Materials and Design 55 (2014) 869–879

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Technical Report

Thinning and residual stresses of sheet metal in the deep drawing process

M. El Sherbiny *, H. Zein, M. Abd-Rabou, M. El shazly

Department of Mechanical Design and Production Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt

ARTICLE INFO

Article history:
Received 23 August 2013
Accepted 20 October 2013
Available online 30 October 2013

ABSTRACT

This paper presents a Finite Element (FE) model developed for the 3-D numerical simulation of sheet metal deep drawing process (Parametric Analysis) by using ABAQUS/EXPLICIT Finite Element Analysis (FEA) program with anisotropic material properties and simplified boundary conditions. The FE results are compared with experimental results for validation. The developed model can predict the thickness distribution, thinning, and the maximum residual stresses of the blank at different die design parameters, including both geometrical and physical parameters. Furthermore, it is used for predicting reliable, working parameters without expensive shop trials. Predictions of the thickness distribution, thinning and the maximum residual stresses of the sheet metal blank with different design parameters are reported. Frictional limitations and requirements at the different interfaces are also investigated.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

For the majority of food and drink containers, the cost of the processed metal accounts for 50–70% of the total cost [1]. From the manufacturer's point of view, a reduction in material usage is of massive importance to cost reductions. Reduction of material can be done by decreasing the wall thickness of the containers, whilst also retaining adequate strength to allow the container to serve its purpose, without fear of failure. The designer must meet these expectations, but also, must determine the material requirements and properties which are suitable for the food or drink being packaged. Traditionally, this process, as well as most metal forming techniques have been tested experimentally using trial-and-error or empirical methods, which are expensive and time consuming approaches, as dies, blank holders and punches are need to be manufactured. Many newly designed dies and punches were successfully implemented but produced somewhat higher percentages of reject products. The reason simply is that the computer aided design (CAD), although tightly follow design codes, it should be tested on a simulation model for the forming process to predict product tolerances, quality, and localized failures. The objective of the work is to successfully simulate the deep drawing process as a required step to validate the quality of the tool design before implementation. The literature contains both experimental and numerical results which are in agreement with each other [2], and the present simulation model has been validated accordingly.

The incentive for doing this research is that deep drawing has come to a stage in the current industrialized world that requires the most efficient, low-cost, manufacturing route to be taken at all times. By making use of finite element analysis and statistical methods, the prediction of results such as the punch force, the blank holder force, the thickness distribution through sections of the metal and the lubrication requirements can be determined [2]. This can significantly reduce the production costs, for higher quality containers by reducing the lead time to production and provides engineers the ability to respond faster to market changes. In doing this, the level of knowledge in how various materials interact at the contact surfaces are enhanced, and the data for dealing with specific materials are also increased, which is another positive outcome.

Colgan and Monaghan [3] have taken a statistical approach, based on experimental design using orthogonal arrays to ascertain which factors most influence the deep drawing process. The geometries for the deep drawing process have been reproduced, and a critical comparison is reported. This work established that the punch/die radii have the greatest effect on the thickness of the deformed mild steel cups. It is made apparent that the smaller the die radii, the greater the force on the blank, resulting in thinner wall thicknesses. It is also shown that the type of lubrication is very much affecting the force on the punch. Although Colgan and Monahan's work [3] concluded that the die radii are noted as a prominent factor, they did not provide enough substance to account for other factors affecting the deep drawing process.

Demirci et al. [4] addressed the problem of the deep drawing process of AL1050 in a different approach by performing experiments and finite element analysis using ANSYS/LS-DYNA software. They investigated the effects of the blank holder forces on differences in the cup wall thickness. The paper shows that under constant pressure the base of drawn cups remains at a constant

* Corresponding author. Tel.: +20 1006044616; fax: +20 237746016.
E-mail address: mgsherbiny@eng.cu.edu.eg (M. El Sherbiny).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.10.055

value until thickness drops dramatically near the cup corners and follows exponential variation towards the outer edge on the cup flange. Taking into account the anisotropic properties of the material they concluded that forces exceeding 10 MPa may result in tearing in the cup walls.

Jawad [5] confirms the previously stated point that increasing the punch radii can slightly decrease the punch load and vice versa. He investigated the effects of punch radii on maintaining the interfacial contact between the punch and the blank, and punch load on thickness through a section of the drawn cup, and finally predicted the resulting localized strain and stress distribution. He concluded that frictional forces act mainly through the edge of the punch in a shearing manner, with little effect on the flat section.

Vladimirov et al. [6] presented the derivation of a finite strain material model for plastic anisotropy and nonlinear kinematic and isotropic hardening. The work is applied to the drawing of cylindrical and square shaped cups. They show that the numerical simulations, can be suitably extracted from the complex mathematical material models and that the phenomena of anisotropic properties can still be accounted for even with large deformations. They further go onto show the applicability of the mathematical work to account for the occurrence of earring during the drawing process.

Fereshteh-Saniee and Montazeran [7] predicted forming load by using various finite element types, and the strain thickness distributions are produced, as reported in [4]. The authors also show that the use of shell 51 elements of the finite element package give a much higher agreement with the experimental results. In making these comparisons, they used an analytical formula to produce a solution to which the level of agreement between the two methods can generally be accepted.

Residual stresses are a system of stresses which can exist in a body when it is free from external forces. Since residual stresses are generated by nonuniform plastic deformation. The maximum value to which a residual stress can reach is the yield stress of the material. Metals containing residual stresses can be stress relieved by heating to a temperature where the yield strength of the material is the same or lower than the value of the residual stress such that the material can deform and release stress. However slow cooling is required otherwise residual stress can again develop during cooling.

Researches for the residual stresses are published by Lange and Bruckner [8]. These investigators have studied the effect of process parameters on the residual stresses. They investigated the effect of the die edge radius and the punch diameter on the axial residual stresses in deep-drawn brass cups and observed that reducing the tool clearance, so that ironing occurs simultaneously with deep drawing, causes a great reduction in the residual stresses.

