Iranian Journal of Materials Forming 7 (2) (2020) 32-43

IJMF

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

Research Article

The Effect of Ridges to Improve Ductility and Reduce Deformation Energy in Deep-Drawing Process

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ARTICLE INFO

Article history:

Received 12 March 2020
Revised 30 August 2020
Accepted 2 September 2020

Keywords:

Deep-drawing
Ridges deformation energy
Cylindrical cups
Forming force

ABSTRACT

In this research, two new methods that improve the drawing depth of deep-drawing processes have been introduced. In the first technique, by creating ridges on the punch surface, the stress concentration is decreased on the blank near the punch edge, in turn increasing the drawing depth. The second method is based on the principle of reducing resistant force in the flange area between the die, the blank-holder and the blank that can decrease the required forming energy. By using the ridges on the flange surfaces of die and blank-holder, the contact surface is reduced, which in turn can decrease the force required for blank forming. The simulation results of finite elements are compared to the experimental data. It is found that the ridged punch may delay the blank rupture and significantly raise the drawability.

1. Introduction

Deep-drawing is widely used while being affordable when a circular metal plate is pulled out by a symmetrical punch inside the die. Most researchers have examined the process variables and their alterations. They tested new geometries and methods for applying force, reducing friction, gaining access to optimal results in increasing the depth of stretching and improving surface quality. For example, using Wi-Fi [1] deep-drawing of circular sheets were carried out with semi-circular punch and the contact of the punch was formulated with sheets at any moment and modelled with finite element methods. Manabe et al. [2] studied the punch speed and combined it with the plate movement to determine the results of the deep-drawing process. In 2003, Brown et al. [3] examined some process variables and optimized the punch and die geometry, sheet force, lubrication and stretching speed in the forming of steel blanks. Kataoka et al. [4] studied the advantages and disadvantages of using lubricants in the formation depth and presented a method to use ceramic dies. In 2005, Yoshihara et al. [5] studied the variation of blank–holder force on the process of magnesium alloy sheets deep-drawing and compared the results with FE simulation. They used a special method to control the blank-holder force throughout the process to investigate its effect on deep-drawing. Gavas and Izciler [6] studied the influence of the distance between the blank-holder and blank on the formation of quadrangular sheets and the results showed that it had a great impact on this process. Warm deep-drawing of magnesium alloy sheet was investigated by Zhang et al. [7]. Palumbo et al. [8] who conducted a research on a method in which heat and punch speed were applied to

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magnesium alloy sheets warm deep-drawing. By comparing the experimental results and numerical data, a relationship between the blank temperature and punch speed was identified that helped achieve an appropriate drawing level. Demirci et al. [9] carried out experimental and numerical studies on the blank-holder force and its effect on the deep-drawing of 1050 aluminium alloy. In 2009, Ozek and Bal [10] investigated the influence of punch and die curvature radius on the elongation coefficient. Raju et al. [11] examined the influence of punch and die radii and blank-holder force in deep-drawing of 6061 aluminium alloy and achieved the optimum amounts of variables. In 2011, Kadkhodayan and Moayyedian [12] investigated the flange wrinkling in an analytical elastic-plastic study. They used the large deflection theory for a strain tensor with neglected nonlinear terms and showed that the results were identical to the theory of small deflection. Bagherzadeh et al. [13] investigated the deep-drawing of two-layer sheet metals with a hydro-mechanical process and the results were compared with the experimental data. Bao et al. [14] achieved good results for the formation of materials by using vacuum in a warm deep-drawing process. Gong et al. [15] used micro punches, dies and blank-holders covered with diamond-like carbon (DLC) to decrease friction. They found that this method could reduce the drawing force significantly and increase the drawing ratio. Ossia and Soltani [16] performed FE simulation of the magnesium alloy warm deep-drawing and showed that the forming force increased by rising the friction coefficient and the limit drawing ratio was reduced. They found that the rising of forming temperature could increase the maximum coefficient of friction for producing allowable parts. Huang et al. [17] examined the micro-deep-drawing process in the presence of ultrasonic vibrations and investigated its effect on the process. The obtained results demonstrated that this method was able to produce high application flexibility micro cups in miniaturization technology. Zein et al. [18] used numerical simulations to estimate blank thinning and spring back without expensive shop trails. In 2015, Reddy [19] tried to optimize parameters of warm deep-drawing process of 2016T6 aluminium alloy with using FEA. He founded that rising of warm deep-drawing temperature leads to an increase in the cup height. The formation of wrinkles was not signifciant with high friction coefficients and thick sheets. In the same year, Reddy [20] studied the formability of super-plastic deep-drawing process of AA1050-H18 conical cups with moving blank-holder. The formability of the conical cups was excellent for the surface expansion ratio of more than 2. Kitayama et al. [21] studied deep-drawing of cylindrical cups by changing blank-holder force. The numerical results showed that this method was useful for deep-drawing of hard-to-draw material. Ma et al. [22] studied the deep-drawing of AA6111 aluminium alloy at raised temperatures and investigated the effect of each process parameter. Their results showed that the blank-holder force had the largest effect on the thin blanks. Jawad and Abdullah [23] studied the effect of punch profile radius on deep-drawing process of a cylindrical low carbon steel cup and showed that the spring back and the cup height increased as the punch profile radius increased. Lin et al. [24] introduced a new method to rise the drawing depth in micro scales. They found that the drawing depth increased by using ridges on the micro-scale punch surface in order to form small circular sheets.

