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Determining frustum depth of 304 stainless steel plates with various diameters and thicknesses by incremental forming †

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Abstract

Nowadays incremental forming is more popular because of its flexibility and cost saving. However, no engineering data is available for manufacturers for forming simple shapes like a frustum by incremental forming, and either expensive experimental tests or finite element analysis (FEA) should be employed to determine the depth of a frustum considering: thickness, material, cone diameter, wall angle, feed rate, tool diameter, etc. In this study, finite element technique, confirmed by experimental study, was employed for developing applicable curves for determining the depth of frustums made from 304 stainless steel (SS304) sheet with various cone angles, thicknesses from 0.3 to 1 mm and major diameters from 50 to 200 mm using incremental forming. Using these curves, the frustum angle and its depth knowing its thickness and major diameter can be predicted. The effects of feed rate, vertical pitch and tool diameter on frustum depth and surface quality were also addressed in this study.

Keywords: Incremental forming; Finite element method; Computer numerical control; Stainless steel

1. Introduction

Incremental forming has attracted the attention of many engineers and manufacturers including automotive, aviation, medical, etc, industries in recent years. This method is mainly used for making a prototype or parts with limited quantities. One of the main advantages of this method is: the possibility of forming plates with no or just simple molds, high formability, requirement for low forming forces, and noiselessness. Considerable forming time and cost, requirement for multistep forming for deep and high slope drawings, and metal spring back are some main disadvantages of this method.

The main components of an incremental forming process are: blank, blank holder, backing plate and tool as well as a forming machine that could be a CNC milling machine (Fig. 1).

Reddy and Cao [1] divided incremental forming into two types: with and without dies and each type includes both positive and negative forming. Negative die-less method is also called single point incremental forming (SPIF).

Martins et al. [2] analyzed three main forming modes in SPIF and concluded that necking of plates is not a suitable criterion for fracture and forming limit diagram (FLD) should instead be used.

Hirt et al. [3] developed a strategy for multistep forming in which a cone shape with low cone angle is formed and the angle is increased gradually in the consequent steps. Yamashita et al. [4] studied the various tool path strategies for SPIF. They showed spiral path generates smoother strain distribution comparing with other ones. Kopac et al. [5] investigated the effect of lubricants on surface quality and fracture time. Jeswiet et al. [6] illustrated that dry forming produces very coarse surfaces as well as unpleasant grooves on surface or fracture of blank. In such these cases more suitable blank holder should also be deployed. Application of a rectangular blank holder for making a circular cone doesn't lead to a pleasant shape because; some sections of the blank that are closer to the edges of the holder are drawn more. Formability is one of the main features in incremental forming which shows the maximum forming angle of a blank metal. Thickness, vertical pitch, feed and spindle speed and tool diameters are the main parameters that affect the formability.

Capece Minutolo et al. [7] investigated the maximum forming angle of an aluminum blank cone with 1 mm thickness and then developed a relevant simulating software. They justified their study by comparing the output of their software with experimental results.

In this research, incremental forming of SS304 frustum out of a sheet metal is studied. Various cone angles and maximum depth considering the cone diameter and thickness are taken

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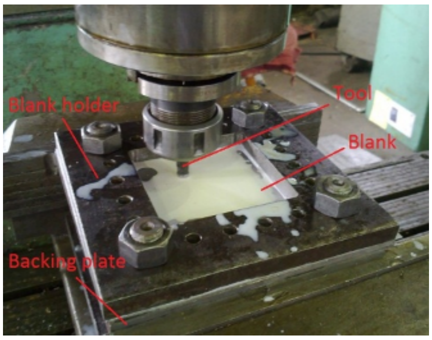
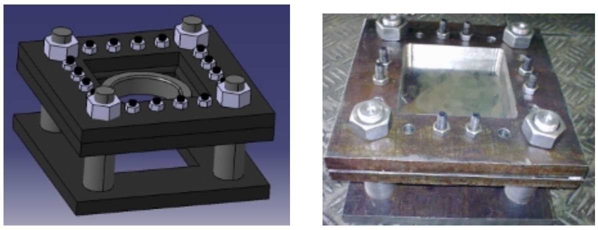


Fig. 1. Incremental forming components.

