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Investigation on Component Wall Angle in Single Stage Incremental Forming of Austenitic Stainless Steel AISI 304 Sheet

The aim of this research work is to study the effect of process parameters in achieving the maximum possible wall angle of the component in single stage incremental forming. Austenitic stainless steel AISI 304 is used as a sheet material. The constant tool rotational speed of 250 rpm, tool feed of 1000 mm/min and incremental depth of 0.5 mm were used as process parameters and the wall angle was varied from 60°. Grid marking technique is used for strain measurements. From the results, it is observed that the maximum height of 45 mm was formed successfully at wall angles 60°, 61°, 63° and 64° without any defects within the experimented process parameters. Further increase in either the wall angle or the process parameters produced fractured component at a height of around 22 mm itself.

Keywords: Single Stage Incremental Forming, Austenitic Stainless Steel, Wall angle, Tool Rotational Speed, Incremental depth

1. INTRODUCTION

Incremental forming is one of the non-traditional forming processes used for developing a prototype of a component. It is also known as die-less forming in which the rotating tool follow the contour of the component to be produced and incremented by a step size to reach the required depth which is controlled by the Computer Numerically Controlled machine(CNC) programming. It finds applications in rapid prototyping of components used in automobile, aeronautics, medical and aerospace industries. Recently, the custom made medical implants like Maxillofacial [1], orthopaedics are manufactured by Fused deposition modeling (FDM), Multi-jet 3D printing and 3D printing [2] respectively. Similar implants can be manufactured using the incremental forming process due to the flexibility to the design changes according to the patient's need. Investigation on incremental forming in different materials like steel [3-5], magnesium alloy [6], aluminium alloy [7-9], titanium [10,11], stainless steel [12-18], polymer [19] etc. have been carried out by many researchers in the past. Information regarding incremental forming of aluminium and magnesium are exhaustive whereas for other materials, it is very limited. Subramanian Chezhan Babu and Velukkudy Santhanam SenthilKumar [14] have performed forming of conical shaped component with wall angle approximately 50° and part depth of 30mm using 0.6mm thick stainless steel sheet. Highest forming limit was achieved at a feed of 1600

mm/min and tool rotational speed of 1000rpm. Sa'id Golabi and Hossain Khazaali [16] have investigated the effect of wall angle on the achieved depth of the component in 0.3-1 mm stainless steel 304 sheet. It was concluded from the result that the maximum depth achieved was 20mm when the wall angle is 64°, whereas, it is only 14.5 mm approximately at 84° in single stage incremental forming. Giuseppe Ingarao et al. [17] have successfully reached the depth of 40mm at a wall angle of 45° in 0.8mm thick stainless steel sheet. Also they documented the energy demand during incremental forming and concluded that the dominant factor in deciding the energy required is the forming time among the process parameters considered.

In order to improve the wall angle more than what is attainable in single stage, incremental forming in multistages was attempted by few researchers. Mohammad Javad Mirnia et al. [20] explained that, in 1mm thick aluminium alloy sheet, the formation of truncated cone with wall angle of 60° for a height of approximately 15 mm was made without any fracture in two stage forming. Li Jun-chao et al. [21] worked on DC06 Steel with 0.8mm thick using three stage forming at a wall angle of 30°. It was concluded that the final thickness value was more than the value predicted by sine law and hence cannot be applied to multistage forming. A novel study on tooling [22,23] was done by Tyler J Grimm et al. They proposed multidirectional tooling and achieved 23% improvement in formability when compared with single tool forming.

Furthermore, few researchers have attempted a hybrid forming [24-28] by combining superplastic, laser, electromagnetic, ultrasonic and friction stir incremental forming to improve the formability. Rubber pad forming is used for fabricating the components for aircraft industry due to the advantage that the parts with different dimen-

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sions and shape can be made using the same flexible rubber pad[29]. But, the disadvantage in this process is to manufacture accurately at least one rigid die, whereas there is no need for die in the incremental forming.

The objective of this research work is to achieve the maximum possible wall angle in single stage operation by using the optimum process parameters.

2. EXPERIMENTAL PROCEDURE

The incremental forming experiments were carried out using 120 x 120 x 1mm AISI 304 austenitic stainless steel sheets. The chemical composition and useful mechanical properties of AISI 304 is shown in Table 1 and 2. The forming tool of High Carbon High Chromium (HCHCr) tool steel was used with dimensions $\phi 14 \times 100$ mm long and is hardened to 50-55 HRC.

Table 1. AISI 304 chemical composition.

