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Experimental and Finite Element Analysis of Single Stage Single Point Incremental Forming

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ABSTRACT

Incremental forming is one of the non-traditional forming processes which is widely used in rapid prototyping and customized component manufacturing. One of the challenges encountered in single stage single point incremental forming (SSSPIF) is difficulty in achieving greater wall angle for a considerable depth. In this research work, the investigation is carried out by experimental and numerical simulation for reaching the maximum wall angle to a possible depth without any defects in SSSPIF. SSSPIF of truncated cone shaped component from 1mm thick AISI304 austenitic stainless steel are made at a different wall angles. Also, numerical simulation using LS-DYNA explicit solver is performed and the results are validated with the experimental values. Components with the wall angle of 64o is successfully made without any defects made in a single stage forming for a depth of 45 mm within the experimented process parameters. Major strain, minor strain and thickness distribution in the sheet material due to forming process are obtianed from experiments and finite element analysis (FEA). From the results of both experiment and FEA, it is observed that the major strain, minor strain and thinning effects are higher in the region below the major diameter of the truncated cone at all experimented wall angles. Also the FEA results have shown good agreement with the experimental values. Further it is seen that the strains are increasing with the increase of wall angle.

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1. INTRODUCTION

A newer non-conventional forming process known as incremental sheet metal forming is used recently for manufacturing customized components and medical implants. In this process, the desired shape and size of the part is imparted by rotating tool with hemispherical head, which moves in a specified generated path. Single point incremental forming (SPIF) is one of the types of incremental sheet forming (ISF) where single tool performs the operation by moving the tool in incremental step-down size. The required shape and size of the component may be obtained in a single stage or multi stage processes. Due to absence of die in this process, the initial investment is much lower when compared with the conventional forming process. AISI 304, an austenitic stainless steel, is very widely used material due to its strength, corrosion resistance and biocompatibility. Due to the characteristic of inactiveness with environment and non-toxic nature makes stainless steel a good candidature for food, chemical and medical industries.

In past, number of researchers have attempted to explore the incremental forming process due to the increase in need for customized components. The deformation mechanism was studied by Jackson and Allwood [1] in SPIF as well as in two point incremental forming (TPIF). It was presented from their study that the deformation is due to (i) shear and stretching in a plane perpendicular to the direction of tool movement and (ii) shear along the tool direction. Gupta and Jeswiet [2] have investigated the effect of tool-sheet interface temperature, which is generated due to the friction between them at high relative velocity of the tool, on formability and geometrical errors. They have suggested that, to certain extent, the higher rotational speed and feed rate of the tool are ideal process parameters for the

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better results. Wall angle of the formed component plays a crucial role in deciding the required forming force. The forming force increases with the increase of wall angle upto 60º and beyond which the force decreases due to the thinning effect of the formed part which may lead to a fracture [3]. The maximum wall angle that can be formed is depending on the type of material and its thickness. In case the part requires wall angle more than the maximum value, multi pass strategy is employed [4-6]. Safari [7] has experimented the two point incremental forming (TPIF) of 1mm thick AA3105 aluminium alloy sheet to form both internal and external cavities using different process parameters. It was concluded from his study that the component with 70º internal and internal cavity for the depth of 95 mm and 40 mm were fabricated by TPIF. Also, it was observed that the rotational speed of the tool and the pattern of forming influence greatly the formation of maximum height in external and internal surface cavitity [7]. Investigation on TPIF of the same complicate shaped component from the same material of 2 mm thickness was carried out by Safari and Joudaki [8]. It was concluded from their findings that the thinning of material was observed around 23.5 – 32.5% at different forming increment and moreover, the higher tool rotational speed and the pattern of forming reduced the thinning to 17.5% [8].