Danckert [9] proposed a finite element simulation of two stage deep drawing process followed by ironing of the cup wall to analyze the residual stresses in the cup wall after the drawing stages and after ironing of steel blank. The results show that the ironing process causes a drastic change in the residual stress and causes a favorable distribution with regard to fatigue strength, stress corrosion resistance and stress cracking.

Danckert [10] and Fereshteh-Saniee and Montazeran [11] investigated the effect of residual stresses in deep-drawing of cylindrical cups by modeling the die profile. These studies showed that the residual stresses in the cup wall are mainly caused by the unbending of the material when the material leaves the draw die profile and the die profile led to a substantial improvement in the dimensional accuracy of the deep-drawn cup. In addition, the effect of the friction coefficient was more pronounced than in the finite-element simulations. The residual stresses are generally developed by mechanical working processes that determine the material deformation and modify the shape of part or the properties of its material [12,13]. In the case of metal sheets deep drawing, such stresses are generated by the incompatibility between the permanent deformations of material and occur in conditions in which some differences exist between the states of deformation of different material strata. Thus, in the case of a cave drawn part, the generation of residual stresses can has the following causes:

- In the regions stressed by bending combined with tensile, regions located in the zones of connecting bottom – wall and wall – flange, the outer face of part, generally, passes into yielding before the inner face.
- In the moment when the applied load is removed, the zones with larger yielding will prevent the zones with smaller yielding to back in an unstressed state. In such conditions, when a difference exists between different surfaces and zones of part concerning the material yielding, the generation of residual stresses in the deformed material will be favored [14,15].

Crina and Monica [16] determined the residual stress distribution through the sheet thickness in the case of cylindrical deep-drawn part. The metal sheets were made of FePO 5MBH steel. The analysis was performed both, experimentally and by simulation, respectively. The experimental tests were performed by using the hole drilling method and for simulation the ABAQUS software was used. A reasonable agreement concerning the stress profiles obtained from the two analysis techniques (experimental and simulation). This work established that stresses are maximum on the outer sheet surfaces and decrease through the sheet thickness, both in the center and at the edge of the part bottom, respectively.

Brabie et al. [17] investigated the influence of the punch shape on spring back intensity and residual stress distribution by simulating the drawing process in the case of conical parts made from steel sheets by using the following two punch shapes: cylindrical and conical. Some differences resulted between the distributions of residual stresses obtained in the case of drawn parts made by using cylindrical and conical punches; such differences can be caused and influenced, among other causes or factors, by the differences that exist between the friction conditions that are created by the punch shape on the part wall; thus, in the zone of part wall, the friction between material and punch exists only in the case of conical punch and is absent in the case of cylindrical punch.

Meguid and Refaat [18] used a method of variation inequalities to develop an analytical method to model the frictional contact in elastoplastic models which undergo large deformations. The effect of nonlinearities arising due to either the geometry or the materials used in the model is handled by using the updated Lagrangian formulation.

Having arrived at a point where the material can be modeled to a very high degree of accuracy and the forming loads can be predicted to complete the drawing process, one may consider various frictional combinations at the contacting surfaces aiming at minimizing such forming loads, and hence cost analysis can be carried out for the manufacture of the container. This paper intends to approach the deep drawing process of thin walled, mild steel, cylindrical containers, by means of a finite element analysis.

2. Simulation of deep drawing process

2.1. Finite element model

Fig. 1 shows a sketch for drawing a circular cup [2]. The important dimensions, Fig. 2, of the blank, die, punch, and blank holder are shown in Table 1. Due to the symmetry, the numerical analysis of the deep-drawing process was performed by using only one

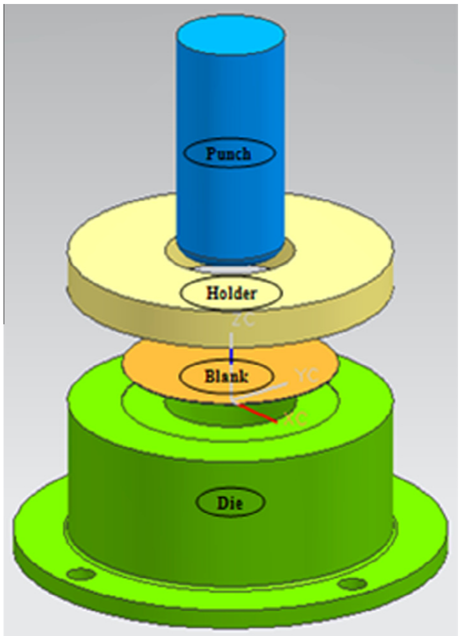

Fig. 1. Sketch of the drawing die assembly.

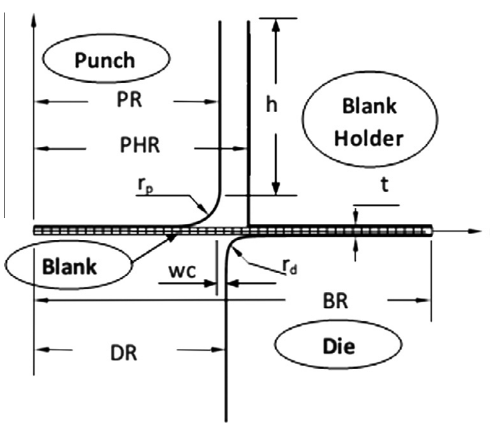

Fig. 2. Geometry of drawing die assembly.

Table 1
Basic geometrical parameters.