Fig. 2. Forming tool.



(a) (b)

Fig. 3. (a) Blank holder; (b) holder with fastened blank.

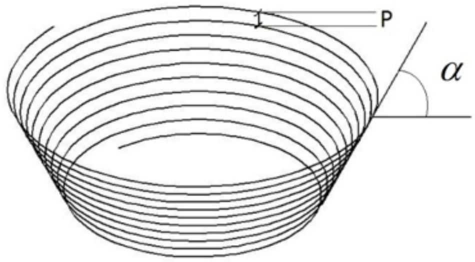


Fig. 4. Tool path.

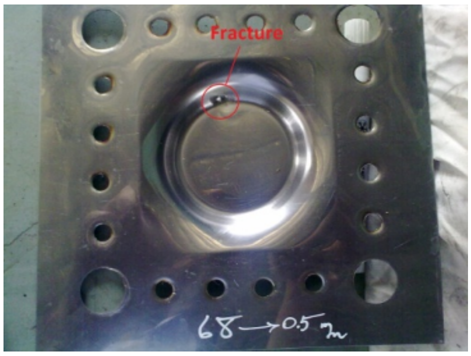


Fig. 5. Formed frustum.

into account to develop applicable curves for designers and manufacturers using ABAQUS finite element software. The results were then confirmed by experimental results of 0.5 and 0.7 mm thickness blanks. In order to consider the effects of supports and produce more accurate shapes, backing rings were also employed during the analysis and tests.

2. Forming frustums by incremental forming

SS304 plates with 0.5 and 0.7 mm thickness were proposed for forming in the experimental study to compare its result with FEA. The frustum major diameter of 78 mm with 63, 68, 73, 78 and 84 degree angle were formed to fracture in order to find the maximum permissible depth. A blank holder, backing plates, forming tools and a CNC milling machine were utilized in this stage.

A hemispherical tip cylindrical tool with 10 mm diameter was made of cemented carbide for this experiment (Fig. 2). The proposed tool diameter was selected according to the frustum diameter and angle as well as vertical pitch.

The SS304 sheets with 0.3-1 mm thicknesses were chosen in this study because of their miscellaneous applications especially in home appliance.

2.1 Blank holder

Suitable blank holder were designed and manufactured to hold parts on CNC table for forming. Similar to the holder CapeceMinutolo et al. [7] proposed in their research, the holder keeps the blank boundaries firmly with bolts and nuts, while some holders may let the blank slide for drawing (Figs. 3(a) and (b)).

To form a frustum by incremental forming a backing ring with a diameter equal to the cone top diameter was set beneath the blank. This ring has a 2 mm fillet on its inner diameter to prevent tearing of the blank.

2.2 Tool path

Since spiral tool path has shown to generate the most suitable strain distribution; it was employed in here for forming (Fig. 4).

The tool leads 1 mm vertically down in each rotary motion with 600 mm/min spindle speed. Machining Coolant has also been used during the forming process to keep the temperature down in the proposed speed and stop galling as well as reducing the friction between the part and the tool. After fastening the blank and starting the CNC machine, the tool pushes the blank down while moving along the programmed spiral path until the fracture of the blank happens (Fig. 5).

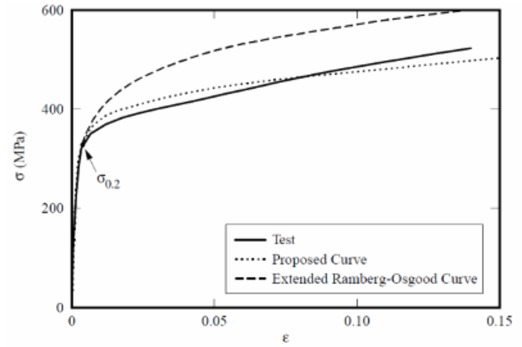


Fig. 6. 304 stainless steel stress-strain curve.