Although, it is customary to use lubricants to reduce the friction between tool and work piece during deep-drawing, discard of large quantities of lubricant waste is an enormous environmental and economic hazard [25]. In addition, the use of any lubricant in processes for metal forming needs cleaning of forming parts and increasing of forming time between continuing production steps to attain a semi-finished part [26]. Consequently, manufacturers have developed different green production strategies under laboratory conditions [27]. Brosius et al. [28] introduced a new lubricant free deep-drawing method by macro structured tools. They controlled the friction between the die, the blank-holder and the blank by creating ridges on them. They also controlled the required energy for the forming process by changing the parameters of ridges.

In this research, punch surfaces with ridges are designed and used to form cylindrical cups composed of SAE 304 stainless steel. First, an FE simulation is used to investigate the formability of deep-drawing by using punch surfaces with/without ridges (called ridged punch and simple punch). Then, drawing dies are designed and experimental studies are conducted. The results of experiments and FE simulation indicate that this method can make double the amount of elongation.

It is found that the method is useful in increasing the drawing depth and has no damaging effect on the thickness distribution of the blank for macro dimensions. The second method presented here is based on the Brosius study [28] and reduces the contact surface of the blank with die and blank-holder in flange area by creating ridges on the die and blank-holder (called ridged die and ridged blank-holder) in turn, reducing the forming force. The experimental data obtained are compared with numerical modelling results.

2. Punch Surface Design with Ridges

Figure 1 is a schematic diagram of the deep drawing process which shows the cups formed with two different methods. The purpose here is to form cylindrical cups composed of SAE 304 stainless steel and an inside diameter of 68 mm and depth of 40 mm with blank thickness of 1 mm.

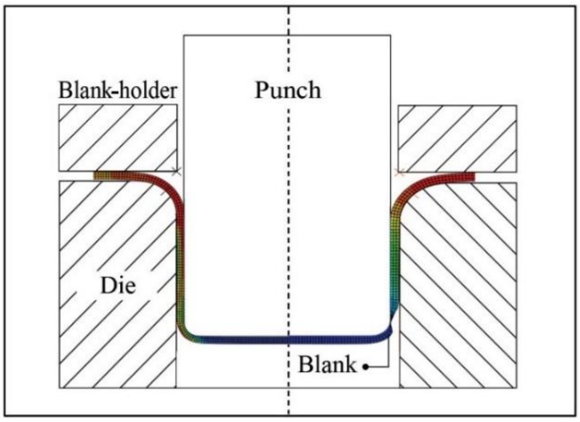


Fig. 1. Deep-drawing schematic.

2.1 Punch ridges design

Figure 2 shows the final cylindrical deep-drawing cups. The ridges are generated on the punch surface near the nose radius (Fig. 3). The five important parameters here are height, clearance, nose radius, shoulder radius, and distance between the ridges and punch nose.

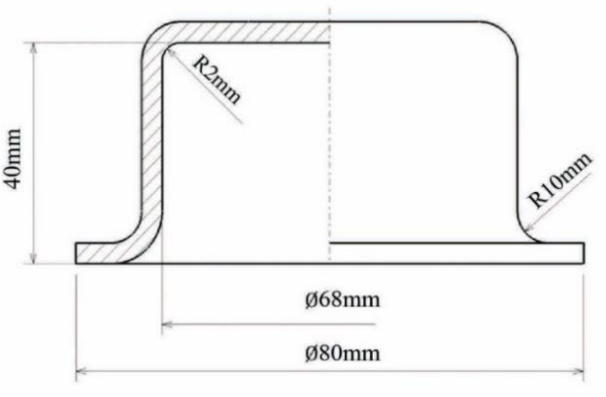


Fig. 2. Geometrical model of experimental component.

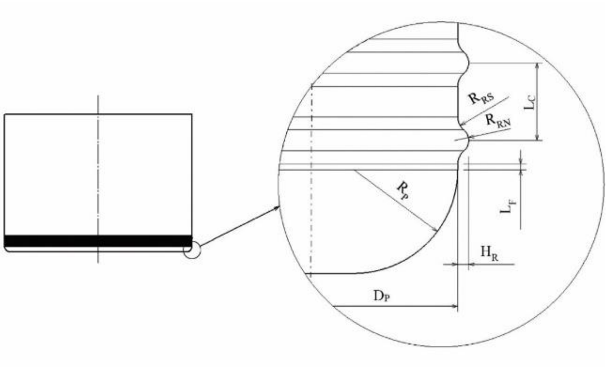


Fig. 3. Ridged punch schematic.

2.1.1 Ridge height

Very high ridge heights often lead to over compression of blanks that produces exterior indentation. The blank thickness in sidewalls decrease throughout the drawing process, hence, extremely small ridge heights lead to the incapability of the ridge efficiency. Consequently, the ridge height in this study is set at 0.05 mm or approximately 5% of the blank thickness.

2.1.2 Ridge clearance

The ridges used in this research are produced by visual projection grinding. An excessive distance between the ridge leads to a scattered drawing force of the ridges on the blank and reduced formability. On the other hand, an extremely small gap causes blade wear and increases the difficulty in the production of grinding blades. Furthermore, the use of small ridge clearances does not guarantee greater formability. The ridge clearance is set to 0.5 mm in this study.