Parameter	Dimension in mm
Blank size radius (BR)	112
Blank thickness (t)	1
Punch radius (PR)	56
Punch nose radius (r_p)	4
Die radius (DR)	57.67
Die shoulder radius (r_d)	6
Radial clearance between punch radius and die radius (wc)	1.67
Cup height of the first draw (h)	63.69

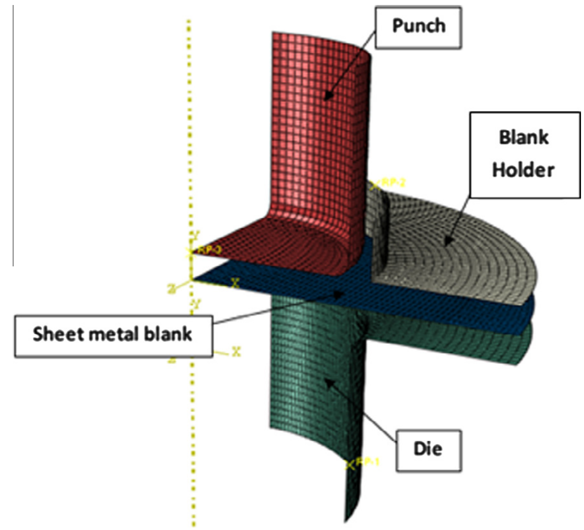

Fig. 3. The model assembly scheme in FEM.

Table 2
Blank material.

Young's modulus (E)	206 GPa	
Poisson's ratio (v)	0.3	
Density (ρ)	7800 kg/m^3	
Yield stress σ_o	167 MPa	
Anisotropic yield criterion	R_{11}	1
	R_{22}	1.0402
	R_{33}	1.24897
	R_{12}	1.07895
	R_{13}	1
	R_{23}	1

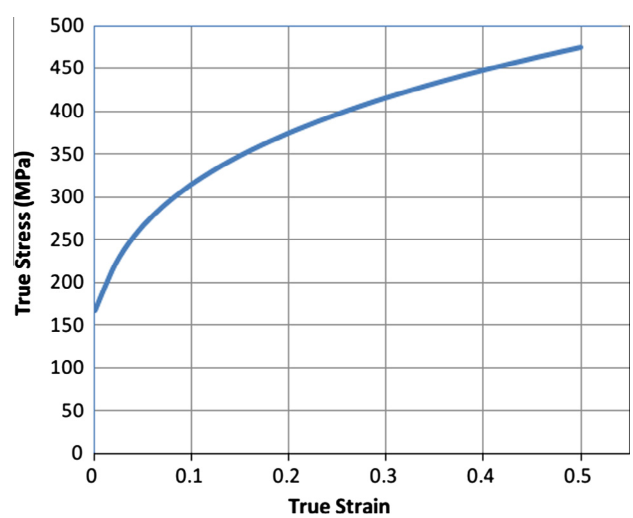

Fig. 4. Plastic true stress vs. plastic true strain curve of mild steel.

quarter of 3D numerical model to reduce the computational time. The model is shown in Fig. 3. Discrete rigid form was used to model the punch, die and holder, whose motion was governed by the motion of a single node, known as the rigid body reference node. Die, punch, and holder were meshed with R3D4 elements. Therefore, only the blank sheet metal (224 mm diameter × 1 mm thickness) was considered deformable with a planar shell base and meshed with reduced integration S4R shell type element [19].

2.2. Material properties

The blank is made of mild steel [20]. The material is modeled as an elastic–plastic material with isotropic elasticity, using the Hill anisotropic yield criterion for the plasticity to describe the anisotropic characteristics of the sheet metal within the simulation programme (ABAQUS/EXPLICIT). Table 2 shows the material

Table 3
Quoted parameters.

Die shoulder radius (r_d)	r_d = (6–10) t for first draw
Punch nose radius (r_p)	r_p = (3–4) t for 6.3 mm ⩽ dp < 100 mm
	r_p = (4–5) t for 100 mm ⩽ dp < 200 mm
	r_p = (5–7) t for 200 mm ⩽ dp
Radial clearance (wc)	wc = (1.75–2.25) t for steel, deep drawing

Table 4
Geometrical parameters.

Blank size radius (BR)	38 mm
Blank thickness (t)	1 mm
Punch radius (PR)	19.7 mm
Punch nose radius (r_p)	2 mm
Die radius (DR)	20.85 mm
Die shoulder radius (r_d)	2 mm
Radial clearance (wc)	1.15 mm
Cup height of the first draw (h)	20 mm

Table 5
Physical parameters.

Young's modulus (E)	200 GPa
Poisson's ratio (ν)	0.3
Tangent modulus (Et)	0.5 GPa
Density (ρ)	7800 kg/m^3
Yield stress (σ_o)	200 MPa
Friction coefficient (μ)	0.1
Blank holder force (BHF)	18 kN

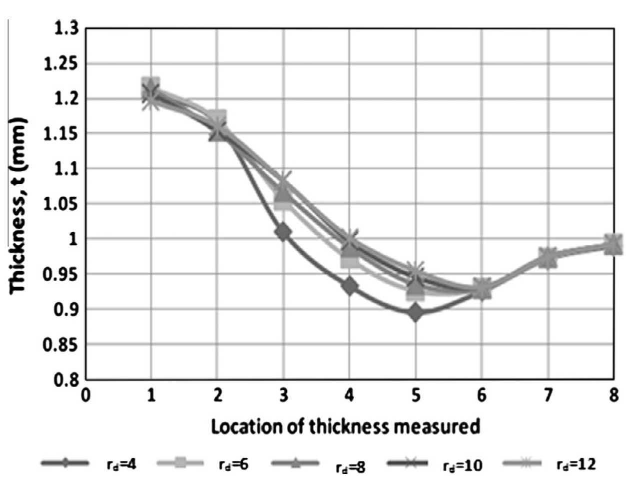

Fig. 5. Distribution of sheet metal thickness with diverse values of the die shoulder radius (r_d, mm).

properties, whilst Fig. 4 shows the plastic true stress, true strain curve of the material behavior.

2.3. Die design parameters

The die design parameters are classified into two categories.

1st category is the tool geometry parameters
- Die shoulder radius (r_d)
- Punch nose radius (r_p)
- Sheet metal thickness (t)
- Radial clearance (wc)

2nd category is the operating parameters
- Blank holder force (BHF)
- Lubrication:
- Coefficient of friction between punch/blank (μ_p)
- Coefficient of friction between holder/blank (μ_h)
- Coefficient of friction between die/blank (μ_d)

The study of the influence of the tool geometry parameters and the physical parameters over thinning of sheet metal in the deep drawing process has been made, according to recommended geometrical values of these parameters from the code, Table 3 [21].