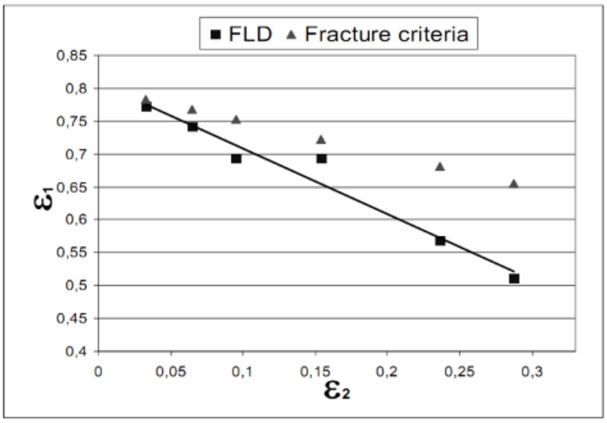


Fig. 7. Forming limit diagram.

3. Simulating incremental forming with finite element software

The simulation process was planned using ABAQUS finite element software. Both explicit and implicit method can be used for this solution, however; implicit solution has shown better conformance with experimental results. On the other hand, much more solution time is required even for forming a simple shape and short tool path in implicit mode. Jeswiet et al. [6] showed that explicit solution needs less analysis time; and since it produces acceptable results and for generation of the applicable curves hundreds of solutions were required, this method was proposed throughout this analysis.

The proposed material, i. e. SS304 plate has the following specifications: density = 8000 kg/m3, Young's module = 190 GPa, elongation = 55% and Poisson's ratio = 0.29. The solid line shown in Fig. 6 was proposed as the plastic behavior of this [8].

In order to determine the fracture event during analysis, FLD is the most important material information needed to be introduced for the software before analysis (Fig. 7). In fact the results of FEA are used to generate applied curves for design engineers and to stop every analysis, forming limit of SS304 gives the main criteria. Hence, FEA substitutes hundreds of experiments required for the generation of the curves.

Cockcroft-Latham criterion presented by Urban [9] was proposed for 0.5 and 0.7 mm thickness plate in here because of its good conformance and result. Fratini et al. [10] considered the blank to be isotropic and showed that little non-homogeneity in various directions didn't have considerable effects on the results.

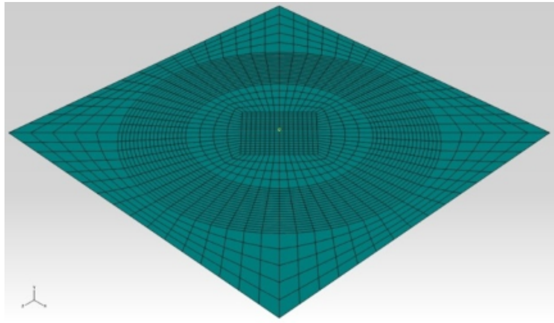


Fig. 8. Sheet meshing.

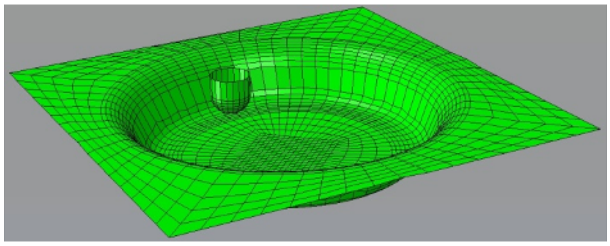


Fig. 9. Simulated frustum.

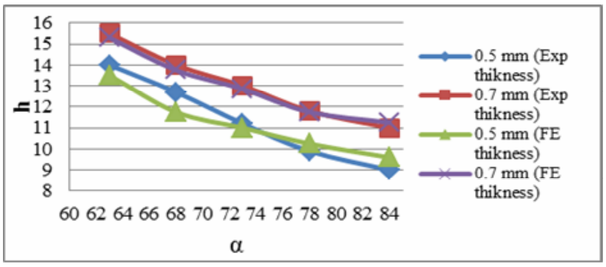


Fig. 10. Experimental and finite element results.

Shell elements were used to model the blank and small mesh sizes were only considered around the tool path by partitioning the model to reduce the analysis time. The best mesh size that leaded to the convergence of the results was then determined by gradually reducing the mesh size (Fig. 8).