Element	C	Cr	Ni	Si	Mn	Fe
Weight %	0.029	17.75	8.11	0.38	1.42	Rest

Table 2. Mechanical Properties of AISI 304

S. No	Property	Value
1	Yield Strength(MPa)	290.6
2	Ultimate Tensile Strength(MPa)	662.91
3	% Elongation	58

The forming process was performed in 15 HP MV76A computer numerically controlled (CNC) vertical machining centre (Make: YCM) with table size of 915 X 560 mm and maximum speed and feed of 8000 rpm and 10,000 mm/min respectively.

The workpiece sheets are clamped in the specially fabricated fixture which is mounted on the machine table. Figures 1 and 2 show the incremental forming tool positioned in the machine spindle and the process of forming respectively.



Figure 1. Incremental forming tool located in the machine spindle

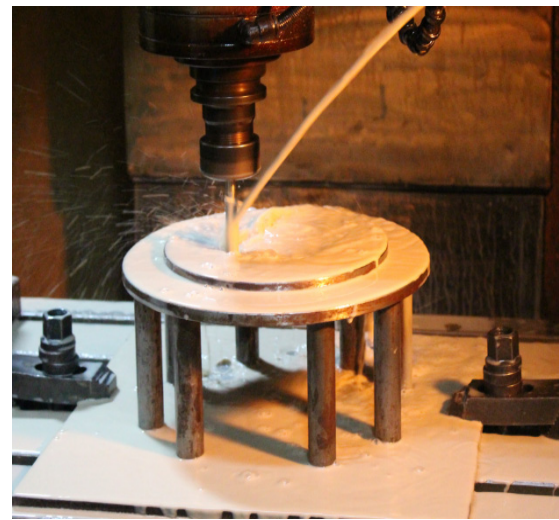


Figure 2. Process of incremental forming

The process parameter for incremental forming is initially set by trial and error method until the formation of the required component shape and dimensions achieved to certain depth without fracture. For further experimentation, the tool rotational speed (N), tool traversing speed (f) and incremental depth (d_i), are kept constant at 250 rpm, 1000 mm/min and 0.5 mm respectively. The wall angle (α) of the component is changed from 60° , 61° , 63° etc.

In order to study the different strains involved, the circular grids with a diameter of 5mm and pitch distance of 6 mm was made by laser etching in the sheet material. The deformation in the grids after incremental forming are measured using coordinate measuring instrument(CMM), vernier caliper with a least count of 0.02 mm and micrometer with a least count of 0.001 mm.

3. RESULTS AND DISCUSSION

The components with the wall angle 60° , 61° , 63° and 64° were formed successfully for a depth of 45 mm without any defects at the set process parameters (N=250 rpm, f=1000 mm/min and $d_i=0.5$ mm). Increase in either the tool rotational speed or incremental depth produced fractured component at a height of approximately 22 mm itself. The successful and fractured components are shown in Figure 3 and 4.

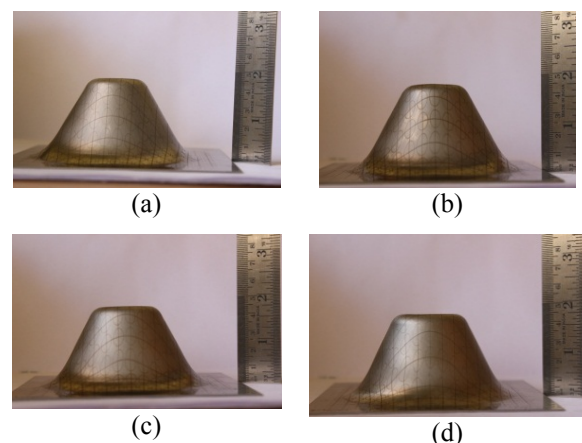


Figure 3. Successful component at N=250 rpm, f=1000 mm/min and $d_i=0.5$ mm with different wall angles(a) 60° , (b) 61° , (c) 63° , (d) 64°

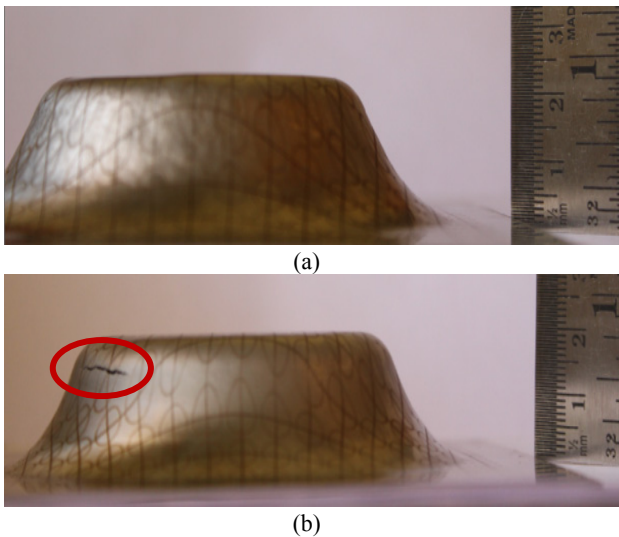


Figure 4. Fractured component at constant $f=1000$ mm/min and (a) $N= 500$ rpm, $d_i=0.5$ mm and $\alpha=60^\circ$; (b) $N= 250$ rpm, $d_i=0.6$ mm and $\alpha=65^\circ$

For the purpose of strain measurements, the formed component is cut by SODICK wire electrical discharge machine (WEDM) which is shown in Figure 5.