3. Validation of the model

Comparison between the results of the present model and earlier experimental results of Colgan and Monaghan [3] were presented [2] to show agreement and to validate the model.

Tables 4 and 5 show the model dimensions and materials properties respectively. The present model is made and analyzed on ABAQUS/EXPLICIT FEA program. It has been shown that the average thickness distribution in the blank of the present finite element analysis model is closer to the average obtained from the experimental results [3]. Furthermore the present results are very close to the numerical results [3], with differences which do not exceed 2.9% on average. It is even more closer to the experimental results with differences do not exceed 0.6% on average.

4. Results and discussion

4.1. The tool geometry parameters

4.1.1. The die shoulder radius (r_d)

The geometry of die influences the thickness distribution and thinning of sheet metal blank in the deep drawing processes. Fig. 5 shows thickness distribution for different values of the die shoulder radius (r_d), while Fig. 6 shows thinning of sheet metal with diverse values of the die shoulder radius (r_d). These results show that for the die shoulder radius (r_d) that is less than six times the thickness of the blank (t), the cup fails due to increasing in thinning, whilst for (r_d) greater than (10t), thinning is stable. Accordingly the die shoulder radius (r_d) should be 10 times the sheet thickness. Also, the geometry of die influences maximum residual stresses of sheet metal blank in the deep drawing processes.

Fig. 7 shows maximum residual stresses for different values of the die shoulder radius (r_d). These results show that for the die shoulder radius (r_d) that is less than six times the thickness of the blank (t), the cup has a large value of the maximum residual stresses, whilst for (r_d) greater than or equal (10t), the maximum residual stresses have smaller values. Therefore, the die shoulder radius (r_d) should be 10 times sheet thickness.

4.1.2. The punch nose radius (r_p)

The geometry of punch influences the thickness distribution and thinning of sheet metal blank in the deep drawing processes. Fig. 8 shows thickness distribution with different values of the punch nose radius (r_p), while Fig. 9 shows thinning of the sheet metal with the punch nose radius (r_p). It is shown that for a punch nose radius (r_p) that is less than three times the thickness of the blank (t), the cup fails due to increased thinning, whilst for (r_p) greater than 3t, thinning is somewhat stable. In addition, the geometry of punch influences the maximum residual stresses of sheet metal blank in the deep drawing processes.

Fig. 10 shows the maximum residual stresses with different values of the punch nose radius (r_p). It is shown that for a punch nose radius (r_p) that is greater than six times the thickness of the blank

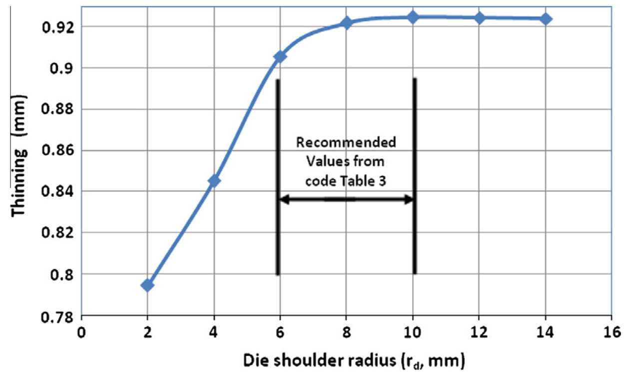

Fig. 6. Variation of the sheet metal thinning with different values of the die shoulder radius (r_d).

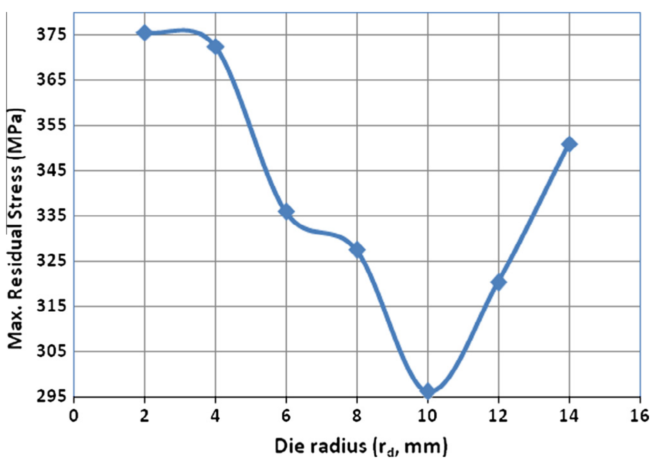

Fig. 7. Variation of maximum residual stresses in sheet metal with different values of the die shoulder radius (r_d).

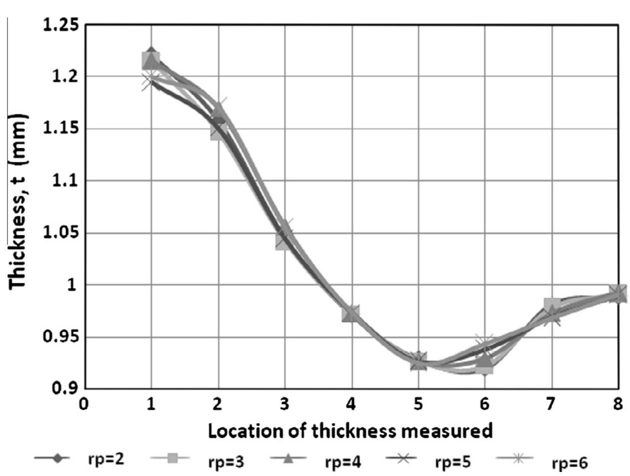

Fig. 8. Distribution of sheet metal thickness with diverse values of the punch nose radius (r_p, mm).

(t), the cup fails due to increased maximum residual stress, whilst for (r_p) selected between ($3t$) and ($5t$), the maximum residual stresses are somewhat reduced.

