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EXPERIMENTAL AND NUMERICAL STUDIES ON SINGLE POINT INCREMENTAL FORMING OF COMMERCIAL ALUMINUM ALLOY

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Abstract: Single point incremental forming (SPIF) is a new innovative and feasible solution for the rapid prototyping and the manufacturing of small batch sheet parts. In the present study, experiments were conducted to analyze the effect of process parameters on the formability of commercial aluminum alloy AA1100. Major process parameters like Wall angle, Step increment, Feed rate, and Spindle speed, are set at three levels and experiments were designed by using the Taguchi method to get the two response parameters, wall thickness and surface finish. Analysis of variance shows that surface roughness depends on step increment by 64.19 % and wall angle by 17.23 %. For thickness reduction, only wall angle (99.79 %) is responsible. For achieving better surface finish we need to control wall angle, step increment, and feed rate while for thickness reduction we have to control only wall angle. This study also incorporated implementation of Hills yield criterion, Von Mises yield criterion, and power-law flow rule in the abacus explicit; which are evaluated through the thickness and strain results of experimental work. SC8R shell elements employed in the simulations good results for forming of pyramid frustum with 45-degree wall angle. The power law is taking less time to complete simulation compared to other two yield criteria. The accuracy of the power law is higher within three simulations. All the three simulations are giving the satisfactory results within 5% error value.

Keywords: SPIF, Prototype, Forming limit curve, Formability, Surface roughness, ANOVA, FEA

I. INTRODUCTION

For small scale production, the most economical sheet metal operation is single point incremental forming as it is a die-less process. The deformation of the material is carried out incrementally and as a consequence, less forming loads are required as compared to the conventional processes. In accordance with figure 1, the sheet undergoes progressive local plastic deformation, produced by the tool which has a hemispherical head. The process is carried out at room temperature and requires a CNC machining center, a hemispherical head tool and a simple support to fix the sheet being formed [1-2]. In incremental sheet metal forming, the blank is incrementally deformed into a desirable shape by hemispherical or ball nose tool traveling along a programmed path. Due to the various advantages including the reduced production cost and time of prototypes, improved formability, easy modification of part design etc. the ISF is being popular as a new innovative forming technology. SPIF process performance is affected by various factors like tool path, sheet material, forming an angle, tool size, step size, forming speeds (tool rotation and feed rate), lubrication and shape. The tool path is generated according to the profile of the CAD models. This package is usually used for material removal in milling and is perfect for SPIF because its built-in path generation algorithm can be used to guide the forming tool. The angle that the side walls of a part make with the horizontal XY-plane is known as a forming angle. The extent of this angle depends mainly on material properties and the sheet thickness. Nonetheless, SPIF parts are controlled by the maximum forming angle (Ø max) to which a material can be drawn from catastrophic failure in a single forming pass. Tool size greatly affects both the formability and the surface finish of the manufactured part through this process. Experiments have shown that smaller radius tools have higher formability than larger ones. The influence of step size on the formability along with how much it influences the SPIF process is still a debatable parameter.

Figure 1: Single point incremental forming set up

Some researchers hold that step size does not influence formability but rather it only affects surface roughness. While others believe that it does influences formability and by increasing the step size there is a decrease in the formability. The influence of forming speed, both rotational spindle speed, and feed rate are important regarding the SPIF process. The relative motion between the tool and sheet is directly proportional to the heat that is generated by friction. Formability differs between materials. Previous literature study reveals that the strain hardening coefficient (n), as well as the interaction between the strength and strain hardening coefficient, have the highest influence on formability. Lubrication is a major influential parameter is SPIF in order to reduce to reduce tool wear and improve surface quality. FEM simulation of SPIF process is a very complicated task due to large and complex model and movement of the forming tool. The time required for getting simulation results is high, so reduction of the computational time of simulation is one of the problems.

