Feed 3000 mm/min & COF 0.3

CAM program is generated with least optimized values. Lubrication is applied gently on the surface of the sheet initially and no lubrication medium is added during the experimentation. It is observed that there are visible burn marks on the formed part and visible cracks along the circumference appeared for a part having forming depth of 18 mm to 20 mm near fillet radius. Larger crack was of 5 mm in length and 1 mm in width while smaller crack was a pin hole.

Summary Of Results And Comparative Study

Forming forces, geometrical accuracy & sheet thinning, are compared analytically, numerically and experimentally of successfully formed sheet from most favorable condition.

Forming Forces

Analytical model for the prediction of axial force Eq. (1) is based upon uniform wall angle and does not incorporate feed rate. It fails to give a good approximation of the numerical axial forces of variable wall geometry. Analytical model gives a maximum axial force at wall angle of 50° due to variation of α in Eq. (1). Experimental forces during the experimentation are estimated directly from the CNC milling machine spindle load as per analytical model purposed by Aggarwal et al. [16] in which cutting forces were directly derived from spindle current and number of revolutions. Analytical, numerical and experimental obtained maximum axial forces are compared as shown in **Table 8**.

$$F_z = 0.0716 R_m t^{1.57} d_t^{0.41} \Delta h^{0.09} \alpha \cos(\alpha) \quad (1)$$

Table 8 Comparison of Maximum Axial Forces F_z

Exp Trial	Analytical (Ana) Results (N)	Numerical (FEA) Results (N)	Experimental (Exp) Results (N)	% Error Exp-FEA	% Error Exp-Ana
1	767.0345	2215.5	2385	7.106918	-60.7323
2	855.7768	2421.8	2600	6.853846	-60.2317
3	767.0345	2455.2	2680	8.38806	-62.9912
4	855.7768	2633.25	2895	9.041451	-61.398

FE analysis predicts better results for the maximum axial force during SPIF of VWA truncated cones as it incorporates material behaviors, thinning and straining of material.

Geometric Profile Comparison

Formed part shows pillow effect of 0.5mm in height which is due to the fact that base of sheet remains in elastic state while rest of the sheet is in plastic state. Profile obtained from FE simulation predicts that the elastic recovery of the sheet elastic is more than that of obtained from experimentation. This difference is due to the explicit nature of the solution and the estimation of the tool path analytically.

Maximum spring back occurs near the base-wall interaction of VWA part. Bend/fillet radius is not effected by spring back because tool form the radius after achieving the desired forming depth as shown in **Fig. 9**

Comparison of spring back is tabulated in **Table 9**

Table 9 Spring back comparison in terms of springback angle

Depth (mm)	Target Profile Wall Angle (Degree)	Actual Profile Wall Angle (Degree)	Spring back angle (Degree)
0	28.17	23.75	4.42
5	34.82	35.57	-0.75
10	40.50	40.39	0.11
15	45.59	42.32	3.27
20	50.27	49.59	0.68
25	54.65	51.42	3.23

Sheet Thinning

Sheet thinning is inevitable during SPIF due to local deformation of clamped sheet that without any die beneath it instead of flow. Excessive wall thinning can lead to the failure of sheet due to tearing. Final thickness of the formed part can be approximated analytically by sine law as indicated in Eq. (2) which is based upon the simple shear forming process.

$$t = t_0 \sin\left(\frac{\pi}{2} - \alpha\right) \quad (2)$$

Where t_0 is initial thickness of the sheet and α is the angle of wall with respect to horizontal while t is the final thickness of the sheet. As geometry is variable wall angle, thickness will be different at different depth heights as the wall angle steeply increases with the depth of the sheet.

Thickness is measured experimentally using ultrasonic thickness gauge GE CL5. Comparison of thicknesses obtained analytically, numerically and experimentally are compared and is shown in **Fig. 10**

Sine law is only an approximation and cannot predict the exact thinning behavior of the sheet. Sine law predicts more thinning in the initial process and less thinning at the final stage of SPIF as shown in **Fig. 11**

FE numerical simulation predicted the similar actual pattern of sheet thinning with maximum percentage error of 8.1 %. Hence, numerical solution give better approximation for sheet thinning.

Conclusion

It is concluded from the experimental results that Feed rate is one of the dominating process parameter for SPIF as it increases the forming forces and stresses that causes the excessive thinning of the sheet and may tearing of the sheet. Tool radius has a major contribution in the forming forces however its contribution as compared to feed rate in stress generation is minimal. Although, lubrication has a minor contribution but when compares to axial forces it shows a significant influence in variance of stresses.

