Numerical analysis on the influence of process parameters on the deep drawn product by using Taguchi method

Nay Chi Than Win1,2, Phyo Wai Myint1,2, Wutyee Nandar1

1. Department of Mechanical Engineering, Yangon Technological University, Insein Township, The Republic of the Union of Myanmar.

2. phyowaimyint@ytu.edu.mm, 3. ntwin14mech@ytu.edu.mm

Abstract. Deep drawing is a metal forming process that involves complex metal flow and widely used in various manufacturing. The process parameters such as punch corner radius and die corner radius affect the product quality. The punch velocity is also important to obtain the desired product shape. However, it is rare to observe the combination of process parameters effects such as punch and die corner radii and punch speed. In this study, the influences of punch corner radius, die corner radius, and punch speed on deep drawn formability and defect formation are analysed. Taguchi Method is applied to build the design of simulations, and the axisymmetric model is used to simulate with Finite Element Analysis-based ABAQUS software. The results showed that the punch corner radius and die corner radius mainly affect stress and strain distribution and the punch velocity affect the formability of the product and the production time.

1. Introduction

As the metal forming process is widely used in the mass production of automobile parts, aerospace industry, electrical components, and beverage applications, the quality is vital importance in industrialization. Deep drawing process can be defined as the process in which the depth of the blank is greater than half of the diameter of the blank. During the process, a blank sheet is experienced to plastic deformation in order to get the desired shape. Deep drawing involves complex material form and the presence of various nonlinearity such as geometric nonlinearity, material nonlinearity, and kinematic nonlinearity. Moreover, several defects like thinning, tearing, wrinkling, earing, and surface scratches are likely to develop during the process. Therefore, it is necessary to optimize the process parameters and geometric parameters to avoid defects in the final products.

In recent decades, a number of appropriate methods and analysis had been developed in sheet metal forming and still optimization of quality control is mandatory. Savas et al. [1] were interested in die and blank holder angle concerning the drawability. In this study, when the die angle α has increased, the deep drawing ratio has increased. Blank holder force is decreased by increasing α angle for a constant value of drawing ratio. Not only the production rate can be improved by optimization in punch speed and also affects draw ability. Yagami et al. [2] showed that the combination of variable punch speed (SPD) and variable blank holder force (BHF) technique can improve the deep drawability and product quality. It is established that the friction coefficient and the plastic anisotropy mainly effect on thickness and formability of the deep drawing process by Santhakumar, J et al. [3] Hadi et al. [4] observed that defects in workpieces vary in the different blank thickness by using FEM modeling. In this study, it was found that the blank thickness is greater than the threshold value then cracking may occur. If the blank
thickness is less than the threshold value, wrinkling may occur. Kanttikar et al. [5] conducted ANSYS software, the finite element analysis of sheet metal forming was carried out, and the results showed that increasing in punch corner radius reduced the punch load along with the reduction of stresses. Reddy et al. [6] applied the Taguchi method to establish relationships between punch nose radius, die profile radius, and blank holder force in influencing sheet thickness. And it is identified that the influence of BHF, punch corner radius, die corner radius is 56.98%, 30.12%, and 12.9% respectively in thickness variation.

Candra et al. [7] studied varying blank holder force in order to prevent the defects like cracking and improve formability by using FEM simulation. The material’s microstructures and mechanical properties can be changed by heat treatment [8]. Lin et al. [9] focused on punch design with micro-ridges. Taguchi method was applied to identify the influence of ridge height, ridge distance, ridge nose radius, and ridge to punch nose distance on thinning rate. The drawing depth can be increased by using the ridged drawing punch more than 60% compared with the non-ridged drawing punch.

Mahmoodi et al. [10] determined the influence of punch corner radius, die corner radius, BHF, clearance between punch and die and the layer arrangement on the occurrence of wrinkling and thinning. And it was found that BHF has the strongest influence on wrinkling and punch corner radius has the greatest effect in thinning. Madi et al. [11] performed the variation of drawing depth with respect to the forming speed. And also presented determining the ideal forming speed can optimize the forming time. Dewang et al. studied the influence of punch velocity on the deformation behavior in deep drawing of aluminum alloy and it was found that the wrinkling was controlled by punch velocity [12]. Ju et al. [13] incorporated experimental and finite element analysis to analyze the drawing speed and the results described that the deeper the draw depth can be obtained by the higher punch speed. When the higher forming speed is used, significant reduction in punch load is found. Bohaâluca et al. [14] optimized the coefficient of friction between blank and die, blank and holder and blank and punch by using the combination of FE model ABAQUS and Taguchi method, so that to avoid the thinning. Numerous researchers performed the fundamental characteristics of drawing process. Optimization of the process parameters such as punch corner radius, die corner radius, punch speed, friction etc., can give the better-quality products which can meet the customer satisfactions.