II. LITERATURE REVIEW

Many researchers have addressed the effect of process parameters affecting the response by incorporating various strategies. Cerro et al. [1] studied SPIF process by the numerical and experimental way to predict surface roughness and stress distribution on the sheet during forming. Hussain et al. [2] have found that the good surface quality of pure titanium formed sheet is obtained by using surface hardened high-speed steel tool and molybdenum disulphide paste with petroleum jelly in a specific proportion. Durante et al. [3]studied about the influence of tool rotation on an incremental forming process of aluminum alloy sheets. The effect of variation in the spindle speed on friction coefficients, forming forces, temperature measurements, and average surface roughness were investigated. In addition to this, they also investigated analytical and experimental investigation of surface roughness using AA7075 T0 sheets by varying the tool radius, vertical step depth, and slope angle. Shanmugananatan and senthil kumar [4] carried out an experimental and numerical simulation to investigate maximum wall angle, surface roughness and sheet thinning of Al 3003(O). Ambrogio et al.[5] attempted to study formability behavior of lightweight alloys by hot incremental sheet forming. They identified the working window as a function of the maximum wall inclination angle and the heat flux required to safely shape the part. In addition, they also investigated high-speed incremental forming in order to study the effect of input variables on surface roughness and part accuracy. Zhaobing et al. [6] studied the impact of influential process parameters on surface roughness using the design of experiments (DOE) along with multi-objective function. Thickness distribution and failure limited diagram are studied by malwad and nandedkar to understand the deformation mechanism behavior of commercial AA8011. Desai et al. [7] presented one factor at a time approach in die less rapid prototyping process to study the effect of process parameters such as feed rate, tool rotational speed and incremental step depth on forming characteristics. Henrard et al. [8] developed a dynamic explicit time integration scheme to make contact between the tool and the sheet metal. Capece et al. [9] done experimental work to find maximum slope angle of frustums of pyramid and cone carried out by incremental forming and validation of FE code. Junchao et al. [10] performed multistage forming for parts which have steep angles based on FE code and experimental validation. Minoru et al. [11] studied the deformation behavior of SPIF process by dynamic explicit finite element code DYNA3D and the effect of tool path on deformation behavior is also evaluated. Dejardin et al. [12] studied about the analysis of shape distortions and springback effects in SPIF. Yuanxin et al. [13] presented a method based on minimum energy principal to find the final shape of the component and also computed stress and strain distribution by Inverse FEM. Robert et al. [14] proposed an elastoplastic algorithm with the help of anisotropic criteria and theory of incremental deformation. The currently used methods of sheet metal forming are suitable for forming of soft materials. However, one important drawback is that the forces on the forming become high when forming thicker material. Therefore, it is generally not possible to substantially form harder and stronger but less ductile materials, such as high-strength alloys. Another drawback is the difficulty to create clearly localized slope changes within complex products in order to meet the requirements. The selection of process parameters (wall angle, tool rotation, vertical step size, tool diameter, and lubrication) is difficult to control thickness reduction and surface quality and ductile damage in incremental sheet metal forming. In the present research work, an attempt has been made to analyze the impact of major process parameters and their mutual interaction on the ductile damage as well as identification of optimum parameter to achieve greater surface finish and to control wall thickness. In addition to this, the experimental runs was also validated with the numerical simulation in order to verify the research campaign.

III. EXPERIMENTAL WORK

All the experiments were performed on 3 axes CNC HAAS Mini Milling machine in the Production department, Indo-German Tool Room, Aurangabad, India is shown in figure 1. In CNC HAAS, the tool is controlled by a computer and is programmed with a machine code system that enables it to be operated with minimal supervision and with a great deal of repeatability. The characterization of this tool path is only a continuous feed rate in X and Y direction of a deformed sheet plane. The feed rate in the Z direction is done in the angular position. Z axis of travel machine is the up-and-down. CNC machine uses computer program written in the notation called G-code. The program can be transferred by using computer system connected with the machine or by using a floppy drive. CAD geometries were generated with UGNX 8.5 and CAM tool paths were designed with UGNX 8.5 CAM. Mill contour machining environment was used to generate contour tool path. Program and tool path were generated for cavity mill, which is cutting operation. Mill finish method was selected and profile cut pattern were used to follow the only periphery. FANUC postprocessor used to generate the program that contains G & M code. Lubricant was used in the form of a thin film over the sheet being formed in the form of a lubricant pool to avoid this and to reduce the impact of friction between the forming tool and the sheet. The clamping system is designed according to guidelines provided in NUMISHEET 2014- benchmark problem 3. The whole apparatus is clamped. to the bottom corners of the working table of the CNC by two T-bolt and nut. Apart from iron, aluminum is currently the next most widely used metal in the world. This is due to the fact that aluminum has a unique combination of attractive properties. Properties such as its low weight, corrosion resistance, and easy maintenance of the final product, have ensured that this metal and its alloys will be in use for a very long time. The chemical composition and mechanical properties are shown in table I and table II respectively. Castrol Illoform TDN 81 was used under the different process conditions on the AA8011 material. The chemical composition and mechanical properties are shown in table I and table II respectively.