Wall thinning is the SPIF process that induces the significant effect on the forming part. It is observed that it is varied according to the depth that limits the SPIF for deep drawing. Larger lengths can be drawn by use of die or hydraulic chamber which will control excessive thinning.

Analytical models may better predict the geometries with Uniform Wall Angle (UWA) as compared to Variable Wall Angle (VWA) geometry as SPIF is still to be completely developed analytically. FE model predicts the better results as compared to analytical models for complex geometries like UWA.

Future Recommendations

Forming Forces and thinning analytical models for VWA geometry for AISI 321 is still an area to be explored. Sine law and other force models developed for UWA can only give the approximation.

Implicit FE approach is iterative however its computation time is high and requires a system with higher specifications. Comparison of both explicit and implicit with experimental studies can give better insight of SPIF for VWA.

Optimization algorithm of larger subset using Artificial Neural Network can be developed for better results.

Work is still going on in the area of SPIF. Literature revealed that analytical models developed by different researchers do not include the frictional effects (nonlinearities). Future research can be done in this aspect.

Declarations

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Declaration of Interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Availability of data and material

Not Applicable

Code Availability

Authors' Contributions

Main Author: Conceptualization of idea, design & fabrication of experimental setup, simulation of the problem, experimentation, paper writing & simulation

Supervisor: All technical & data analyzing guide

Co Authors: Helped in simulation trials, data collection & finalization of research paper writing

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Figures

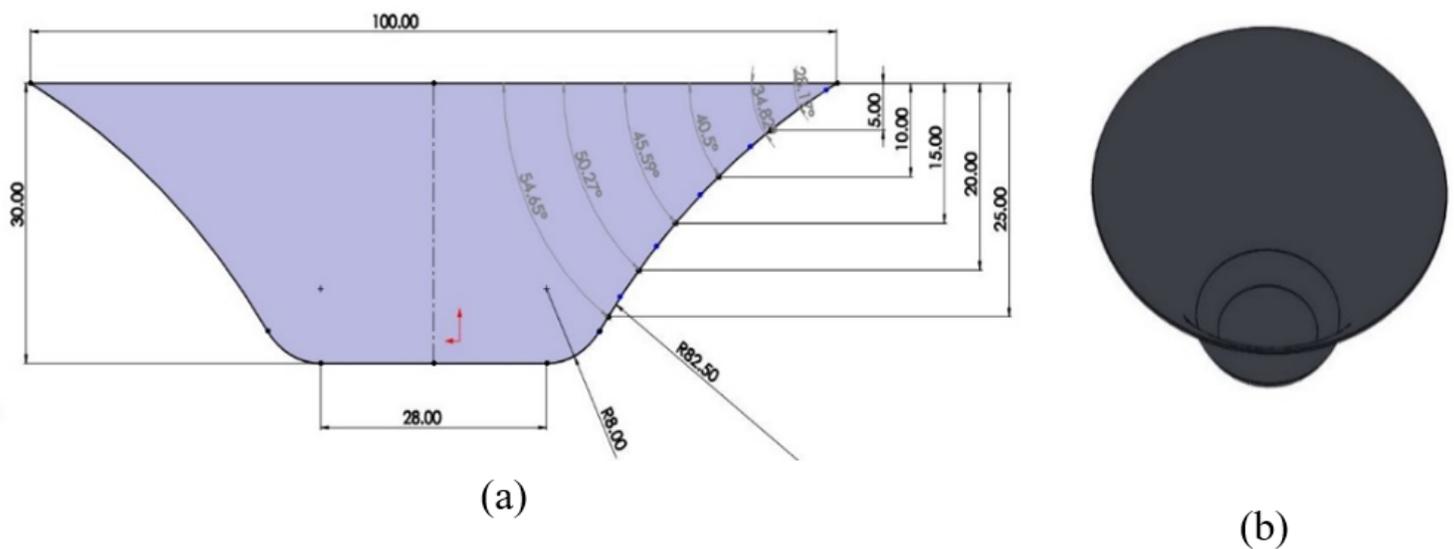
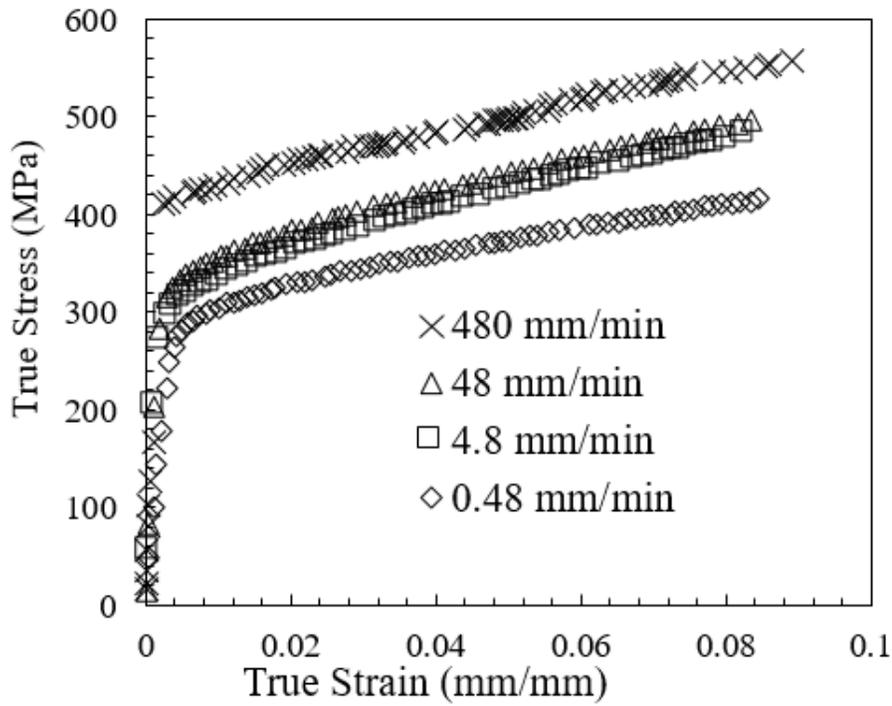