4.1.3. Sheet metal blank thickness (t)

The original blank thickness has some effect on the thickness distribution and thinning of sheet metal blank in the deep drawing

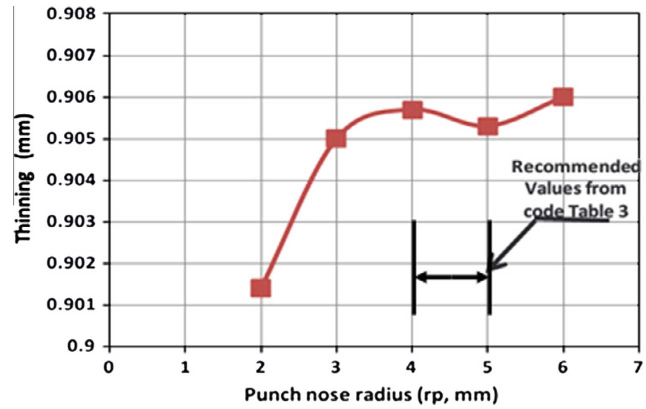

Fig. 9. Variation of the sheet metal thinning with different values of the punch nose radius (r_p).

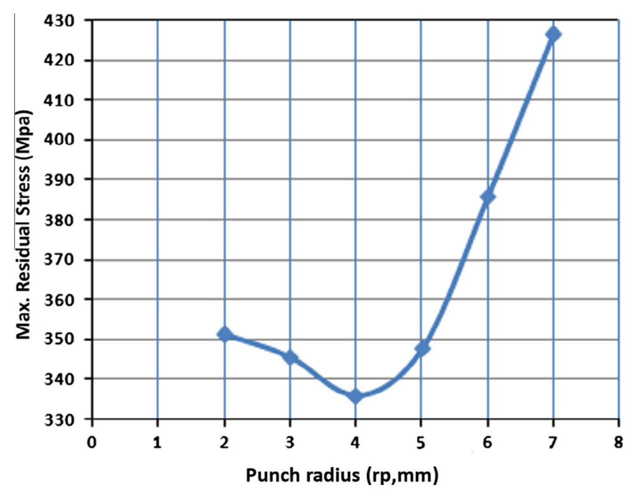

Fig. 10. Variation of the maximum residual stresses in sheet metal with diverse values of the punch nose radius (r_p, mm).

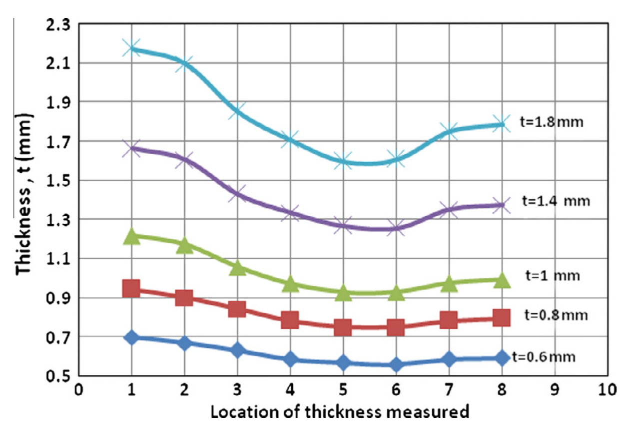

Fig. 11. Distribution of sheet metal thickness with several values of the blank thickness (t).

processes. Fig. 11 shows thickness distribution with several values of the blank thickness (t), while Fig. 12 shows the percentage of thinning of sheet metal with different blank thickness (t).

It is shown that the average distribution of the wall thickness is increasing with increasing the blank thickness. Also, the % of

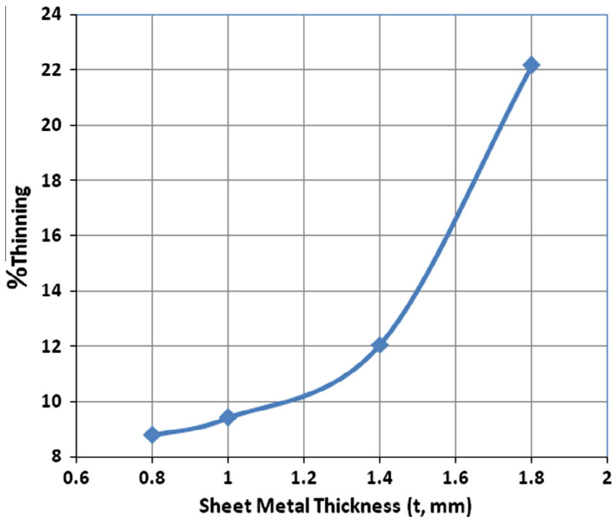

Fig. 12. Variation of % the sheet metal thinning with variation of the blank thickness (t).

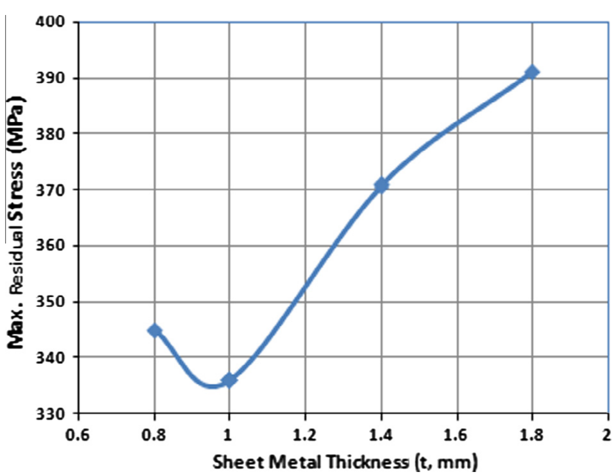

Fig. 13. Variation of the maximum residual stresses in sheet metal with variation of the blank thickness (t).

thinning is increasing with increasing of the blank thickness. Taking into account, the blank thickness and the punch diameter effects, the limiting drawing ratio (LDR) decreases as the relative punch diameter increases [22]. Slightly thicker materials can be gripped better during the deep drawing process. Also, thicker sheets have more volume and hence can be stretched to a greater extent with increasing in thinning.

The original blank thickness also has some effect on the maximum residual stresses of sheet metal blank in the deep drawing processes. Fig. 13 shows the maximum residual stresses with several values of the blank thickness (t). It is shown that the maximum residual stresses increases with increasing the blank thickness.