Also, to overcome the limitation in successful formation of the required wall angle, Duflou et. al. [9] have attempted heat assisted SPIF since the temperature helps in improving the formability of the material. In order to improve the precision and formability in SPIF, researchers employed different strategies like heating the sheet metal during forming process [10] and stretching forming in conjunction with conventional SPIF [11]. It was observed by Vahdani et al. [10] in their investigation that the maximum depth of formed component was not improved in hot SPIF eventhough there is an improvement in formability of the DC01steel material. Laser forming, one of the advanced forming processes, is used for making the different curved surfaces using the heat generated by the laser beam. Safari and Mostaan [12] have studied the formation of cylindrical surfaces with curvature of arbitary radius using laser forming. It was presented that the parallal lines of irradiation are necessary for producing the intended surfaces and the number of such lines is the important parameter for the success of forming [12]. The saddle shape with larger radius of curvature was successfully made by laser forming using spiral irradiating lines [13] and recommended the Out-to-In spiral pattern over In-to-Out spiral pattern for the better performance. But, in laser forming, more number of passes are required to produce larger angle and hence the cost of manufacturing may be high when compared with the IF process.

Apart from experimentations, researchers used FEA to simulate ISF and investigate the forming characteristic of the sheet metal [14-16]. Blaga and Oleksik [17] have tried 3 different forming paths to create a frustum of a cone using DC04 steel sheet and concluded that the spiral path is the best among used strategies due to the occurrence of homogenous distribution of strains. Similar spiral path was used in both experimentation and FEA to produce truncated cone in Stainless steel 304, DC06 and aluminum alloy AL5052 by Golabi and Khazaali [18], Li et al. [19] and Wang et al. [20]. Experiment and FEA was carried out by Neto et al. [21] using circular path and found that stress and strain FEA results are in good agreement with experimental results. Researchers used analysis software like ABAQUS [22-23], LS-DYNA [24] for predicting different output parameters efficiently. Shrivastava and Tandon [25] employed Radioss as a solver for explicit simulation and HyperView and Hypergraph for post processing. To measure the strains in the incrementally formed components, Centeno et al. [26] utilized ARGUS software for circle grid analysis. Nasulea and Oancea [27] has developed Tool Motion Points Generator (TMPG) software to input path for simulation in ANSYS. To improve the formability, Wang et al. [28] developed a newer spiral path strategy by interpolation and translation of a generated points from Unigraphics software. FEA was performed in double sided ISF and Multi stage ISF to find the strains and fracture limits by Moser et al. [29] and Wu et al. [30].

It is clear from the literature survey that the increase in the wall angle beyond certain value limits the height of the component formed in single stage of forming. Also, it is observed that most of the researchers investigated the components made with wall angle 30º to 60º for a part height of 25 to 60mm and increasing the wall angle above 60º produced the component height within the range of 10 to 35mm by single stage. So, it is obvious that producing a component with the wall angle more than 60º for a depth more than 35 mm in SSSPIF has imposed a challenge to the researchers. The main aim of this paper is to investigate the SSSPIF of 1 mm thick AISI 304 stainless steel component with wall angle more than 60º for a part depth of more than 35mm by experimental and FEA methods by selecting suitable process parameters. Also, the effect of wall angle formation on the various strains due to the deformation to understand the thinning and fracture of the component.

2. FINITE ELEMENT ANALYSIS

Simulation of single stage incremental forming was carried out in four different stages. In first stage, the individual parts like blank material, tool, clamping plate and backing plates are 3D modeled and assembled. In second stage, this model was imported to finite element simulation software. Also, meshing, boundary condition, material properties and contact between parts are applied. In third stage, the CNC code for forming is converted into displacement curve and the final stage is solving and post processing.

LS-DYNA explicit solver is used for FEA of single point single stage incremental forming to determine the deformation characteristics of the material. In order to show the backing plate in the assembly, the full model is cut and shown in Figure 1. Total number of 62712 Belytschko-Tsay shell element with two integration points is considered for the forming simulation.

AISI 304 stainless steel sheet of 1mm thickness was considered as the blank material and necessary mechanical properties like Young's modulus of 2.1E5 MPa, Poisson's ratio of 0.3, density of 8000Kg/m^3 was applied. The hemispherical tool head is shown as spherical ball. The blank is considered as deformable and all other parts of the assembly are considered as rigid. Frictional coefficient of 0.1 and 0.4 are assumed for blank & tool and blank & supporting plates respectively using CONTACT ONEWAY SURFACE TO SURFACE keyword in LS DYNA. X, Y & Z coordinates of a path of a rotating tool from CNC code is converted into curve and stress strain curve of raw material was used as an input for simulation. Since the chosen tool path is spiral, partial or symmetrical model cannot be used and hence full model is used for simulation. The advantage of using spiral tool path over other is that no mark can be observed during step down tool movement. The approximate simulation time is around 140 hours for each full model. From the FEA results major, minor and thickness strain are measured and validated with the experimental work.