Though the combination with the punch speed and process parameters are less studied in recent decades. Therefore, the influence of punch speed on the production time and formability, the predominant factor of defects and reduction of stress by punch corner radius and die corner radius are observed in this investigation. Energy consumption of deep drawing is mainly based on the punch velocity. The aim of this investigation is to determine the influence of process parameters such as die corner radius, punch corner radius and punch speed on stress and strain distribution by combining a statistical approach based on Taguchi Technique and Finite Element Method. ABAQUS software is adopted to perform the finite element analysis of deep drawing process.

2. Material and Methodology
The Taguchi method was used in studies to design experiments and determine the influence of process parameters on the properties of the formed parts [3]. The advantages of Taguchi (DOE) can reduce the number of tests and save manpower, material resources and financial resources. Taguchi Method treats optimization problems in two categories: Static Problem and Dynamic Problem. In static problem, there are three signals to noise ratios for common interests for optimization. 1. Smaller the better 2. Larger the better 3. Nominal is the best. In this investigation, the thickness distribution is interested and as it should be uniform in deformation, therefore, it involves in nominal the best category. The process parameters, punch corner radius, die corner radius and punch speed were studied and three levels were used for each parameter. Taguchi orthogonal L9 array was used to investigate the effect of three parameters. The high order interactions among the above three factors are assumed negligible and the information on the main effects can be obtained by running 3^3 = 27 simulations. However, the appropriate Taguchi orthogonal array for the above three parameters with three levels is L9 to conduct nine simulations. The selection of the level values was performed by considering the shape and height
of the drawn product and the conditions of convergence in simulation process. The level selection of the process parameters is shown in Table 1 and L9 orthogonal array is presented in Table 2.

Table 1. Level Selection of the process parameters

| Process parameters          | Level |
|----------------------------|-------|
|                            | 1     | 2     | 3     |
| Punch Corner Radius(mm)    | 0.4   | 0.5   | 0.6   |
| Die Corner Radius(mm)      | 1.2   | 1.5   | 1.8   |
| Punch Speed(mm/s)          | 10    | 20    | 30    |

Table 2. Taguchi Orthogonal L9 Array for parameters level selection

| Simulation No | Punch Corner Radius(mm) | Die Corner Radius(mm) | Punch Velocity (ms⁻¹) |
|---------------|-------------------------|-----------------------|-----------------------|
| 1             | 0.4                     | 1.2                   | 10                    |
| 2             | 0.4                     | 1.5                   | 20                    |
| 3             | 0.4                     | 1.8                   | 30                    |
| 4             | 0.6                     | 1.2                   | 30                    |
| 5             | 0.6                     | 1.5                   | 10                    |
| 6             | 0.6                     | 1.8                   | 20                    |
| 7             | 0.8                     | 1.2                   | 20                    |
| 8             | 0.8                     | 1.5                   | 30                    |
| 9             | 0.8                     | 1.8                   | 10                    |

The geometrical dimensions in Figure 2 are shown in Table 3. In the drawing model, the punch, die and holder performed as rigid body and the blank, stainless steel SS304 was considered as the elastic plastic deformable body. The main material properties of the blank are presented in Table 4.

Table 3. Geometric parameters in drawing process

| Parameters                  | Value |
|-----------------------------|-------|
| Diameter of the blank (mm)  | 11    |
| Thickness of the blank (mm) | 0.5   |
| Diameter of die (mm)        | 3.2   |
| Diameter of punch (mm)      | 2.6   |
| Die corner radius (mm)      | 1.2–1.8 |
| Punch corner radius (mm)    | 0.4–0.8 |

Table 4. Main material parameters of the blank

| Parameters                  | Value |
|-----------------------------|-------|
| Density of material (kg/m³) | 7800  |
| Young’s Modulus (GPa)       | 200   |
| Yield Stress (MPa)          | 340   |
| Poisson’ ratio              | 0.29  |

The tensile test of SS 304 was conducted with a sheet thickness 2mm and punch speed of 5mm/min. The plastic strain and flow stress play the important role in plastic deformation of the material. The deep drawing process undergoes irreversible or permanent deformation and hence the elastic and plastic properties of the material are predominant. The flow stress and plastic strain of SS304 is presented in
Figure 1. The schematic diagram Figure 2 shows the geometrical model of before and after the drawing process and geometrical dimensions. The coefficient of friction is set as 0.18 for all interaction properties between the punch, the holder, the die and the sheet.

3. Finite element simulations
The problems of nonlinear materials and geometrically nonlinear problems with plastic deformations can be solved by using ABAQUS software. ABAQUS software was employed to simulate the deep drawing process with dynamic explicit method. The boundary conditions are applied in forming process. The blank holder, punch, and die were considered as the rigid bodies. Surface to surface contact model and a penalty contact method was selected. To accelerate the computing speed, the quarter of model (axisymmetric geometry) was built. Sheet metal is a deformable solid C3DQR and meshed with the 8 nodes linear brick and C3D4 the 4 nodes linear tetrahedron presented in Figure 3. The die, punch and holder are R3D4 4 node and 3D bilinear rigid quadrilateral. The sheet metal is meshed with 1824 elements. The model is with total 4848 elements and 6018 nodes. The inertia forces are ignored and the model is quasi static, the kinetic energy of deforming part does not exceed the small fraction of internal energy[15]. When dynamic explicit method is employed to the model of quasi-static simulations, millions of time increments would be literally required and increasing the speed of process in the simulation is necessary to obtain an economical solution.