Figure 1

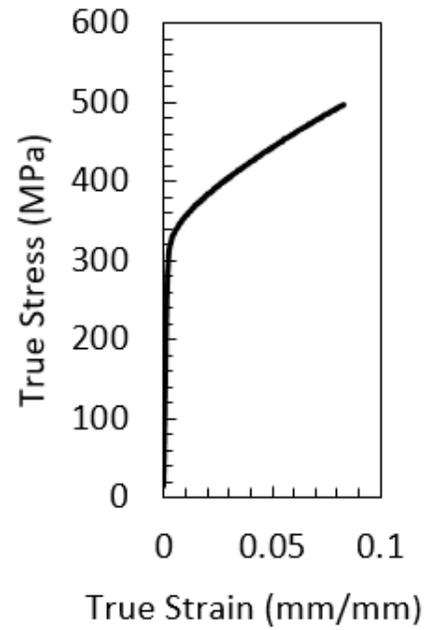
Profile dimensions of VWA truncated cone and its 3D model



(a)



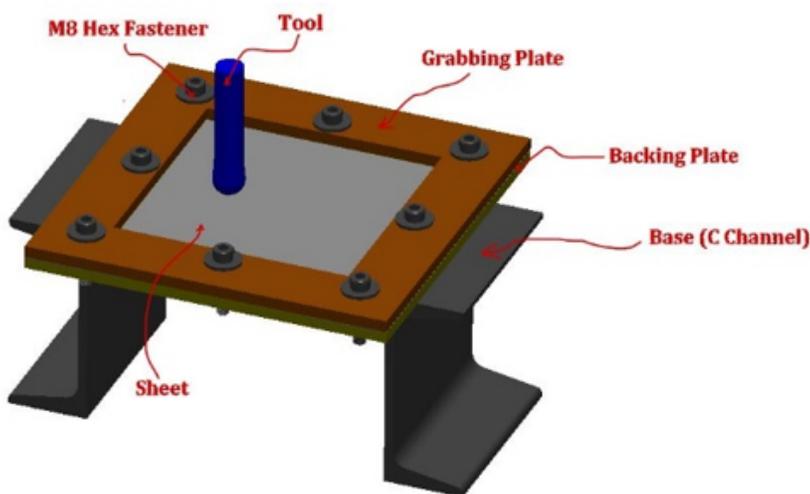
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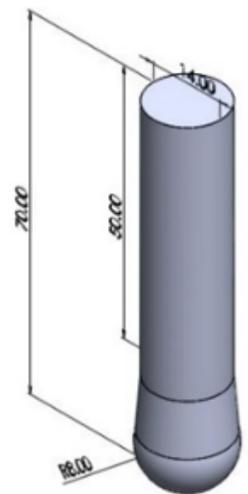
(c)