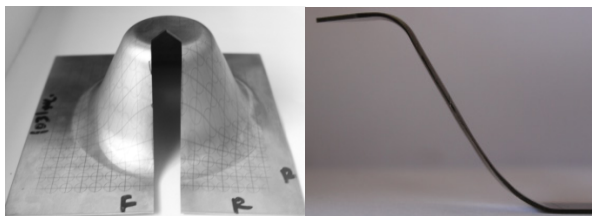


Figure 5. Cut portion from the formed component

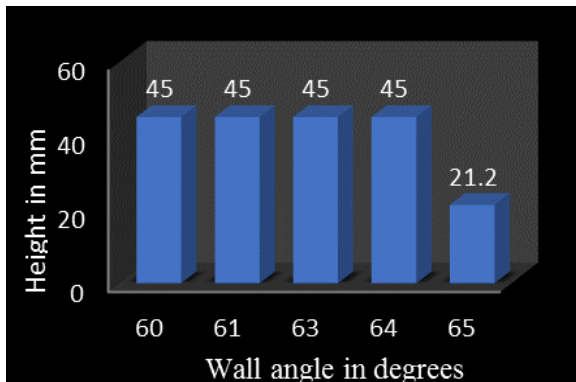
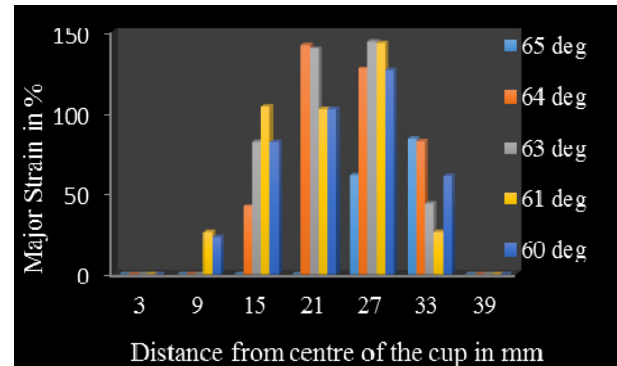


Figure 6. Graph on Maximum height versus wall angle

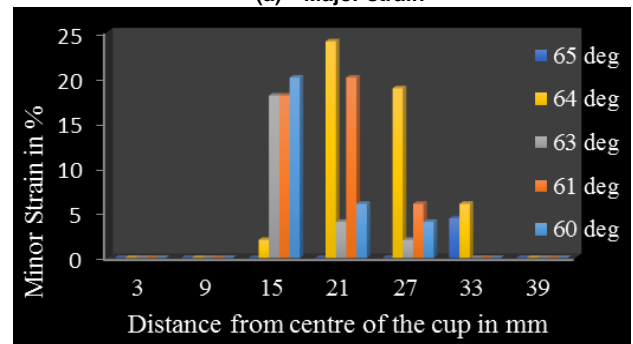
The maximum height of the component that was achieved at different wall angles is shown in Figure 6. Also, Figure 7 shows the calculated percentage major strain, minor strain for different wall angles and Figure 8 indicates the % thickness strain at 64° wall angle.

It is seen from Figures 7 & 8, that there is no deformation at the bottom of the cup similar to the deformation characteristics in conventional deep drawing process. The deformation starts only from the region just close to the bottom corner radius of the cup initially. The deformation is maximum at region below the top corner radius. As the distance from center of the cup increases, the amount of deformation reduces or remains constant at the region near the clamping. It is due to the reason that the material is bent in the radius of the fixture and then stretched between the clamping and the

rotating tool. Further movement of the tool downward causes more stretching in the region near the top corner radius and at the same time the clamp restricts the material movement against the stretching of material by the downward movement of the tool in region closer to the clamping. It is clearly indicated by the extent of ovality of the etched circular grids in this region.