2.1.3 Ridge nose radius

In design of the ridge nose radius, the emphasis should be put on allowing the ridges to draw the blanks deeply during the forming process, which causes the dispersion force of drawing. Moreover, specific consideration should be paid to prevent ridges that are too tiny, which would lead to penetrate into the blank during the forming process. In this study, the ridge nose radius is fixated at 0.05 mm. Moreover, and for the similar reason, the shoulder radius of ridges is fixed at 0.2 mm to avoid jammed blank in the ridges.

2.1.4 Distance between ridges and punch nose

A very short distance between the first ridge and nose of the punch causes interactions between the ridges and the punch shoulder which affects, in turn, the product dimension. On the other hand, a large distance reduces the influence of ridges on formability. This distance is taken as 0.2 mm in this study.

3. Die and Blank-holder Surfaces with Ridges

To reduce the friction force between the cylindrical deep-drawing parts, ridges are designed on the surfaces of the die flange and blank-holder (Fig. 4). The related parameters here are ridge radius, ridge shoulder radius and ridge clearance (see Table 1).

Table 1. Dimensions of ridges on die and blank-holder surfaces

Dimension parameter (mm)	**Value**
Ridge radius, R_R	2
Ridge shoulder radius, R_S	1
Ridge clearance, C_R	8

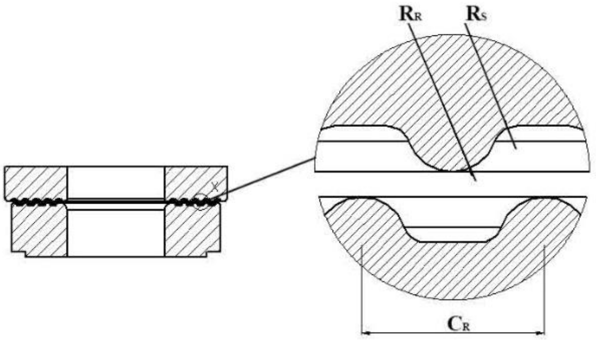


Fig. 4. Ridged die and blank-holder schematic.

If the radius of the formed ridges is too small, they may penetrate the sheet leading to an increase in the frictional force between the die and the blank surface and also the forming force. Moreover, the small distance between the ridges increase the number of ridges which raises the contact area between the die and blank and also the total force applied to the blank. On the other hand, large distance causes bending of the sheet in the space between the ridges and wrinkling. A shoulder radius for the ridges is also considered to increase the strength against wear.

4. Finite Element Simulation

The dynamic explicit solver in Abaqus software is used to simulate the FE model. The problem is simulated symmetrically and the die, blank-holder and punch are considered to be rigid. A one millimeter thick SAE 304 stainless steel sheet metal is used as the blank (Table 2). The density of SAE 304 stainless steel is 7800 kg/m^3.

Table 2. SAE 304 Stainless steel, chemical composition (wt. %)

C	**Si**	**Mn**	**P**	**S**	**Ni**	**Cr**
≤0.08%	≤1.00%	≤2.00%	≤0.045%	≤0.03%	≤10.50%	≤20.00%

To determine the engineering stress-strain behaviour of SAE 304 stainless steel, tensile tests were performed on a Zwick-Z250 uniaxial tensile test machine at room temperature. Tensile specimens of stainless steel 304 were prepared to have the dimension with a gauge length of 50.0 mm, width of 12.5 mm according to ASTM-0557 M-02 standard and are cut in the direction of 0 which conforms directly to the rolling direction. According to the punch speed the tensile tests are carried out with testing speed of 0.002 (1/s). The engineering stress-strain curve for SAE 304 stainless steel is illustrated in Fig. 5.

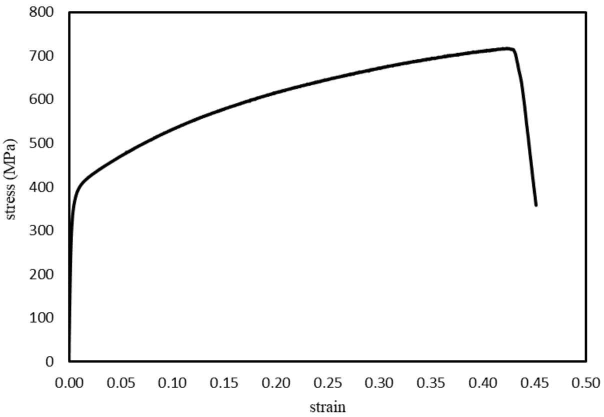


Fig. 5. stress-strain relationship of SAE 304.

The 132 mm diameter and 1 mm thick blank is meshed with shell elements of type CAX4R to 660 units after mesh generation. The die clearance value is set to 1 mm, which is the same as the thickness of the blank, to investigate the influence of ridged punch on formability of the blank. Clearance between the blank and blank-holder is considered as 0.4 mm and the friction coefficient as 0.3, which are obtained experimentally. In this simulation, the blank holder is fixed and punch travels 40 mm towards down along the Z axis. For both simple and ridged punches, the FE analyses are performed.

A geometric model of the ridged punch including the geometric images of lower die, blank and blank-holder and also the dimensions of the ridged punch, die and blank-holder may be seen in Fig. 6 and Tables 3-5.