Figure 2

(a) Tensile test specimen as per ASTM E8 standard (b) Stress-Strain diagram of AISI321 sheet at different strain rate; and (c) at strain rate of 48mm/min only



(a)



(b)

Figure 3

(a) Experimental Setup for SPIF (b) Hemispherical forming tool for SPIF R8 Tool DMG Mori 1035 V ecoline vertical machining center is used as machine tool having SINUMERIK 840D HMI capable of displaying spindle load forces while machining/forming with max feed force of 5 KN. Toolpath is generated using Siemens NX 1872 CAD/CAM.

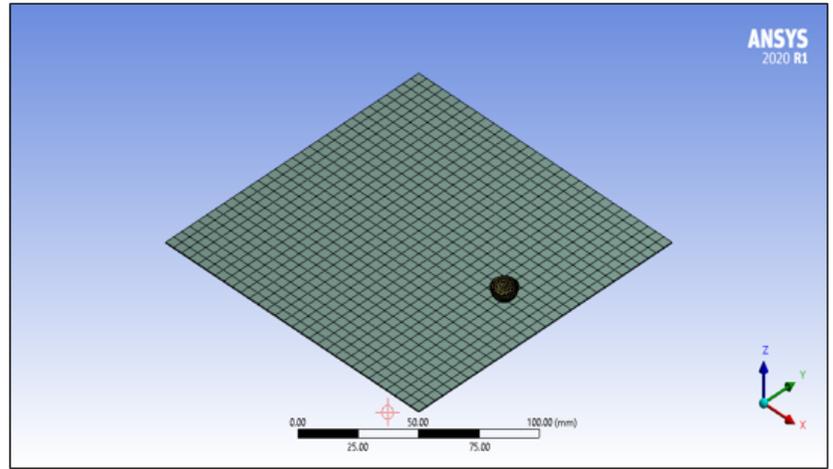
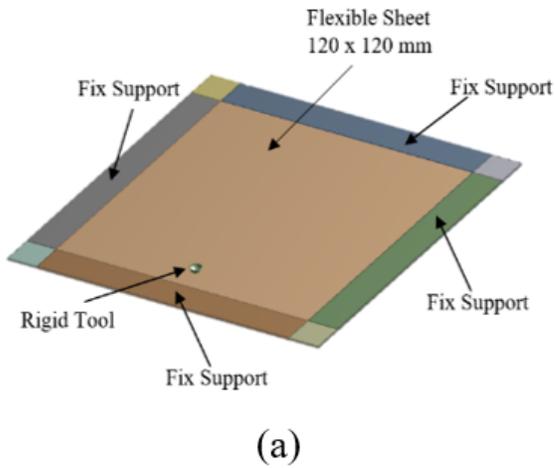


Figure 4

(a) Modeling simplification in FEM for SPIF (b) Meshed Quadrilateral sheet element and rigid tool tri element