4.1.4. Radial clearance (wc)

Radial clearance is an important parameter, formulated as the difference between die radius and punch radius (wc = DR − PR). Fig. 14 shows thickness distribution with different values of the radial clearance (wc), while Fig. 15 shows thinning of the blank with the radial clearance (wc). It is shown that the distribution in sheet metal thickness is increasing when reducing the radial clearance (wc). In addition, for the radial clearance (wc) that is less than the blank thickness (t), the

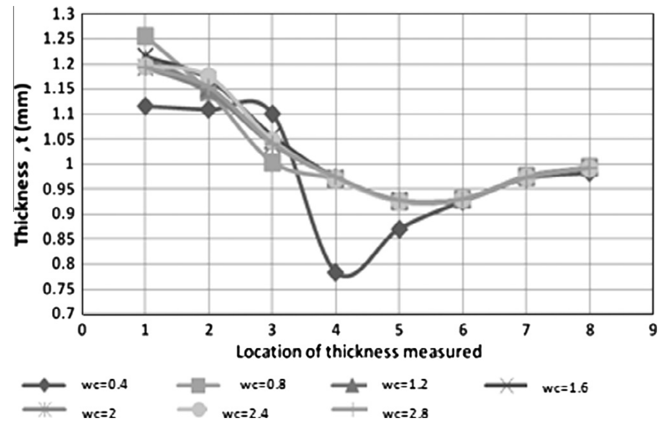

Fig. 14. Distribution of sheet metal thickness with several values of the radial clearance (wc, mm).

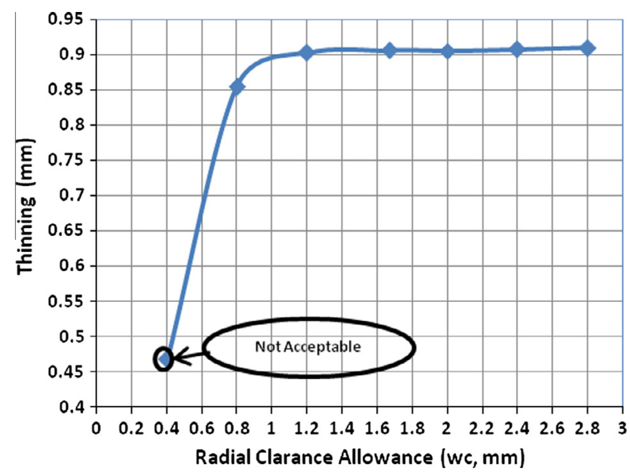

Fig. 15. Variation of the sheet metal thinning with different values of the radial clearance (wc).

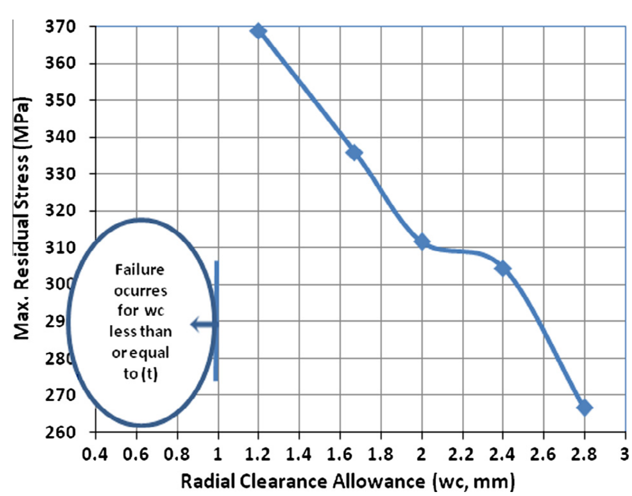

Fig. 16. Variation of the maximum residual stresses in sheet metal with several values of the radial clearance (wc, mm).

cup fails due to increased thinning. Whilst for the radial clearance (wc) greater than the blank thickness (t), thinning is stable. The radial clearance which is less than ($0.5t$) is not

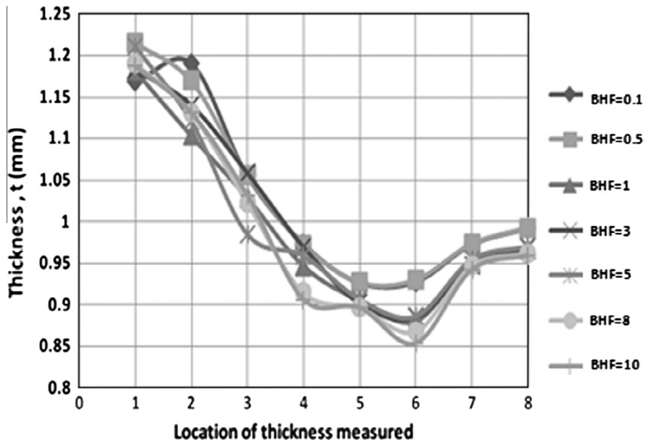

Fig. 17. Distribution of sheet metal thickness with different values of the blank holder force (BHF, ton).

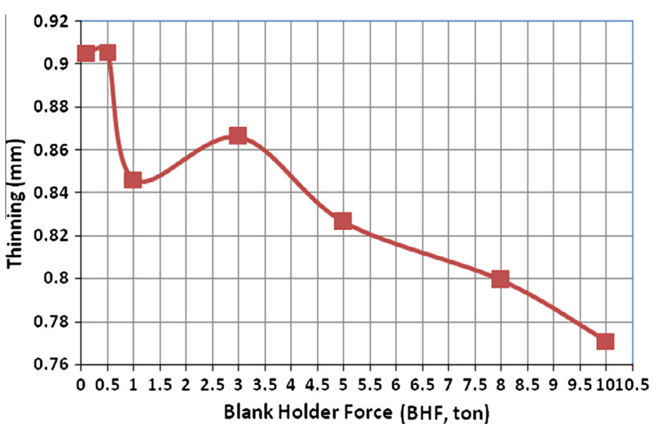

Fig. 18. Variation of the sheet metal thinning with different values of the blank holder force (BHF).