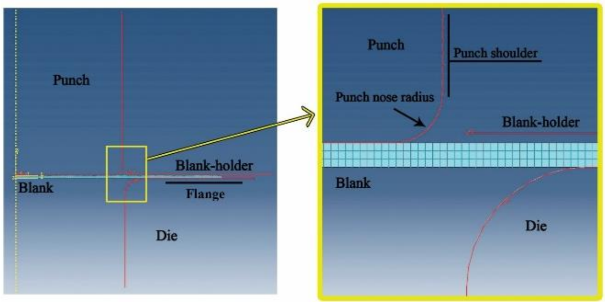


Fig. 6. Deep-drawing simulation model.

Table 3. Ridged punch dimensions

Dimension parameter (mm)	**Value**
Punch diameter, D_P	68
Punch nose radius, R_P	2
Ridge height, H_R	0.05
Ridge clearance, L_C	0.5
Ridge nose radius, R_{RN}	0.05
Ridge shoulder radius, R_{RS}	0.2
Ridge to punch nose distance, L_F	0.2

5. Deep-drawing Experiment

To examine the improvement of formability by using ridged punch, die and blank-holder, both simple and ridged ones are used in the experiment.

5.1. Equipment

The equipment applied in the deep-drawing experiment include a hydraulic press machine with a maximal load of 60 tons and deep-drawing dies, Figs. 7 and 8.

Table 4. Blank and tooling condition for deep-drawing test (method 1)

Parameter	Value
Punch diameter (mm)	68
Punch nose radius (mm)	2
Die inner diameter (mm)	70
Die outer diameter (mm)	153
Die shoulder radius (mm)	10
Blank-holder inner diameter (mm)	70
Blank-holder outer diameter (mm)	165
Drawing ratio	1.92
Blank diameter (mm)	132
Blank thickness (mm)	1

Table 5. Blank and tooling condition for deep-drawing test (method 2)

Parameter	***Value***
Punch diameter (mm)	68
Punch nose radius (mm)	2
Die inner diameter (mm)	70
Die outer diameter (mm)	153
Die shoulder radius (mm)	5
Blank-holder inner diameter (mm)	70
Blank-holder outer diameter (mm)	165
Drawing ratio	1.69
Blank diameter (mm)	132
Blank thickness (mm)	1

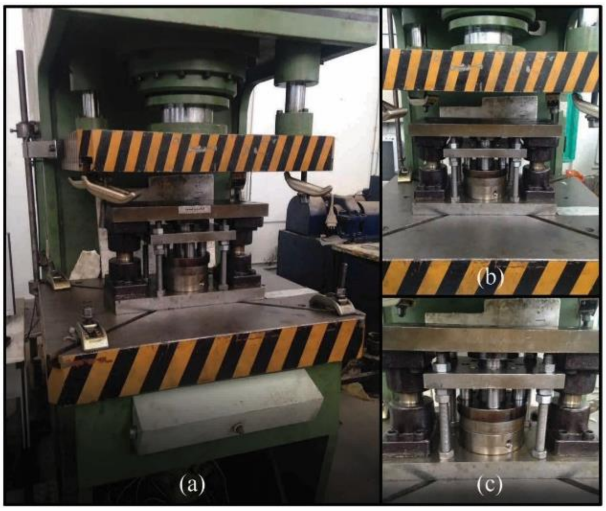


Fig. 7. The experimental equipment, (a) 60 tons hydraulic press machine, (b) deep-drawing die that installed on the press machine, (c) die.