(a) Major strain



(b) Minor strain

Figure 7. Percentage Major and minor strains measured for different wall angles

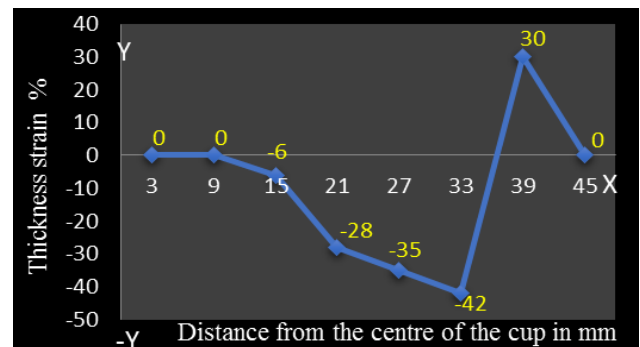


Figure 8. Percentage thickness strain at 64° wall angle

From the observation of grid pattern after deformation by incremental forming, it is seen that the material is elongated in both major and minor directions, but the extent of deformation is more predominant in major axis than that of minor axis. This is due to the reason that the downward movement of the rotating tool causes more stretching than that caused by the circumferential travel movement of the tool. Thus, the material is subjected to biaxial stretching and consequently maximum thinning occurs in the region near the top corner radius due to volume constancy.

From Figure 6, it is observed that the maximum height of 45 mm was achieved at the wall angles of $60-64^\circ$ without any defects when the process parameters are set at $N = 250$ rpm, $f = 1000$ mm/min and $d_i = 0.5$

mm. The fracture was noticed at a depth of 21.2 mm for the process parameters of $N = 250$ rpm, $f = 1000$ mm/min and $d_i = 0.6$ mm when the wall angle is 65° . This is attributed to the fact that when the wall angle of the component is increased, the bending of the material is more and the deformation is increased by the combined effect of stretching and bending. Hence, at higher wall angle, the increasing local necking effect causing more thinning of material which leads to a fracture at a short depth itself. Increasing either the tool rotational speed or incremental depth increases the combined effect of stretching and bending which contributes to the formation of minute crack at the early stage of forming itself. Also, the higher tool rotational speed produces more vibration which is responsible for the poor surface finish of the component especially at a region nearby the bottom corner radius. Similar results by Gabriel centeno et al. [18] have been achieved for 70° with maximum depth of 23.8mm for 0.8mm thick AISI304 sheet and Sa'id Golabi and Hossainkhazaali [16] worked with 0.7mm thick sheet at a wall angle of 64° for an approximate height of 15.5mm.

4. CONCLUSIONS AND POSSIBLE FUTURE WORK

In this research work, incremental forming of 1.0 mm AISI 304 sheet was experimented to achieve maximum possible wall angle. The following conclusions are arrived at:

- The component was formed successfully at a wall angle of 60° , 61° , 63° and 64° to a depth of 45mm at constant set process parameters.
- For 65° the fracture occurred at a depth of 21.2 mm for the same set process parameters.
- Increasing the tool rotational speed and incremental depth also result in earlier fracture.
- The maximum values of major strain, minor strain and thickness strain of 144%, 19.2% and -42% (Thinning) respectively are observed.
- The maximum attainable wall angle of a cup for a depth of 45mm is 64° in a single stage incremental forming within the experimented process parameters.
- Only a very short height cups can be formed beyond the wall angle of 64° by single stage incremental forming process.

Further work to achieve the maximum wall angle by attempting multi stage incremental forming process and different path generation is under progress.

CONFLICT OF INTEREST AND FUNDING

The authors declare that they have no conflict of interest. Also, this research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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**ИСТРАЖИВАЊЕ КОМПОНЕНТНОГ УГЛА
ЗИДА КОД ЈЕДНОФАЗНОГ ИНКРЕМЕНТНОГ
ОБЛИКОВАЊА ЛИМА ОД АУСТЕНИТНОГ
НЕРЂАЈУЋЕГ ЧЕЛИКА AISI 304**

**С. Кумар Д, Етхирац Н, Сивабалан Т, М. Фархан
МР, Бернадет Т**

Проучава се утицај параметара процеса на постизање максималног угла зида код компоненте при једнофазном инкрементном обликовању. Аустенитни нерђајући челик AISI 304 је коришћен као материјал за израду лима. Коришћени су параметри: константна ротациона брзина алата 250 грт, брзина помоћног кретања 1000 мм/мин, инкрементна дубина 0,5 мм и угао зида који је варирао око 60°. Напон је мерен техником која користи решетку материјала. Утврђено је да се максимална висина од 45 мм успешно формира када

је угао зида 60° , 61° , 63° и 64° без појаве дефеката у експерименталним условима. Даље повећање угла

зида или параметара процеса давало је компоненте са пукотинама при висини од приближно 22 мм.