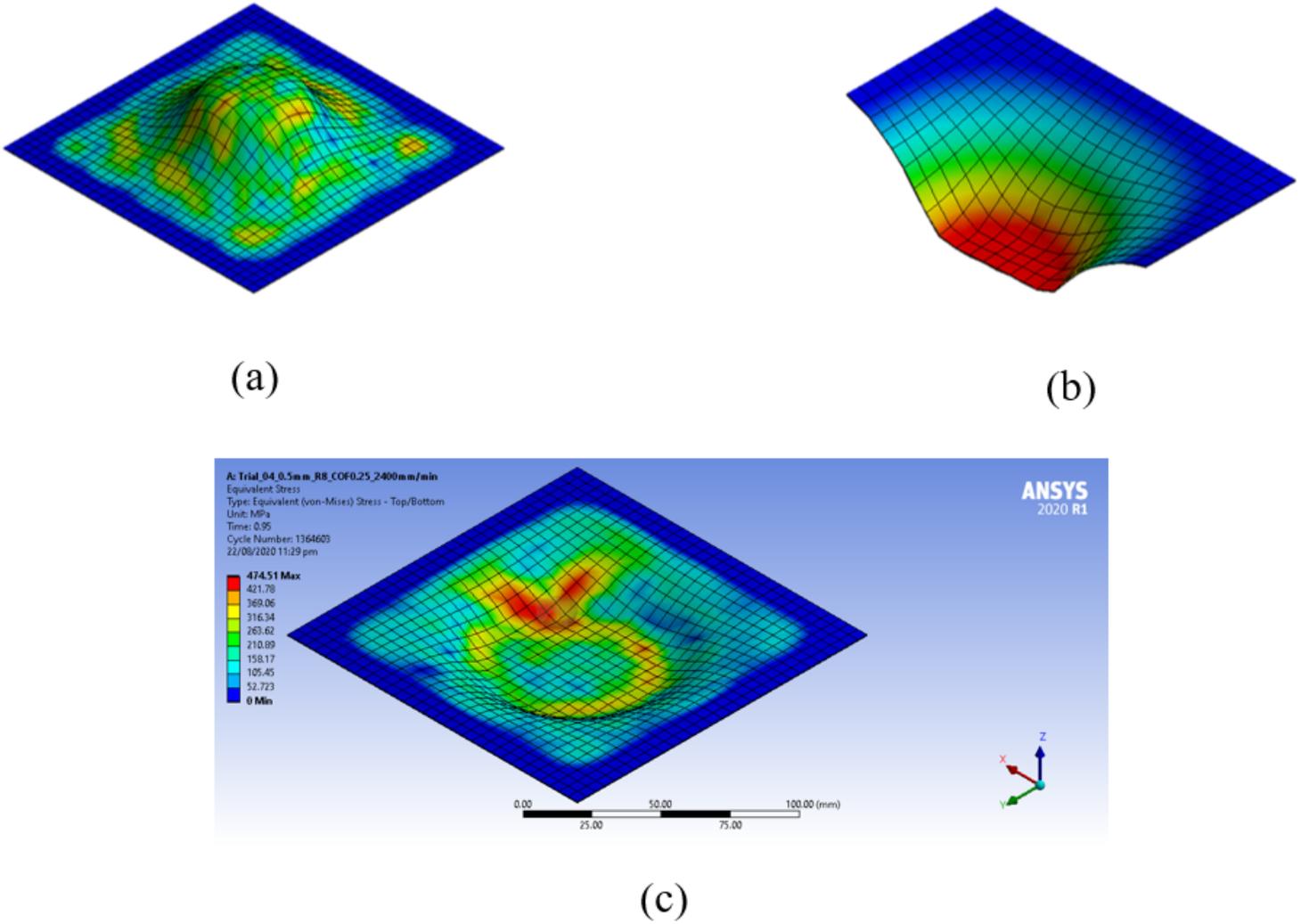


Figure 5

FEM Results (Trail 4) (a) Bottom View (b) Sectioned View (c) Maximum stress at Tool-Sheet Interaction depicting localized stresses near tool-sheet interaction