3. EXPERIMENTAL WORK

Truncated cone shaped components of austenitic stainless steel AISI304 are produced in a YCM make computerized numerically controlled (CNC) vertical machining center. The important specification of the machine such as maximum spindle speed and feed rate of 8000 rpm and 10000 mm/min, respectively. Purchased sheet is sheared into required dimension of 120x120x1mm and is laser etched with 5mm diameter circular grids. The blank is clamped firmly between the clamping and backing plate in a custom designed fixture. The tool diameter of 14mm with hemispherical end is made of High carbon high chromium (HCHCr) tool steel and heat treated to have the hardness in the range of 52–55 HRc. The setup of single point incremental forming process is presented in the Figure 2.

Initially the range of process parameters used are as follows: tool traversing speed 200 to 1250 mm/min; tool rotating speed 250 to 1000 rpm; and incremental depth 0.1 to 0.5mm. The process parameters are selected based on successful formation of the component without any defect and surface finish. For further experimentation the tool traversing speed of 1000 mm/min, tool rotating speed of 250 rpm and step down depth of 0.5mm are fixed and the wall angle is varied. In order to minimize the heat generated during forming process a continuous coolant of Blasco cut 4000 strong water soluble lubricant was used.

During forming process, the circular grids are deformed and to measure the size of the grids, the cup is cut into two halves (Figure 3) and measured using Arcs video measuring system (AVMS model- SVP 2010) at M/s Kosaka calibration lab, Chennai. Thinning effect is calculated by measuring the thickness before and after the forming process using MGW dial thickness gauge.

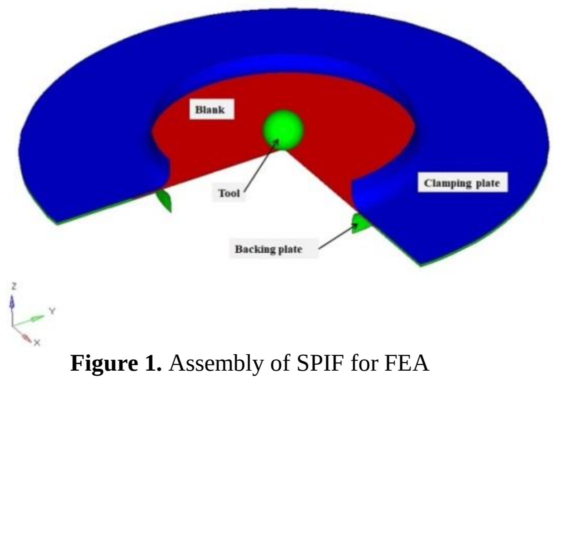

Figure 1. Assembly of SPIF for FEA

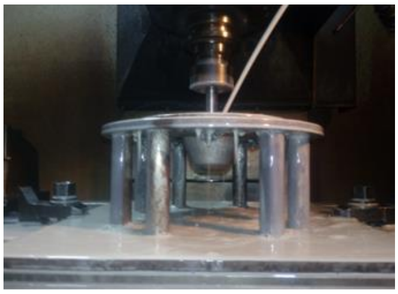

Figure 2. SPIF

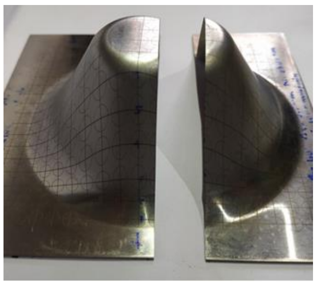

Figure 3. Half cut portion of the formed component

4. RESULTS AND DISCCUSSSION

The incrementally formed components by single stage SPIF experiments and FEA at various wall angles keeping the depth of 45mm as constant are shown in Figure 4 (a) and (b).