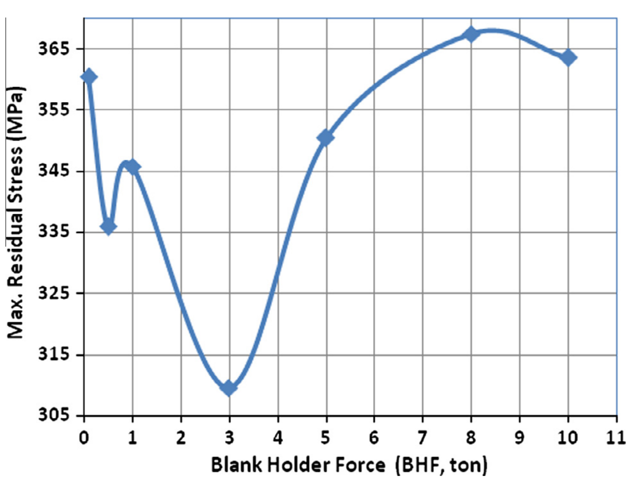

Fig. 19. Variation of the maximum residual stresses in sheet metal with different values of the blank holder force (BHF).

Fig. 16 shows the variation of the maximum residual stresses with different values of the radial clearance (*wc*). It is shown that the maximum residual stress is reducing with increasing the radial clearance (*wc*). In addition, for the radial clearance (*wc*) that is less than the blank thickness (*t*), the cup fails due to increased the maximum value of the residual stresses. Whilst for the radial clearance (*wc*) greater than (2*t*) of the blank thickness, the maximum value of residual stress is reduced.

4.2. The physical parameters

4.2.1. Blank holder force (BHF)

Fig. 17 shows distribution of sheet metal thickness with different values of the blank holder force (BHF, ton). The blank holder force (BHF) required to hold a blank flat for a cylindrical draw varies from very little to a maximum of one third of the drawing pressure [23]. Fig. 18 shows thinning of the blank with the variation of the blank holder force (BHF). The higher the blank-holder force, the greater will be the strain over the punch face, however the process acceptable because the percentage of reduction in thickness is more than 45%, while the maximum allowable percentage of reduction in thickness is 45% [20].

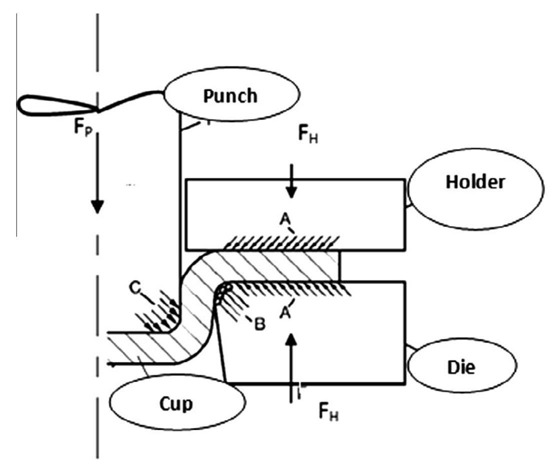

Fig. 20. Friction areas when a deep drawing a cup. (A) friction area between sheet metal blank and holder and sheet metal blank die; (B) friction area between sheet metal blank and the die radius; (C) friction area between sheet metal blank and the punch edges; Fges, total drawing force; FN, blank holder force; 1, punch; 2, blank holder; 3, die; 4, cup; 5, flange area; 6, cup wall; and 7, base of the cup [25].

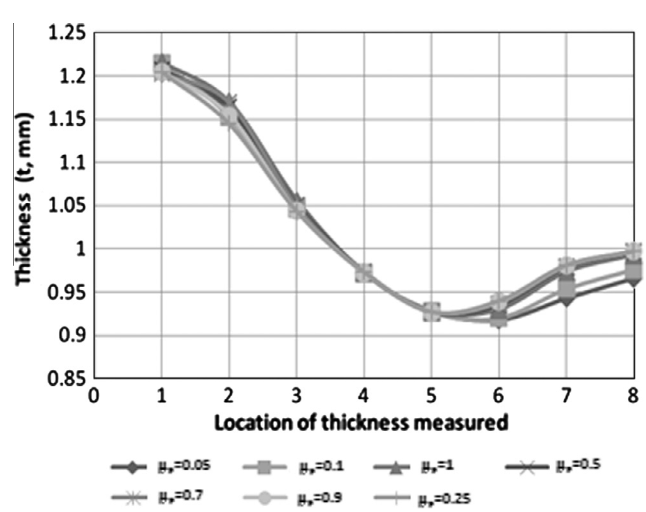

Fig. 21. Distribution of sheet metal thickness with different values of the coefficient of friction between punch/blank (μ_p).

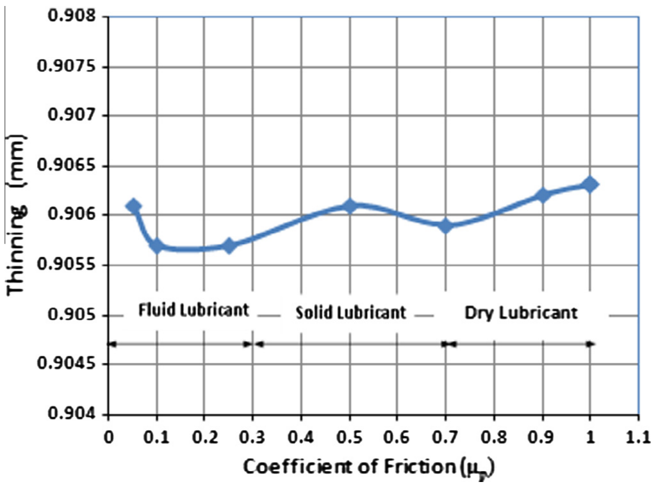

Fig. 22. Variation of the sheet metal thinning with different values of the coefficient of friction between punch/blank (μ_p).