The tool and blank holder were considered to be rigid (analytical rigid) because; their deformations did not affect the results. The holder was fixed and the tool has only been moving along 3 main axes, i.e. x, y and z along the programmed spiral path. Since spindle rotation did not have a substantial effect on forming analysis, it was not considered in modeling. The spiral tool path defined in the developed VDISP subroutine considers 1 mm vertical pitch and 600 mm/min feed rate.

Forming process was started as close as it could to the backing ring inner diameter to maximize forming accuracy and depth measurement (Fig. 9).

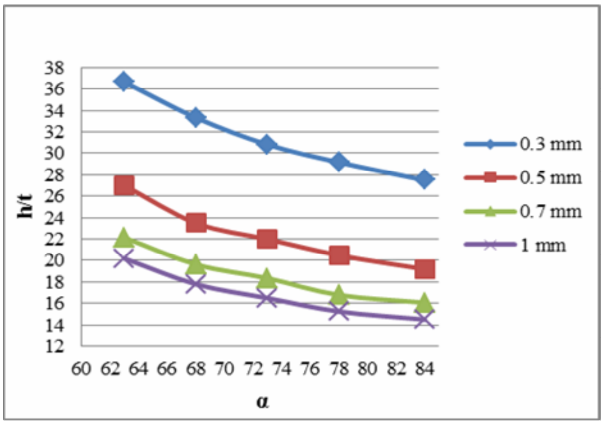


Fig. 11. Final practical curves.

Table 1. Effect of tool diameter on achievable depth.

Thickness (mm)	d_{tool} (mm)	h (mm)
0.5	6	9.5
	10	11
	14	12.25

Table 2. Effect of vertical pitch on achievable depth.

Thickness (mm)	p (mm)	h (mm)
0.5	1	11
	1.5	10.5
	2	10

The resultant frustum depth at which the part was fractured is shown by curves in the conclusion of this paper. Fig. 10 shows the resultant frustum depth verses its angle curves found from both experimental and analytical results for 0.5 and 0.7 mm plates. These curves verify the results determined from FEA. Considering various parameters that increase measurement errors, the maximum deviation of the experimental and FEA results were found to be less than 10%.

As could be expected, forming frustums with larger than 78 mm cone diameters with similar angles up to fracture limit did not lead to different frustum depth both in experiment and analysis. Obviously if the blank boundaries were not firmly clamped and the holder let the blank slide, different results would be concluded. Since the main purpose of this research is generation of applied curves from which the depth of a frustum with various thicknesses and angles could be determined, the effect of frustum larger diameter or at least the range of diameters for which the resultant curve could be applied should also be considered. As the reference diameter considered in this research was 78 mm, it was decided to find the range of diameters that their depth and angle were not much different from this reference diameter. The maximum acceptable deviation of the results from those of 78 mm was assumed to be 10%. Fig. 11 shows the resultant curves concluded after hundreds of analysis and include 0.3, 0.5, 0.7 and 1 mm thickness plates.

The required data for other thicknesses from 0.3 to 1 mm was found using FEA (Fig. 11). To investigate the accuracy of the acquired curves a sample 0.5 mm thickness plate was considered as the blank for forming a frustum with 62 mm top diameter and 68 degree cone angle. The achieved depth from experimental test was 11.75 mm while the acquired curves shows that the maximum depth is 11.9 mm, i.e. less than 2% deviation.

The vertical coordinate shows the dimensionless ratio of frustum depth to plate thickness and the horizontal coordinate depicts the maximum achievable angle. The curves were found by analysis performed on cones with 63, 68, 73, 78 and 84 degree angle. However, since these curves were generated for frustums with 78 mm major diameter, it is important to know the range of diameter covered by these curves so that the maximum error would be less than 10%. The curves also show that the maximum deviation between experimental and numerical results occurs in small angles when the diameter is increased. For example the maximum deviation between the depths of a 100 mm diameter frustum with 78 mm one occurs in 63 degree angle (α). Therefore, decreasing the angle increases the effect of increasing the frustum major diameter.