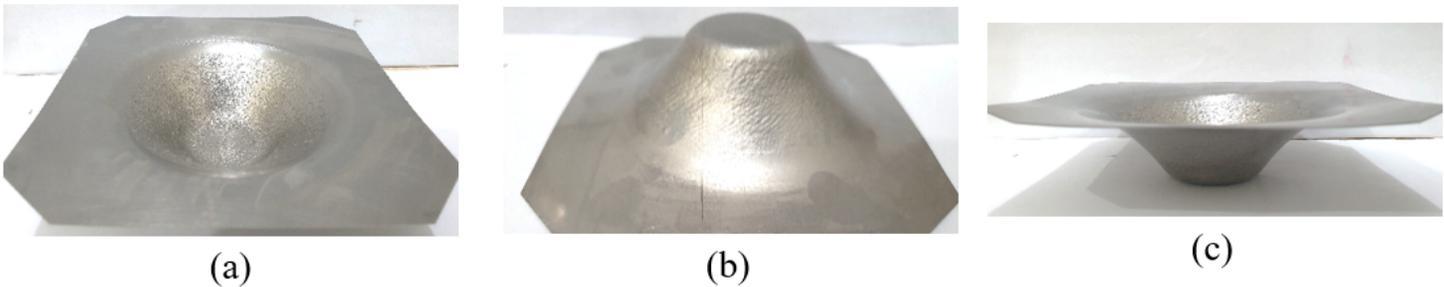


Figure 6

Experimental Trial 1: Successfully formed Truncated Cone VWA geometry

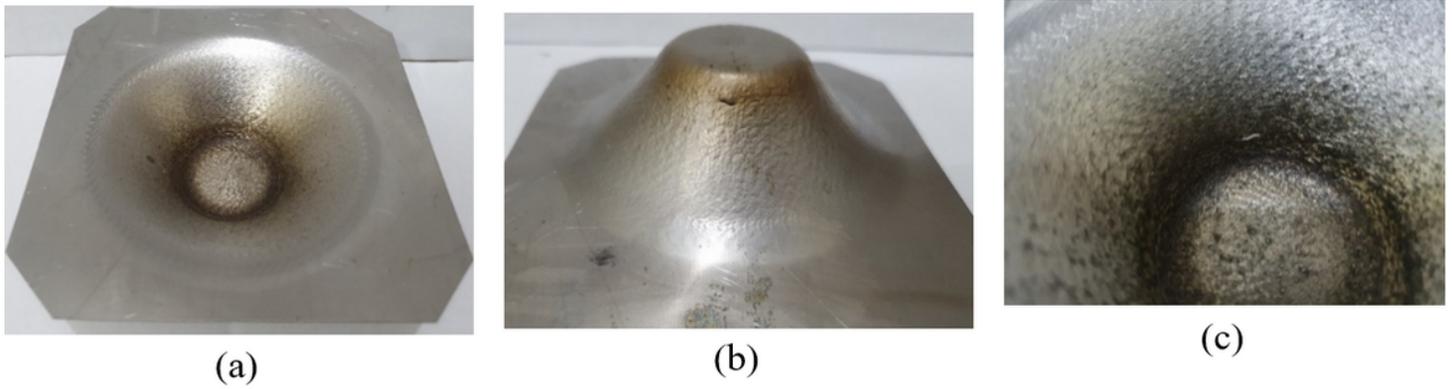


Figure 7

Burn marks & major & minor cracks along the circumference

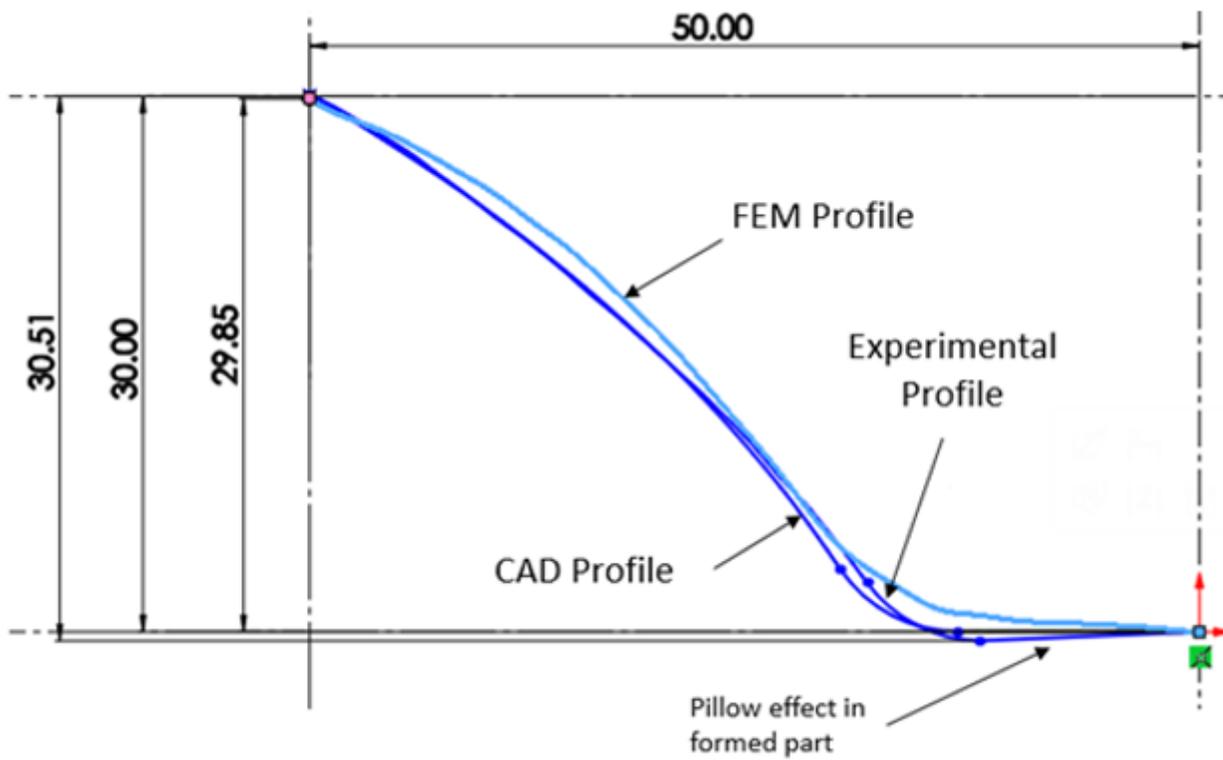


Figure 8

Comparisons of Shape Profiles: i) Problem statement profile (Actual/CAD Profile) ii) Simulation