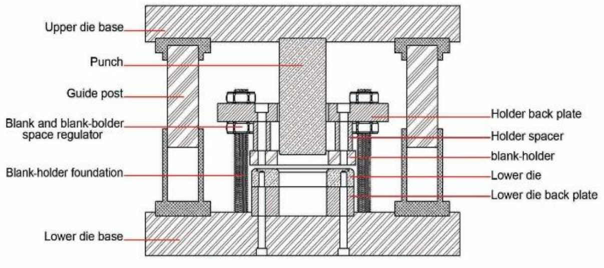


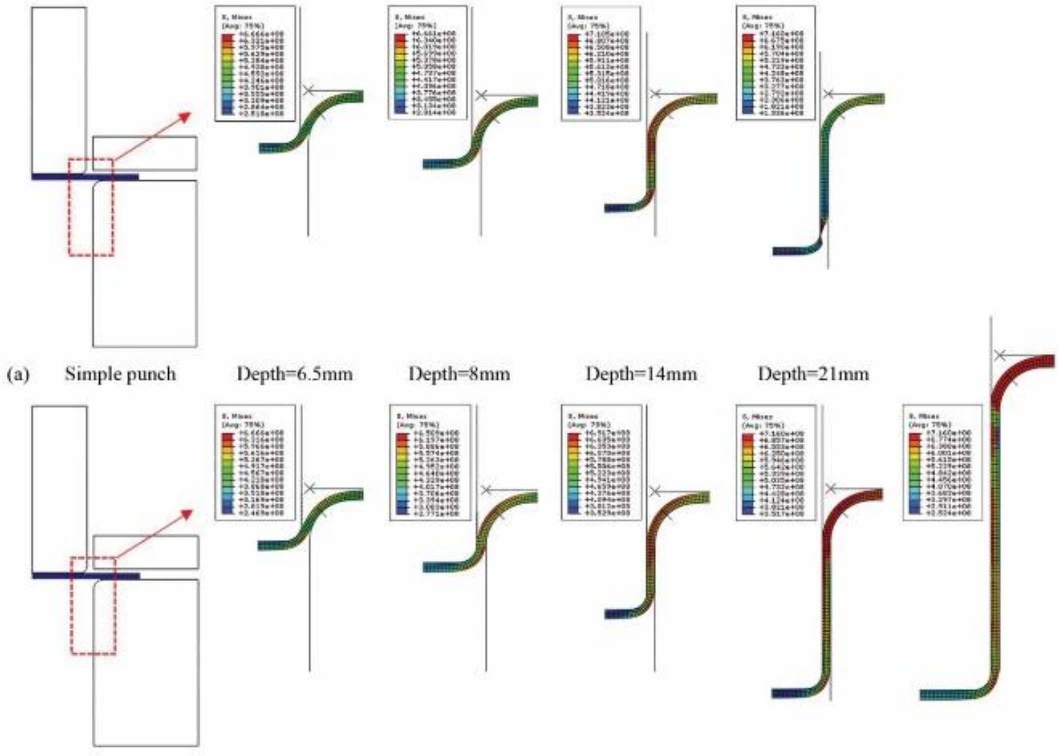
Fig. 8. Die unit of deep-drawing.

5.2. Experimental procedure

The stainless steel 304 sheet metal is used as a test material with a rolling thickness of 1 mm. It is cut into circular blanks of 132 mm in diameter by using a CNC laser cut device to produce blanks with favourable quality. The circular blanks are first wiped clean before they are placed in the groove of the lower dies. Deep-drawing experiments are performed using punch, die and blank-holder surfaces with and without ridges at room temperature. When formed cups starts to tear, the depth is reduced by 1 mm, and the procedure continues repeatedly until no rupture is detected. When the maximum forming depth is achieved, the experiment is repeated again in the same conditions to make the results repeatable.

6. The Drawing Mechanism

The sheet is drawn up to 40 mm and the stress distribution in a draw blank with simple and ridged punches is shown in Fig. 9. Figures 10 to 14 show a comparison of thickness distribution from the edge to the center of the sheet by using FE modeling for both types of punches at different depths of the process. At the beginning of the process, the distribution of stress in two blanks is the same because the ridges still do not reach the blank (depth =6.5 mm). Afterwards, however, (depth = 8 mm), stress in both blanks increases. When a simple punch is used, the punch nose radius plays the main role in the drawing and the friction forces applied to the blank. However, when a ridged punch is used, the spacing between the ridge noses and the lower die is lower than the blank thickness and, as a result, the ridges penetrate into the blank. Therefore, both the nose radius and ridges of punch affect on drawing and friction forces on the blank. In this case, the stress on the blank and close to the radius of the punch nose becomes less when the ridges are used.



(a) Simple punch Depth=6.5mm Depth=8mm Depth=14mm Depth=21mm

(b) Ridged punch Depth=6.5mm Depth=8mm Depth=14mm Depth=25mm Depth=40mm

Fig. 9. The blank stress distribution during deep-drawing process with ridged and simple punches.

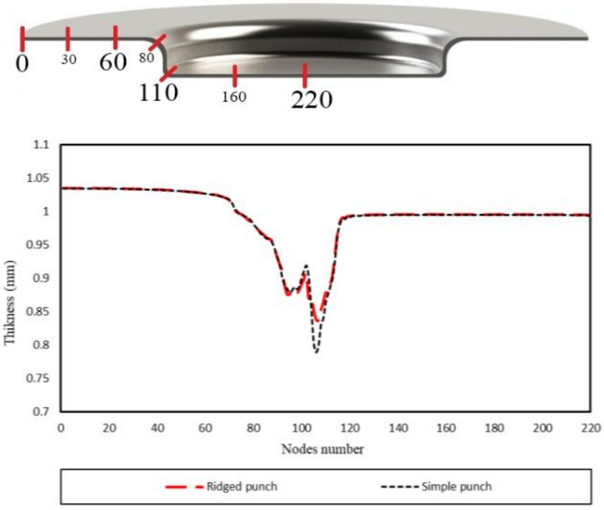


Fig. 10. Drawn cup thickness distribution for both punches with 10 mm of forming depth.

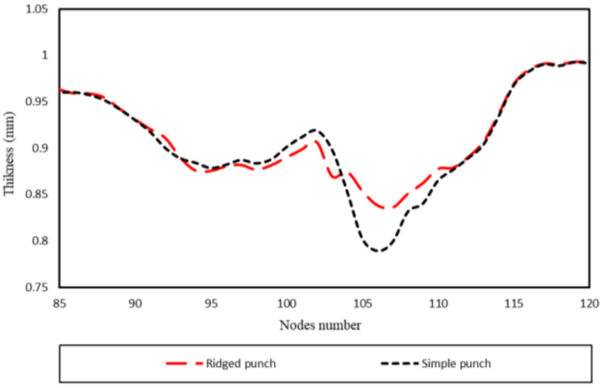


Fig. 11. Comparison of thickness distribution of drawn cup with 10 mm forming depth for both punches for nodes 85 to 120.