Table I
Chemical Composition of AA 8100

Element	Contribution (%)
Al	97.3-98.9
Fe	0.6-1
Mn	0.2
Zn	0.1
Cu	0.1
Ti	0.08
Cr	0.05
Mg	0.05
Reminder	0.15

Table II: Mechanical Properties of AA 810

Parameter	Value
Density	2.71 g/cm^3
Young's modulus	72 GPa
Poisson's ratio	0.27
Ultimate tensile strength	150 MPa
Maximum elongation strength	50-60 %

The Experiments were performed to analyze the effect of wall angle, step size, and tool diameter, spindle speed and feed rate on formability of commercial aluminum alloy. At initial stage experiments were carried out by using material AA8011. Constant angle test was designed to evaluate the formability of material at an angle 550, 650 and 75 0. During these experiments, spindle speeds of 1000 rpm and feed rate of 1500 mm/min were held constant throughout the experiments. All the parts were formed in a cone shape with a diameter of 94 mm and to achieve the depth of 50 mm. Following table III shows the variable parameter combination during the experiments. For AA8011 experiments were formed according to L9 orthogonal array to obtain the quantitative values of response parameters. The orthogonal array is generally used to minimize the cost of experimentation and process time and meaning optimisation results should comes out.

Table III: Single point incremental forming parameter and their levels

Factors	Unit	Level 1	Level 2	Level 3
Wall angle	degrees	55	65	45
Step increment	mm	0.2	0.5	1
Feed rate	mm/min	500	800	1200
Spindle speed	rpm	600	800	1000

The experimental work is also carried out to validate simulation results. The ASTM E8 standard is used to carry out the tensile testing. The load cell is a strain gauge based type with full wheat-stone bridge configuration. Driven cross head is moved with the speed of 0.5 mm/min. The tests are carried out till the breakage of specimens. In order to compare numerical condition and experimental condition, the same step size, same tool diameter, the same tool path is used in the simulations and experimentation. The depth of cut in milling is 1mm which generates step size of 1mm in incremental sheet forming. The major length of the square cone is 100 mm. The taper angle of 450 is provided to the contour. The forming tool is made heat treated HSS of diameter 10 mm. The Total depth to be cut is given as 35mm in the negative z direction.

IV. DESIGN OF EXPERIMENTS- TAGUCHI METHOD

The technique of laying out the conditions of experiments involving multiple factors was first proposed by the Englishman, Sir R.A.Fisher. The method is popularly known as the factorial design of experiments. A full factorial design will identify all possible combinations for a given set of factors. Since most industrial experiments usually involve a significant number of factors, a full factorial design results in a large number of experiments. To reduce the number of experiments to a practical level, only a small set of all the possibilities is selected. The method of selecting a limited number of experiments which produces the most information is known as a partial fraction experiment. Although this method is well known, there are no general guidelines for its application or the analysis of the results obtained by performing the experiments. Taguchi constructed a special set of general design guidelines for factorial experiments that cover many applications.

Table IV: Plan of Experiments Using L9 Orthogonal Array

Exp. No.	Wall angle	Step increment	Feed rate	Spindle speed
1	55	0.2	500	600
2	55	0.5	800	800
3	55	1	1200	1000
4	65	0.2	800	1000
5	65	0.5	1200	600
6	65	1	500	800
7	45	0.2	1200	800
8	45	0.5	500	1000
9	45	1	800	600

Taguchi has envisaged a new method of conducting the design of experiments which are based on well-defined guidelines. This method uses a special set of arrays called orthogonal arrays. These standard arrays stipulate the way of conducting the minimal number of experiments which could give the full information of all the factors that affect the performance parameter. The orthogonal arrays method lies in choosing the level combinations of the input design variables for each experiment. The L9 orthogonal array is meant for understanding the effect of 4 independent factors each having three-factor level values as shown in table IV.

V. NUMERICAL STUDY

The Abaqus/CAE 6.13 is used to perform the simulation results. In the simulation, total three parts are modeled viz., sheet metal, forming tool. Sheet metal is modeled as a 3D solid rectangular sheet of dimension 220mm × 220 mm × 0.8 mm. In the simulation the tool diameter, tool rotational speed, feed rate and step depth are 10 mm, 1000 rpm, 600 mm/min and 1 mm respectively. The sheet is then divided into two sections, one where clamping is taking place and other where machining taking place. Use of two sections gives advantages of changing mesh. Clamping area is coarse meshed while the working area is fine meshed. Shell type of element SC8R is used to mesh the sheet.