Profile obtained via FE analysis & iii) Experimental shape profile

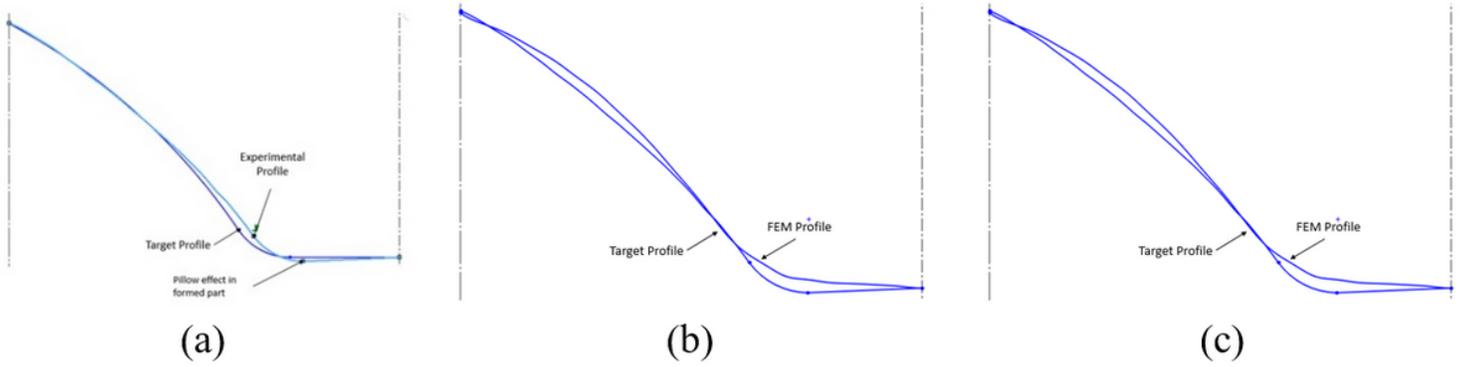


Figure 9

Comparison of profiles (a) Pillow effect occurs in actual part along with elastic spring back of sheet (b) FE profile is in conformance with target profile difference. (c) Indication of spring back approximation in FE profile induced by SPIF