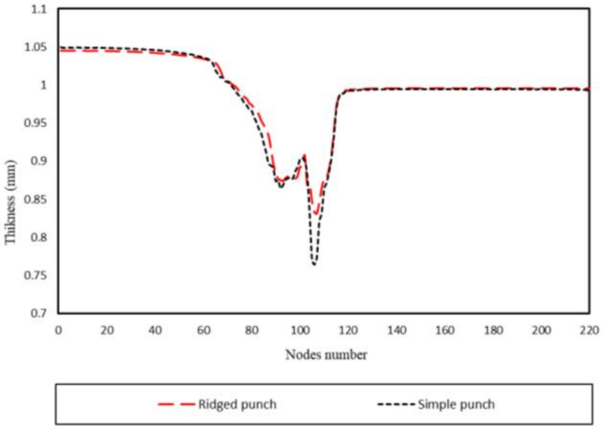


Fig. 12. Drawn cup thickness distribution for both punches with 15 mm of forming depth.

As the simple punch continues downward and reaches 14 mm of depth; punch nose radius stress increases significantly and the thickness of the blank decreases. When the blank stress near the punch nose radius exceeds the maximum flow stress (depth = 21 mm), the blank starts to tear. However, when ridged punches are used, the corresponding stress for the depth of 14 mm decreases and the speed of thinning is considerably lower than that of without ridges. At the same time, the forces of drawing and friction applied to the blank are reduced and some ridges slightly contact the blank.

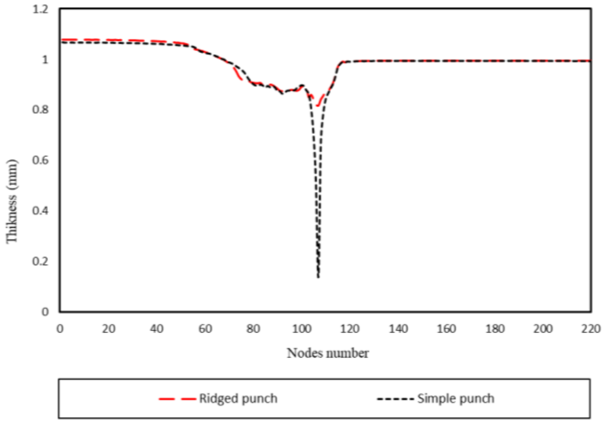


Fig. 13. Drawn cup thickness distribution for both punches with 20 mm of forming depth.

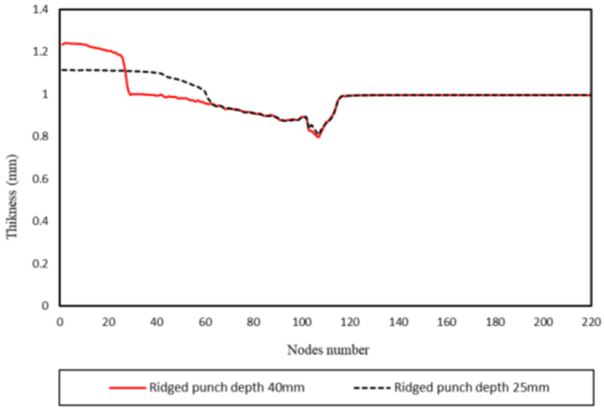


Fig. 14. Drawn cup thickness distribution for ridged punch with 20 and 40 mm of forming depths.

As the punch goes more downward (depth = 25 mm), the blank's diameter decreases and the flange thickness increases. The effects resulting from the increasing of the flange thickness outweigh the thinning effect caused by increased drawing force exerted on the flange, hence, the flange thickness increases before entering the die cavity. At the same time, the depth at which the ridges push into the blank increases in areas around the shoulder of the lower die, and the force of drawing on the blank increases. In addition, the stress in the vicinity of the nose radius decreases continuously. At the 40 mm depth, the flange part disappears gradually and the stress observed at the lower die shoulder of the blank becomes considerable, while it is significantly lower near the punch nose radius. In this case, applied drawing force on the blank is divided between the punch nose radius and the ridges. Here, the ridges perform a role of applying drawing and friction forces to the blank. However, in forming by simple punch the applied forces to the blank is only carried out by the punch nose radius.

To understand the process more clearly, two important parts including nodes 103 to 113 and nodes 93 to 103 are considered. In the region between the nodes 103 to 113, thickness is reduced and eventually the blank is torn from the same area. The thickness distribution curve that obtained by ridged punch is lower than that of the simple one in the area between nodes 93 and 103. As the gap between the tip of ridges and die is less than the thickness of blank, the ridges pressing the blank which reduces the thickness in this area more than that of the simple punch. This thickness reduction is about 0.01 of the total thickness of the sheet.

7. Results and discussions

The experimental and FE results are presented to examine three parameters of forming force, forming height and thickness distribution. Fig. 15 shows a comparison of two punches load-travel relationships obtained from simulation and experiments results. It is seen that the force drops at the end of deformation which indicates the failure has occurred. Both simulation and experimental results indicate that when the height of the drawing is the same and the ridges do not meet the blank, the drawing forces of both punches are similar. When the ridges touch the blank the deep-drawing force increases at about 2.5%. Fig. 16 shows the forming heights obtained experimentally in ascending order.