The tool is modeled as a rigid analytic surface. Modeling tool as rigid part gives a computational advantage. The reference point is defined at the tip of the tool. Thus, the tool movement can be defined by selecting only a reference point. The mass property is necessary to assign when the part is modeled as a rigid tool. For three different simulations, three different definitions of the same material are used. Density, elastic and plastic data is same for all the simulations. The power law is given by the equation $\sigma=K\varepsilon n$, where K=312 MPa, n= 0.138 for commercial aluminum alloy as per results of tensile testing. Von Mises criterion applied to material if R11=1; R22=1; R33=1; R 12=1; R23=1; R13=1 values are given potential option of material plasticity. For Hills criteria, AA8011 Lankford coefficients are: R0=0.625; R45=0.667; R90=0.695. These values give R11=R23=R13=1, R22=1.032, R33=0.925; R12=1.04.

The boundary condition of arresting translation of sheet metal in three mutually perpendicular directions is implemented by applying the U1=U2=U3=0 condition. This condition is applied because sheet metal is not allowed to slide from clamping area and which leaves the clamping area elements free to rotate around x, y, z-axes. The interaction between tool and sheet are given through general contact algorithm. Coloumb‟s friction law is implemented through the mechanical option of interaction properties. Friction value equal to 0.1 is considered. The similar conditions were maintained for the actual experimental study.

VI. RESULT AND DISCUSSION

The thickness is measured from top to bottom at the depth of 15 mm, 30 mm, 45 mm, 60 mm and 70 mm. Surface qualities are measured at five different points and average response of wall thickness (mm) and surface roughness. In the Taguchi method, the term „signal‟ represents the desirable value (mean) for the output characteristic and the term „noise‟ represents the undesirable value for the output characteristic. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available depending on the type of characteristic: Target is best, Smaller is better, and Larger is better.