Increase in wall angle beyond 64° produced a fracture at a region close to the smaller diameter of the cone at a height of 21.2mm itself. This may be due to the reason that more bending and stretching causes higher deformation in early stages of forming and further movement of the tool cause fracture at a shorter height. The component with a fracture which is produced at a wall angle of 65° is shown in Figure 5.

4. 1. Effect of Wall Angle on Major and Minor Strain

The results of the experimentation and FEA show that the strain in the major direction is increasing enormously with the increase of wall angle whereas it is marginal increase in case of minor direction. The comparison between major and minor strain observed in the experiment and FEA at different wall angles are presented in the Figures 6 and 7, respectively.

From Figure 6, it is observed that the FEA results are in good correlation with the experimental values. The maximum and minimum variation between the experiment and FEA is 10 and 0.2% at the deformed zones among all the experimented wall angles. Major strain increases with the increase of wall angle due to the reason that, the material undergoes more stretching and bending when the wall angle increases. At all wall angles, the major strain is noticed very close to the region below the blank clamp in both FEA and experiment. It may be attributed to the reason that the excessive strain at this region due to restriction on material flow imposed by the blank holder and the stretching and bending caused by the rotating tool. The same region was reported by Shrivastava and Tandon [25] during formation of truncated pyramid in SPIF.

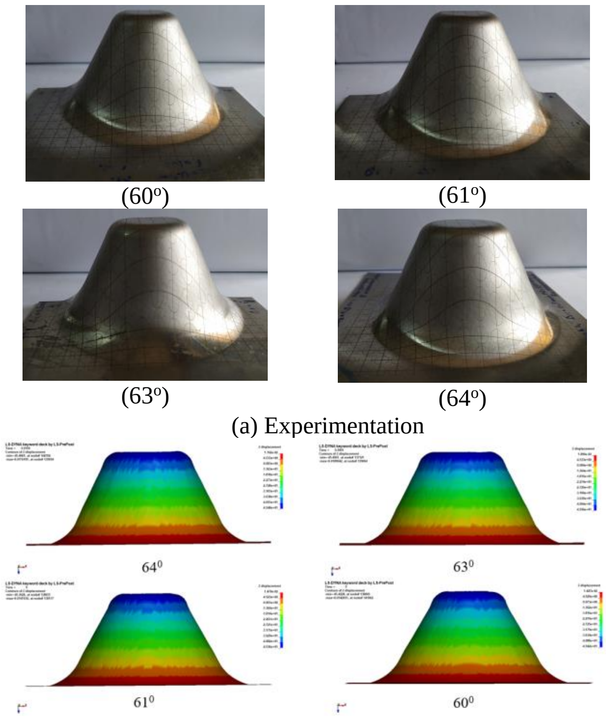

Figure 4. Component formed at different wall angles

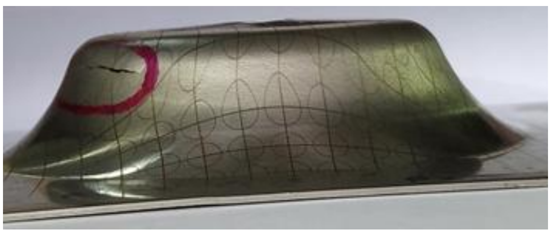
Figure 5. Component formed with 65° wall angle

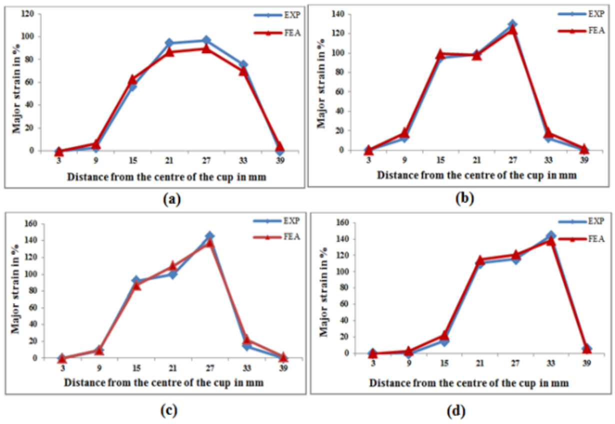

Figure 6. Comparison of Major strain at different wall angles (a): 60°; (b): 61°; (c): 63° and (d): 64°