The same analysis was conducted for determining the range of thicknesses that could be covered by these curves. The results of analysis show that increasing the plate thickness could increase the deviation of the results when the diameter is increased. Obviously combination of these effects were needed to be considered in the analysis i.e. variation of thickness, angle and diameter to keep deviation less than 10%.

Finally it was found that these curves could cover all the frustums made from SS304 with the large diameters from 50 to 200 mm and the thicknesses form 0.3 to 1 mm with less than 10% deviation between finite element and experimental results. New data should be extracted from larger range.

4. Effect of tool diameter, vertical pitch and feed rate

To have a good understanding about the effects of tool diameter, vertical pitch and feed rate on incremental forming of a frustum, a number of experiments were performed. Two tools with 6 and 14 mm diameters were made to form frustums with 73 degree half cone angle from a blank with 0.5 mm thickness at this stage. The results show that reducing the tool diameter decrease the depth of the frustum (Table 1).

To investigate the effect of vertical pitch, 1.5 mm and 2 mm tool pitch were compared with the 1 mm one considered throughout this research. It was found that increasing the pitch not only reduces the frustum fracture depth but also deteriorates the surface finish (Table 2).

The proposed sample was formed with two more feed rates. Apparently this speed range does not considerably affect the

Table 3. Effect of feed rate on achievable depth.

Thickness (mm)	F $\left(\frac{mm}{min}\right)$	h (mm)
0.5	600	11
	1200	11.3

achievable depth (Table 3). Obviously more speed will generate more heat and consequently advances the fracture time. Feed rate also depends on the CNC machine capabilities and do not constrain forming in this research. All above parameters could be a good topic for further research in incremental forming.

It was also important to know the effect of backing ring location during forming process. In all conducted tests and analysis, the backing rings were placed at the center of the blank holder. By moving the backing ring to the edges and far from the center of the holder, it was found that there is not much difference between the depths of the frustum formed in this case with previous models. The experimental results on a 0.5 mm plate with 78 degree angle and 62 mm diameter with considerable eccentricity confirmed the results and showed good agreement with the developed curves with less than 4% error.

5. Discussion and conclusion

Various aspects of forming a frustum from a SS304 plate using incremental forming were studied in this research. The result of frustum diameter and depth along with cone angle were researched on various SS304 plate thicknesses to generate applied curves for manufacturing engineers in this research using finite element analysis. The results were then confirmed with experimental study for a fully clamped plate. A computer subroutine was developed for finite element analysis to simulate incremental forming of the proposed blank with the required specification. Hundreds of models were analyzed to develop applicable curves that cover any blank from 0.3 mm to 1 mm thickness and major frustum diameters from 50 to 200 mm with less than 10% deviation. The curves may be used for generation of a frustum with up to 84 degree angle and more than 90% precision.

It was shown that in similar conditions i.e. equal frustum angle and diameter, although thinner sheets allow for more ratio of depth to thickness (h/t) (Fig. 11), they allow for less frustum depth (Fig. 10) because of maximum strain limitation. On the other hand, increasing the frustum angle (i.e., making more cylindrical geometry) leads to less formed depth, since more strain is induced in a small region. Besides, the tool path has closer horizontal distance which makes an adverse affect on plate surface and advances plate fracture. Increasing the cone angle augments the overlapping of tool paths that increases the surface defects and may separate small pieces form the blank and generates and propagates crack. The tool path overlapping increases the strain in a smaller region and make the blank locally thinner and then leads to crack generation.

Although feed rate did not have considerable effect on deformability of blank, increasing tool diameter increases the depth of the formed frustum. However, increasing vertical pitch will not only reduce the depth but will also worsen the surface finish of the part. Investigating the effect of eccentricity of the backing ring was another subject studied in here and it was verified that the curves are still applicable.

Studying the effect of loose boundary clamps and the process of blank drawing and its influencing parameters in incremental forming are the authors' future topics for research.

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Nomenclature

- h : The frustum height
- t : The sheet thickness
- α : Frustum wall angle with perpendicular to its axis
- p : Vertical pitch

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