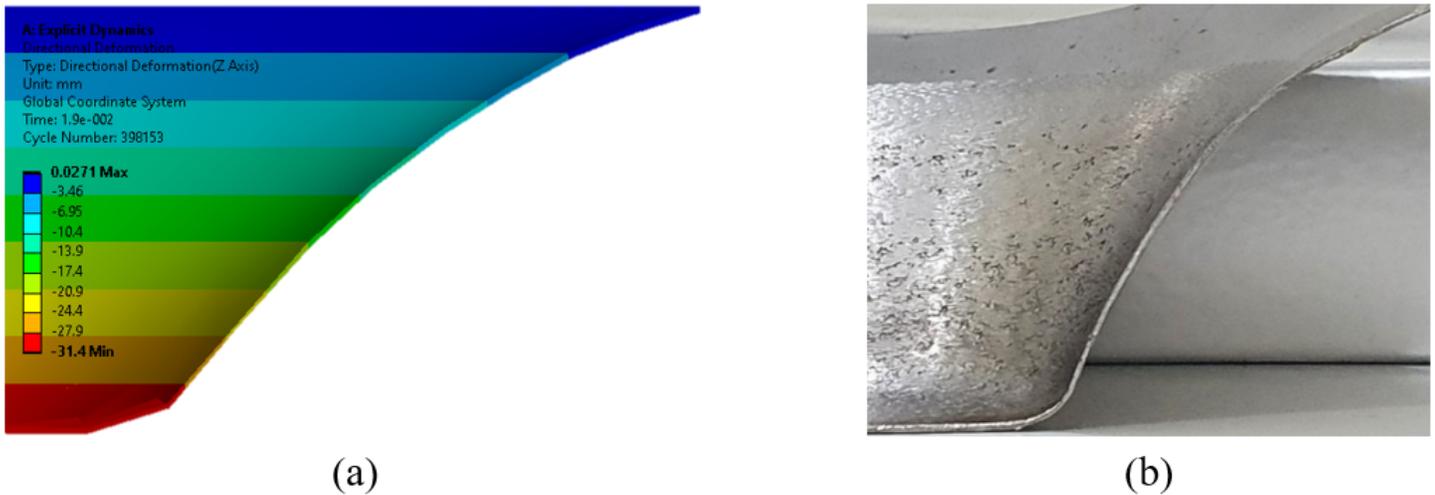


Figure 10

Side by Side Thinning Comparison (a) FE Model predicting the thinning (b) Thinning in actual part formed using SPIF. Numerical simulation is in conformance the actual thinning behavior of sheet

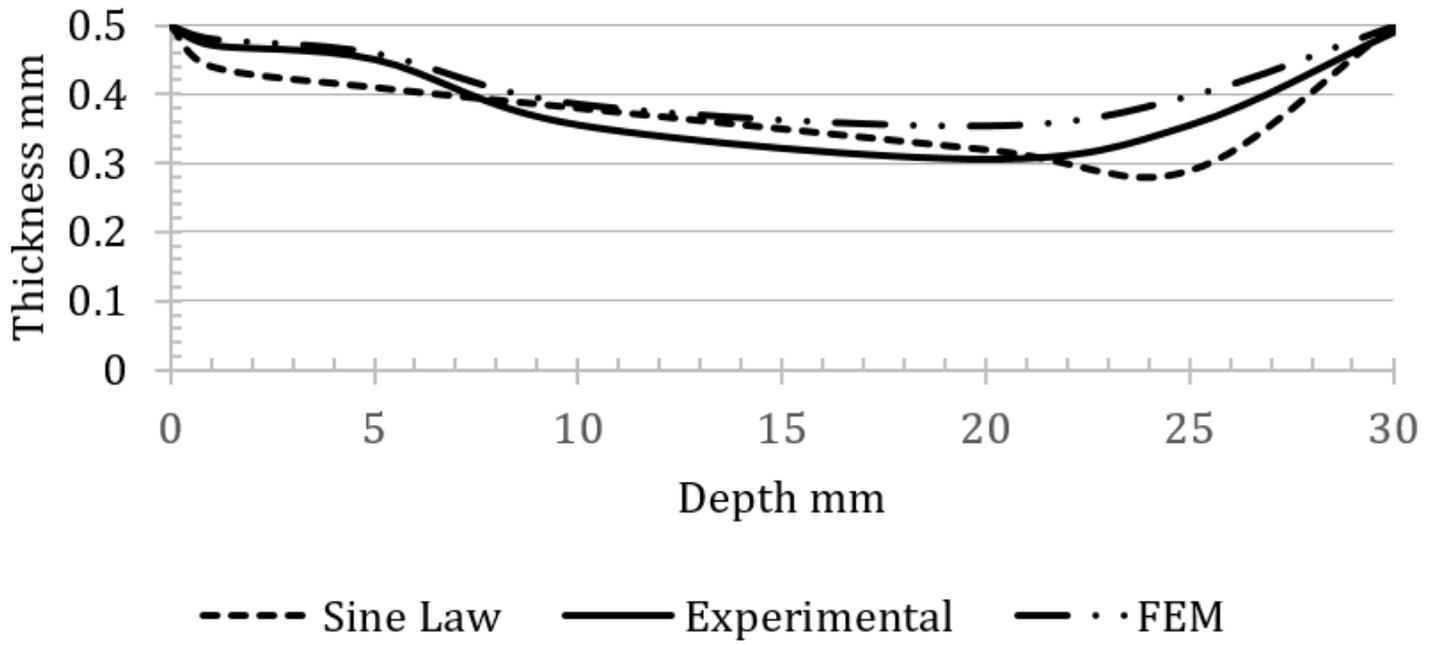


Figure 11

Comparison of sheet thicknesses analytically, numerically and experimentally