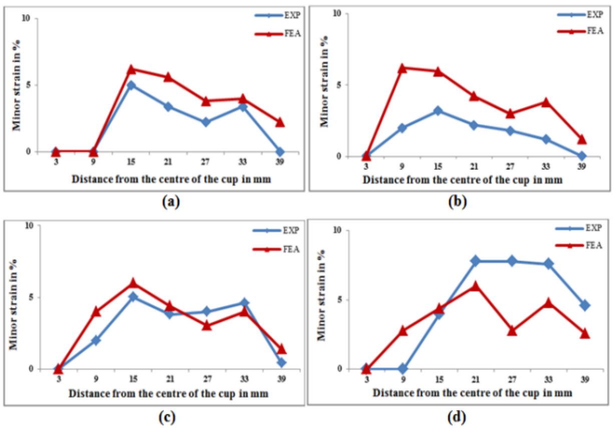

Figure 7. Comparison of Minor strain at different wall angles (a): 60°; (b): 61°; (c): 63° and (d): 64°

It is seen from the Figure 7 that the minor strain increases with the increase in wall angle and the results of FEA and experiments are in good agreement. Maximum of 7% and minimum of 0.4% minor strain variation are observed between FEA and experiment among all the experimented wall angles. In the forming zone, the diameter of the cone increases with increase in wall angle which deforms the material circumferentially and hence the minor strain is more. The minor strain increases from the major diameter region of the cone to the minor diameter region just before the bottom corner radius similar to the results obtained by Neto et al. [21].

In general, increase in the wall angle increases the axial force required to form. Also, biaxial straining and severe stretching caused by the downward spiral movement of the tool while forming the depth causes more strain. The above may be the reason for increase in major and minor strain when the wall angle is increased.

4. 2. Effect of Wall Angle on Thickness Strain

Figure 8 shows the thickness strain comparison between experiment and FEA at various wall angles. Increase in wall angle, increases the thinning effect in the formed region in both experiment and FEA. The FEA result shows good association with the experimental values. The maximum thinning ranges from 0.49mm to 0.68mm in FEA and 0.45mm to 0.65mm in experiment with the increase of wall angle. As discussed earlier in section 4.1, both major and minor strain increases with increase in wall angle which leads to decrease in thickness below the blank clamping region near the major diameter of the cone component. Shrivastava and Tandon [25] observed that the maximum thickness reduction in the earlier stage of forming at a same region and also stated that the severity of reduction in the thickness is more when the wall angle increases. It is also observed that the corner region near the clamping plate causes more thinning due to changes in tool direction and twisting.

The reason for this severe thickness reduction was attributed to the bending of the material at the earlier stage of forming and is not disturbed throughout further forming process. Also more and more severe localized thinning occurs when the wall angle is increased to certain value. Beyond which the unexpected failure of the formed component is observed.

4. 3. Forming Limit Diagram

The forming limit diagrams (FLD) showing the distribution of major and minor strain for different wall angles from LS DYNA post processing are presented in Figure 9.

It is observed from the figure that the number of points falling above both necking and failure limit curve are increasing when the wall angle is increased. Moreover, the maximum value of major strain is increasing more when compare to maximum value of minor strain as the wall angle is increased. This may be attributed to the reason that severe strain caused by the biaxial straining and stretching due to depth of formation when the wall angle is increased.

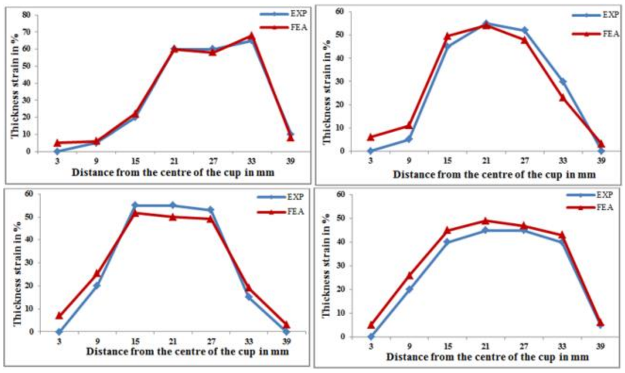

Figure 8. Comparison of thickness strain at different wall angles (a): 60°; (b): 61°; (c): 63° and (d): 64°