The nine simulations were conducted and the equivalent plastic strain and Von Mises stress were measured at nine locations, as show in Figure 4. While conducting nine simulations, Von Mises stress and equivalent plastic strain are observed according to nine measured positions of the deformed part in Figure 8 and 9.
4. Results and discussion

The results obtained from numerical analysis are described in below. The distribution of Von Mises stress and equivalent plastic strain for the simulation number 1 with the punch corner radius of 0.4 mm, die corner radius of 1.2 mm and punch velocity of 10 mm/s are shown in the Figure 5 (a) and (b). The localized thinning at the right corner of the bottom is significant and failure can be occurred in that region due to stress localization. The punch velocity is 10 mm/s and according to time increment, the running time took much longer than others. The significant localized thinning effect was also occurred for the other simulation numbers 4, 5 and 9.

It was found that the formability is better in increasing the punch velocity from 10 mm/s to 20 mm/s and 30 mm/s. The results obtained from numerical analysis for the punch velocity of 20 mm/s, punch corner radius of 0.8 mm, die corner radius of 1.2 mm are shown in the Figure 6 (simulation number 7). It was found that the places occurred the maximum stress and maximum strain are changed under the same die corner radius and the different punch corner radius and punch speed.

The results obtained from the deep drawn simulation with the punch speed of 30 mm/s, punch corner radius of 0.8 mm and die corner radius of 1.5 mm are shown in the Figure 7 (simulation number 8).

The maximum stresses are occurred on the wall for both cases and the maximum strain was occurred at the bottom of punch nose for the punch velocity of 20 mm/s and at the flange area in the case of the punch velocity of 30 mm/s. The similar results with simulation number 8 are obtained for the simulation numbers 2, 3 and 6. The larger height of the deep drawn product was obtained from the simulation number 7. The results described that it is important to choose the correct parameters to get the desired shape of the deep drawn product.
The stress distribution on the nine positions of deep drawn part from flange area to the bottom centre is shown in the Figure 8. The results showed that the maximum stress localization was found at two places or three places for some simulation and mostly at the flange area and punch nose. The distribution of equivalent plastic strain is shown in the Figure 9. The maximum strain distribution was found at the places of wall, punch nose and bottom area. The simulation results described that the quality of the desired product is controlled by the punch corner radius and die corner radius and punch velocity.

Figure 8. Stress distribution on the deformed part from flange area to bottom centre
The smaller the best on S/N ratio of Taguchi technique was applied by using MINITAB software, which shown in Table 5 and Table 6 to analyse the influence of factors on the stress and strain distribution. The results in the Table 5 show that the punch corner radius has the strongest effect on the stress distribution and the die corner radius effect is more significant than the punch velocity.

Table 5. Response for signal to noise ratios of stress distribution

| Level | Punch Corner Radius | Die Corner Radius | Punch velocity |
|-------|---------------------|-------------------|---------------|
| 1     | -55.31              | -55.11            | -54.41        |
| 2     | -54.97              | -55.06            | -54.71        |
| 3     | -53.03              | -53.13            | -54.18        |
| Delta | 2.29                | 1.98              | 0.53          |
| Rank  | 1                   | 2                 | 3             |

Table 6. Response for signal to noise ratios of strain distribution

| Level | Punch Corner Radius | Die Corner Radius | Punch velocity |
|-------|---------------------|-------------------|---------------|
| 1     | 5.298               | 2.500             | 5.436         |
| 2     | 2.780               | 5.299             | 3.335         |
| 3     | 5.998               | 6.277             | 5.305         |
| Delta | 3.217               | 3.778             | 2.102         |
| Rank  | 2                   | 1                 | 3             |

The results in the Table 6 show that the die corner radius has the strongest effect on the strain distribution. The results obtained from simulation show that the increase in the punch speed reduces the processing time and the decrease in production time. And it was found that the part can be formed with good formability by applying the higher punch speed.
5. Conclusion
The cylindrical cup section deep drawing process was performed with numerical analysis to prevent localized thinning and stress and strain localization by appropriate selection of the influence parameters such as punch corner radius, die corner radius and punch speed. Taguchi method was used to design the finite element simulations and analyze the effects of the influence parameters on the deep drawing process by using MINITAB software.

The punch corner radius and die corner radius are mainly significant on the stress and strain distribution. The punch velocity can improve production time and effects on formability of the final part. The obtained results described that the quality of deep drawn product was affected by the punch corner radius, the die corner radius and the punch velocity. It can be concluded that the optimized parameters to obtain the desired deep drawn product with minimum stress and strain distribution and localized thinning are punch corner radius of 0.8 mm, die corner radius of 1.2 mm and punch velocity of 20 mm/s.

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