From the experimental and simulation results shown in Figs 15-17, some of the following important results are obtained. In case of using simple punch, the results show that rupture occurs at a 21 mm forming height. On the other hand, the use of ridged punch confirms the effect of ridges on dispersing of drawing force on the blank when the drawing depth attains the height of 40 mm. No defects, like wrinkles and cracks were seen when the blank formability increased up to 100%.

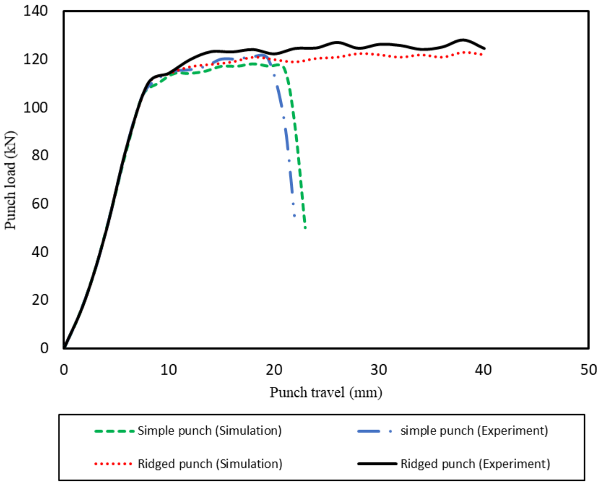


Fig. 15. Comparison of two punches load-travel relationships.

The results of both FE analysis and experiments of ridged die and ridged blank-holder are presented to investigate the forming force and height. Fig. 18 illustrates the experimental and simulation results for deep-drawing and forming force during the process using both die and blank-holder surfaces with and without ridges. Results indicate that the ridges on die and blank-holder surfaces cause an approximate 5% decrease in deep-drawing force and the punch can reach more depth.

Figures 19 and 20 show the drawing force and forming heights results during the forming process for different types of punch, die and blank-holders. It is seen that when the ridges are used on all parts simultaneously, the drawing depth reaches its maximum value. In addition, the use of ridged die and blank-holder reduces the forming force. Moreover, although the ridged punch increases the forming force, but it is less than that of its reduction in the previous case. Generally, to increase the drawing depth, all ridged parts may be used simultaneously.

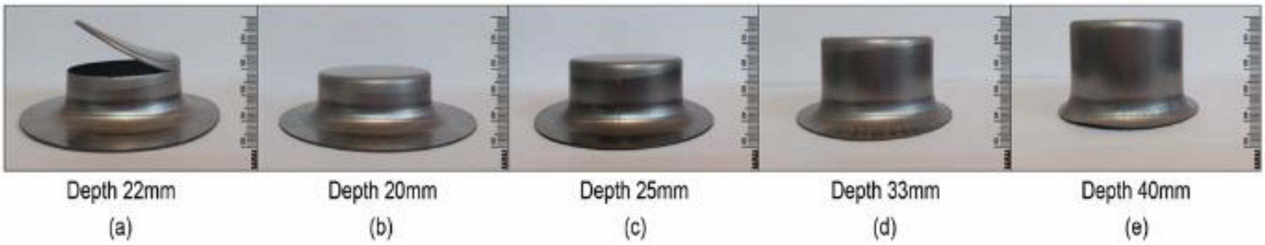
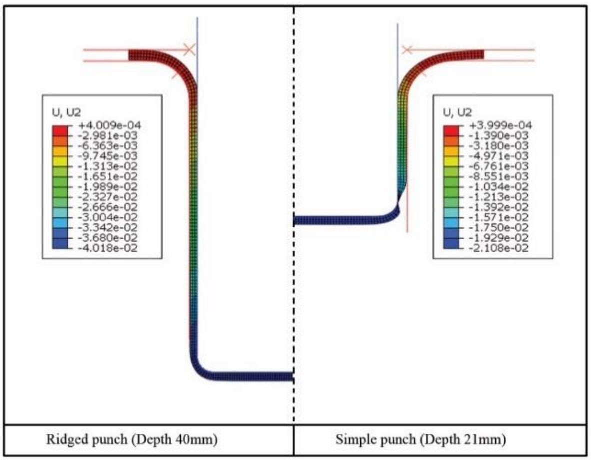


Fig. 16. Cups made by, (a) simple punch, (b), (c), (d), (e) ridged punch.



Ridged punch (Depth 40mm)

Simple punch (Depth 21mm)

Fig. 17. Maximum depth cup simulation results for both punches.

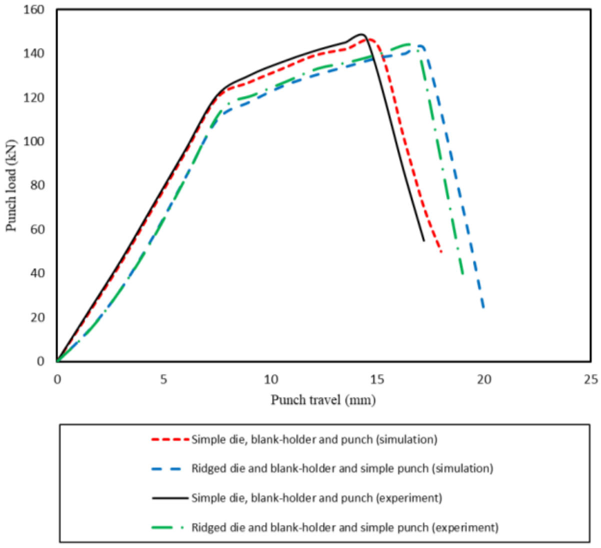


Fig. 18. Comparison of punch load-travel relationship obtained from simulation and experiments results of simple and ridged dies and blank-holders.