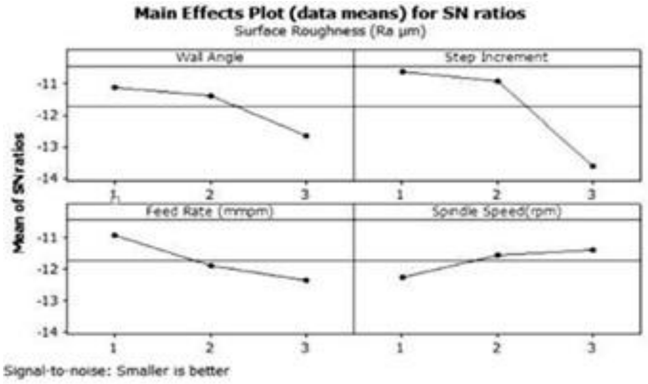


Fig. 2. S/N Ratio Graph for surface Roughness

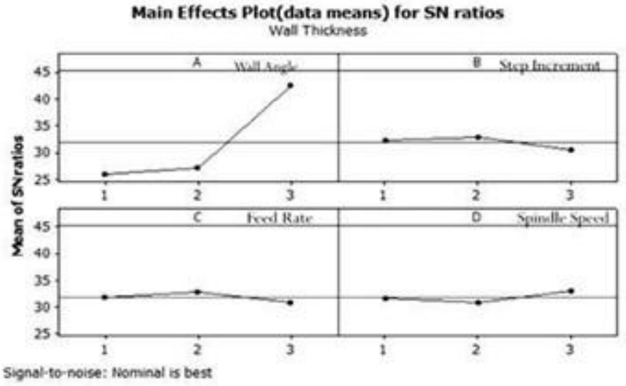


Fig. 3. S/N ratio graph for wall thickness

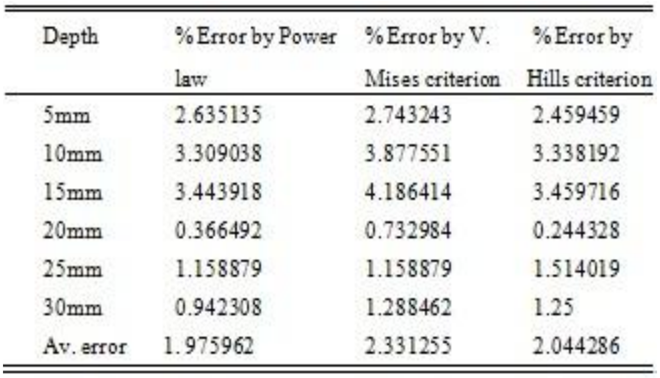
From the S/N ratio analysis in Fig. 2 and Fig. 3 reveal that, optimal conditions for Surface finish are wall angle 550 (level 1), Step Increment 0.2 mm (level 1), Feed rate 500 mm/min (level 1) and Spindle Speed 1200 rpm (level3). S/N ratio analysis of Fig. 3 shows only wall angle affect significantly on sheet thickness reduction because there is no large deviation of S/N ratios of Step increment, Feed rate and Spindle speed from the mean value. ANOVA was used to determine the significant parameters influencing surface finish and wall thickness in the forming of AA8011. Table IV shows summary of ANOVA results for surface roughness and wall angle. In this study, the analysis was a level of significance as 5% and level of confidence as 95%. From the above ANOVA results, it is clear that surface roughness depends on step increment by 64.19 % and wall angle by 17.23 %. For thickness reduction, only wall angle (99.79 %) is responsible. For achieving better surface finish.

Table V: ANOVA results for surface roughness and wall thickness

		ANOVA for Surface Roughness			ANOVA for Wall thickness		
Factors	DOE	Sum of Squares	Mean of squares	Contribution	Sum of Squares	Mean of squares	Contribution
Wall angle	2	1.0114	0.5057	17.23	0.38315	0.19158	99.79
Step increment	2	3.7685	1.8843	64.19	0.0002	0.0001	0.05
Feed rate	2	0.6664	0.3332	11.35	0.0003	0.0002	0.08
Spindle speed	2	0.4244	0.2122	7.23	0.0003	0.0001	0.07
Error	0	0			0	0	
Total	8	5.8707			0.3839		

It is essential to control three parameters but for thickness reduction we have to control only one parameter i.e. wall angle. The parameter which defines the contact between sheet and tool are important for surface finish means the surface finish depends on the contact area and contact time between tool and sheet. More thickness reduction can be achieved for greater wall angle, this is only due to the less sheet material is available for deformation at large wall angle. For simulation, results of thickness are taken from the cut view, as after cutting the real component thickness measurement is easier if it is partitioned. At each 5mm increment in Z direction after the completion of forming, the result of the thickness of element is taken at the edges where Elements for 5 mm, 10 mm, 15 mm, 20 mm, 25 mm and 30mm. depth are 1909, 1907, 1905, 1903, 1901 and 1899 respectively. As per Fig. 4 and 5 for each sample partitioned. above-mentioned element, the thickness is measured when tool just passed over that element.

Table VI. Percentage Error Values between experimental and numerical Results



Depth	% Error by Power law	% Error by V. Mises criterion	% Error by Hills criterion
5mm	2.635135	2.743243	2.459459
10mm	3.309038	3.877551	3.338192
15mm	3.443918	4.186414	3.459716
20mm	0.366492	0.732984	0.244328
25mm	1.158879	1.158879	1.514019
30mm	0.942308	1.288462	1.25
Av. error	1.975962	2.331255	2.044286

Instantaneous thickness value of that element was noted and the final thickness of component measured after the completion of the process. The formed specimen was cut into two parts and then thickness measurement was carried out by the use of vernier caliper. Vernier caliper is selected over micrometer because it provides linear contact while micrometer provides the areal contact. As thickness is changing sensitively, use of line contact is preferred. Measurements of thickness along cut section are carried out as Shown in Fig. 6. Table V shows the result of thickness found by experimental and simulation way. Output request STH provides the thickness result of shell elements. The results of 1909, 1907, 1905, 1903, 1901 and 1899 elements are given in the table IV for Power law, Von Mises and Hills yield criterion respectively.