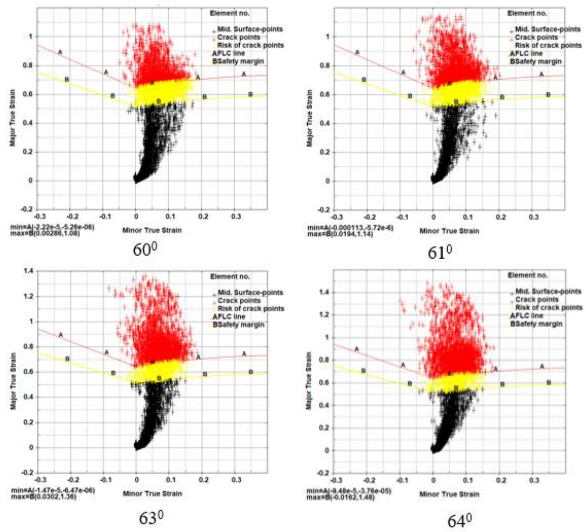

Figure 9. FLD for different wall angle

5. CONCLUSION

The investigation on experiment and FEA of single stage single point incremental forming of truncated cone using AISI 304 austenitic stainless steel sheets are made to determine the maximum possible wall angle that may be achieved for the height of 45 mm. From the results of study, the following conclusions are drawn:

- Components to a depth of 45 mm are made successfully in single stage of forming up to the wall angle of 64° in the experimented process parameters.
- Good correlation exists between the experimental and FEA results.

- Maximum variations in the major and minor strain are 10 and 7%, respectively.
- Maximum thinning of 0.65mm and 0.68mm was observed at the region close to the larger diameter of the truncated cone at wall angle of 64° in both experiment and FEA, respectively.
- Severe major, minor and thickness strain is observed when the wall angle and depth of the component increased.
- FLDs also show more strain distribution above the limiting curves when the wall angle increases.
- Due to longer analysis running time, the success of FEA of incremental forming is a challenging one.

Further investigation of FEA of multi stage SPIF and reduction in analysis running time is under progress.

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Persian Abstract

چکیده

شکل گیری افزایشی یکی از فرایندهای شکل گیری غیر سنتی است که به طور گسترده ای در نمونه سازی سریع و ساخت قطعات سفارشی استفاده می شود. یکی از چالش هایی که در شکل گیری افزایشی تک مرحله ای تک مرحله ای (SSSPIF)وجود دارد ، دشواری در دستیابی به زاویه دیواره بیشتر برای عمق قابل توجه است. در این کار تحقیقاتی ، تحقیق با شبیه سازی تجربی و عددی برای رسیدن به حداکثر زاویه دیواره تا عمق ممکن و بدون نقص در SSSPIF انجام شده است. SSSPIF از اجزای مخروطی شکل بریده شده از فولاد ضد زنگ آستنیتی AISI304 با ضخامت ۱ میلی متر در زاویه دیواره های مختلف ساخته شده است. همچنین ، شبیه سازی عددی با استفاده از حلگر صریح LS-DYNA انجام شده و نتایج با مقادیر آزمایشی تأیید می شوند. اجزای دارای زاویه دیواره ۶۴ درجه با موفقیت ساخته می شوند و هیچ نقصی در یک مرحله تشکیل نمی شود و برای عمق ۴۵ میلی متر در پارامترهای فرآیند آزمایش شده ایجاد می شود. کرنش عمده ، کرنش جزئی و توزیع ضخامت در ورق به دلیل فرآیند تشکیل از آزمایشات و تجزیه و تحلیل عناصر محدود (FEA)بدست می آید. از نتایج هر دو آزمایش و FEA ، مشاهده شده است که اثرات کرنش عمده ، کرنش جزئی و نازک شدن در منطقه زیر قطر اصلی مخروط کوتاه شده در تمام زوایای دیواره آزمایش شده بیشتر است. همچنین نتایج FEA توافق خوبی با مقادیر آزمایشی نشان داده است. بعلاوه مشاهده می شود که با افزایش زاویه دیواره ها کرنشها در حال افزایش هستند.