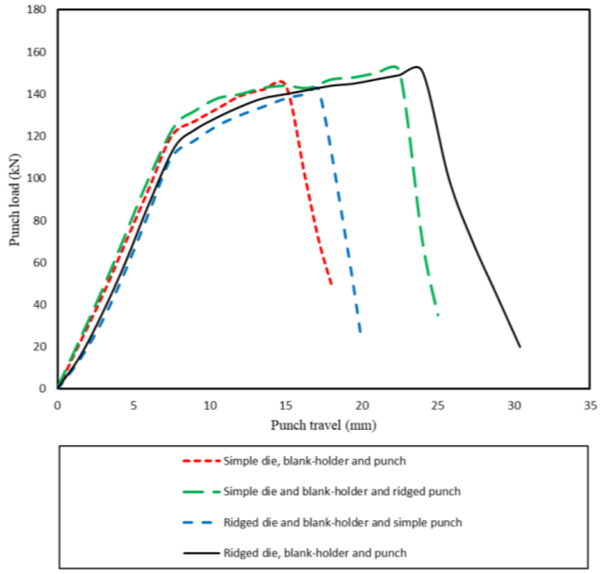


Fig. 19. Comparison of punch load-travel relationship obtained from simulation results of simple and ridged dies, blank-holders and punches.

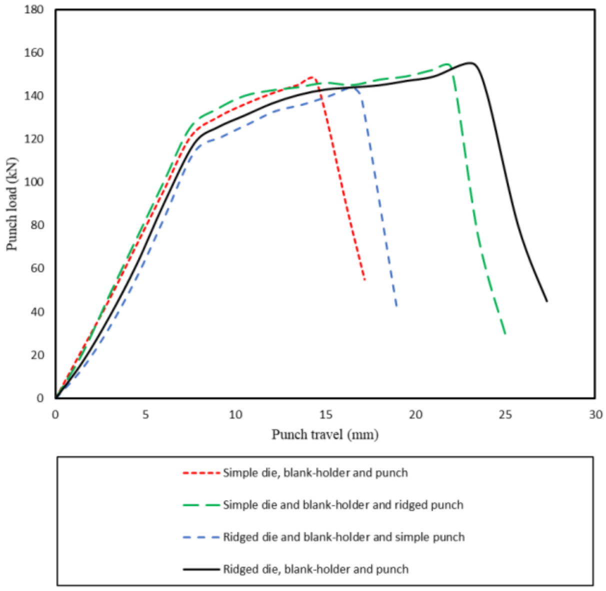


Fig. 20. Comparison of punch load-travel relationship obtained from experimental results of simple and ridged dies, blank-holders and punches.

8. Conclusions

SAE 304 stainless steel sheet metal is used in this study for the deep-drawing of a cylindrical cup for both ridged and simple punches. A comparison between the simulation and experimental results reveals a high degree of consistency. It is found that using ridged parts does not generate any unpleasant change in the thickness distribution. In addition, the effect of ridged punch on the dispersion of the drawing force on blanks and the delay of the rupture is confirmed and the drawability has increased at about 100%.

The use of ridges on the surface of die and blank-holders in the flange area can reduce the friction force and can act as an alternative for lubrication. The results confirm that using this method can increase the drawing depth and reduce the forming force. Although, the ridged punch increases both drawing depth and force, but the ridged die and blank-holder increases the drawing depth and reduces the forming force. Hence, the combination of all ridged parts definitely rises the drawing depth. However, the outcome of the forming force depends on the interaction of these methods.

9. References

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بررسی تأثیر برجستگی‌ها در افزایش شکل پذیری و کاهش انرژی تغییر شکل در فرآیند کشش عمیق

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چکیده

در این تحقیق، دو روش جدید برای افزایش عمق کشش در فرآیند کشش عمیق ارائه شده‌اند. در روش اول با ایجاد برجستگی‌هایی برروی سطح پانچ، تمرکز تنش در ناحیه‌ی گردشدگی لبه‌ی پانچ کاهش یافته و در طرف مقابل عمق کشش افزایش می‌یابد. روش دوم بر اساس اصل کاهش نیروی مقاوم بین ورق، ورق گیر و قالب در ناحیه‌ی فلنج ورق می‌باشد که می تواند باعث کاهش انرژی شکل دهی شود. با استفاده از برجستگی‌هایی بر روی سطح قالب و ورق‌گیر در ناحیه‌ی فلنج سطح تماس کاهش یافته که در عوض می تواند باعث کاهش نیروی لازم برای شکل دهی ورق شود. از مقایسه‌ی نتایج شبیه سازی اجزا محدود با نتایج آزمایش‌ها، نتیجه شده است که پانچ دارای برجستگی باعث تأخیر در پارگی ورق و افزایش عمق کشش می‌شود.

واژه‌های کلیدی: کشش عمیق، انرژی تغییرشکل برجستگی ها، فنجان های استوانه ای، نیروی شکل دهی