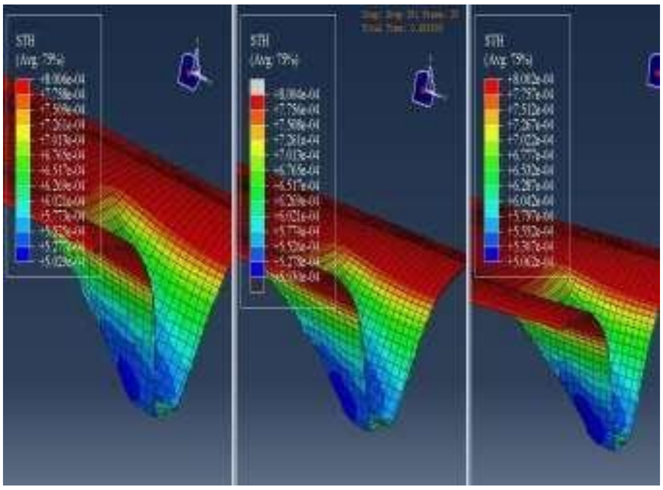


Fig. 4 Thickness distribution by Hills yield, von Mises yield, and power law respectively

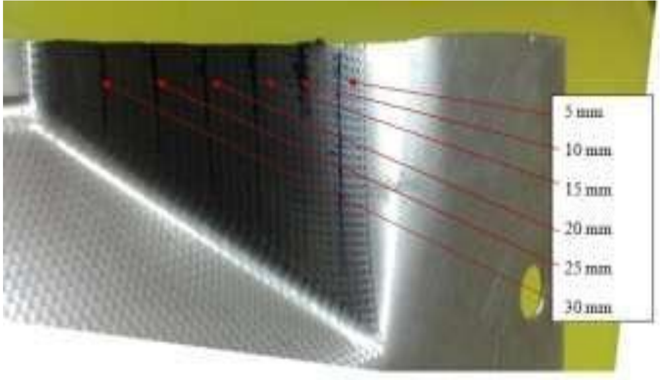


Fig. 5. Thickness measurement of specimen

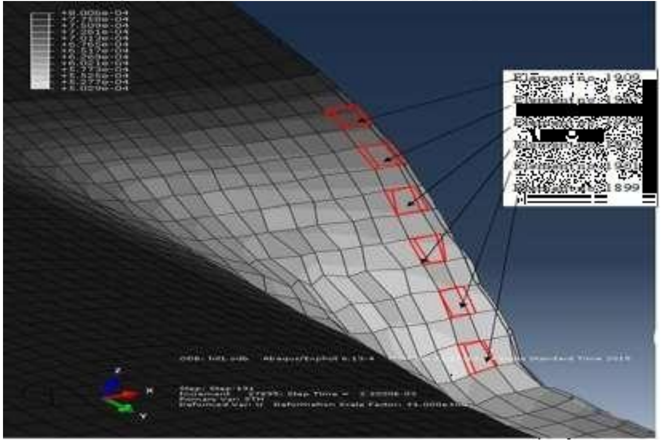


Fig. 6. Element selection at various depth

The maximum deviation of thickness results of simulation from measured thickness is given in the form of percentage error (Fig. 6). The maximum error is induced when von mises criterion is used. The value of the maximum error is 4.18%.The minimum value of the error is in the use of Hills criterion (0.24% for depth of 20 mm). The error percentage is calculated by comparing predicted and experimental thickness values.

Fig. 7 Thickness measurement at different heights of formed sheet metal

All simulation results are within the 5% error value. At corner, the maximum reduction of thickness is shown in the simulation. This is because, at corner, the material undergoes biaxial stretching. As at corner and 35mm depth curvature is present, thickness is not be measured at that point. Also from the cut section measurements it is clear that as depth increases the thickness is decreases. The metal flows due to elasto-plastic deformation in the direction of forming forces and reduction is observed along the depth. It has been obviously seen that as the wall angle increases, thickness stain is very severe. In the whole research work, care has been taken to have positive thickness strain as no failure were observed in the investigation.

VII. CONCLUSIONS

The conclusions can be made out of this investigation, The smaller vertical step forming forces decreases and larger depth can be achieved with the better surface finish. From the ANOVA results, it is clear that surface roughness depends on step increment by 64.19 % and wall angle by 17.23 %. The thickness reduction depends on only wall angle, its dependency is 99.79 %. The Feed rate and spindle speed do not have a significant effect on surface finish and thickness reduction. The tool size affects both the formability and the surface finish of the manufactured part. The Biaxial stretching at the corners and plain strain stretching at the sides produced. This is the reason crack occurred mostly at the corner. Simulation of single point incremental sheet forming is successfully carried out in the abaqus. Load rating in the simulation is implemented with three different laws. The thickness and nominal strain results obtained by the study are within the acceptable region. Maximum errors obtained due to Von Mises criterion is 4.18%. For Hills criterion, 0.24% is the minimum error value. This study suggests that use of power law is more suitable for the numerical study of SPIF process.

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