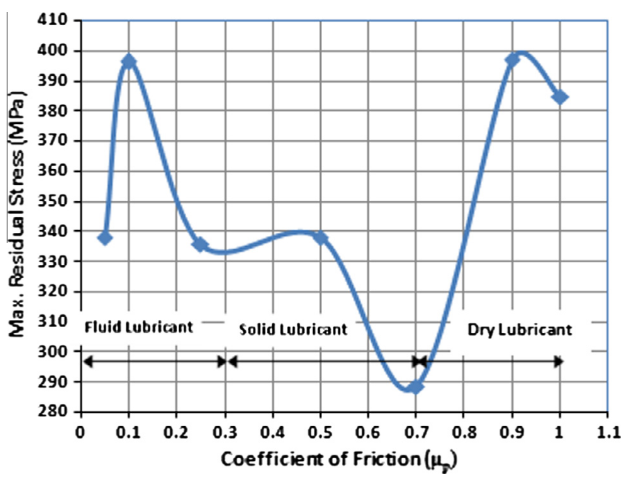

Fig. 23. Variation of the maximum residual stresses in sheet metal with different values of the coefficient of friction between punch/blank (μ_p).

is limited by the strain in the side-wall. If the tension reaches its maximum value, the side-wall will fail by splitting [24]. It is shown that the cup collapse due to thinning with the increase of the blank holder force (BHF) over 0.5 ton.

Fig. 19 shows the maximum residual stresses with different values of the blank holder force (BHF). It is shown that the maximum value of the residual stresses is decreasing with increasing of blank holder force (BHF) when BHF is smaller than or equal 3 ton. But the maximum value of the residual stresses is increasing with increasing of BHF above this value.

4.2.2. Coefficient of friction parameters

In Sheet Metal Forming processes, friction plays an important role. Together with the deformation of the sheet, the friction determines the required punch force and the blank holder force. Consequently, the friction influences the energy which is needed to deform the sheet material. Friction also influences the stresses and strains in the work piece material and, hence, the quality of the product. Therefore, it is important to consider the friction between the tools and the work piece.

During deep drawing, hollow bodies are produced from metal blanks using punches, dies and blank holders. In no other forming operation are the friction and, as a result, the lubricating conditions so complex. In one drawing operation a particularly low coefficient of friction is required in one area and a particularly high coefficient of friction in another. Friction also influences the stresses and strains in the work piece material and, hence, the quality of the product. Therefore, it is important to consider the friction between the tools and the work piece. Fig. 20 shows the different frictional interfaces and generally illustrates the deep drawing configuration [25].

4.2.2.1. Coefficient of friction between punch/blank (μ_p). The drawing force in the flange necessary to form the sheet metal is applied by the punch on the base of the cup and transferred from there through the wall into the flange. This transmission of force calls for the highest possible coefficient of friction on the punch edge. This demonstrates the first significant rule for lubrication in this case: neither the punch nor the sheet metal blank should be lubricated in this area. Even if this consideration was optimal for an isolated forming operation and force transfer, one still has to consider punch wear. This friction area requires lubrication in the dry or boundary mode, with a high coefficient of friction and anti-wear behavior [25].

Fig. 21 shows thickness distribution with different values of the coefficient of friction between punch/blank (μ_p), while Fig. 22 shows thinning of the blank with the variation of the coefficient of friction between punch/blank (μ_p). Fig. 23 however, shows the maximum residual stresses with different values of the coefficient of friction between punch/blank (μ_p).

For fluid lubricant, it is shown that the thickness distribution in sheet metal thickness is decreasing with increasing of the coefficient of friction between punch/blank (μ_p). For solid and dry lubricants, the distribution in sheet metal thickness is stable with increasing the coefficient of friction between punch/blank (μ_p). It is also shown that the thinning of sheet metal is increasing by small values with increasing the coefficient of friction between punch/blank (μ_p). On the other hand, for solid and dry lubricant, the thinning grows with increasing the coefficient of friction between punch/blank (μ_p).

Maximum residual stresses have smaller values when increasing of the coefficient of friction between punch/blank (μ_p). On the other hand, for fluid lubricant, the maximum residual stresses show higher values. Also, particularly for dry lubricant, the maximum residual stresses are increasing with increasing of the coefficient of friction between punch/blank.

4.2.2.2. Coefficient of friction between holder/blank (μ_h). The main function of deep drawing lubrication is to achieve minimum

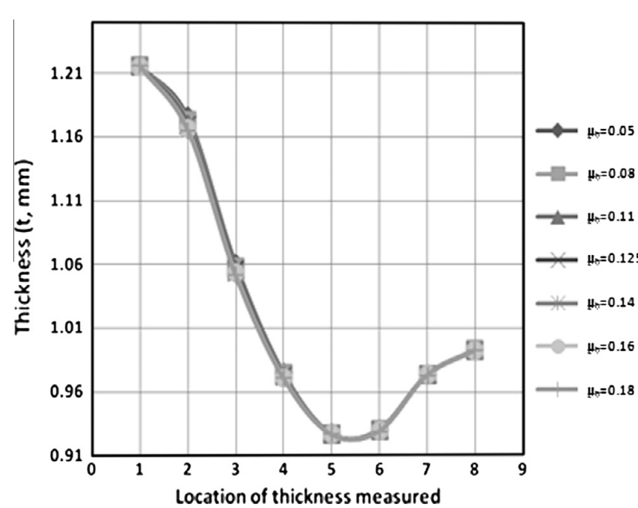

Fig. 24. Distribution of sheet metal thickness with different values of the coefficient of friction between holder/blank (μ_h).

friction in the blank holder area. This includes the lubrication on the blank holder side, which, as much as possible, should be a lubricant ring in order to reduce the friction in the region of the punch edge to as little as possible. However, in the case of high viscosity oils and drawing pastes, if the applied lubricant film is excessive, there is the risk that hydrostatic effects on the blank holder side of the flange cause reduction of sheet metal contact with the blank holder resulting in wrinkling [25].

Fig. 24 shows thickness distribution with different values of the coefficient of friction between holder/blank (μ_h), while Fig. 25 shows thinning of the blank with the variation of the coefficient of friction between holder/blank (μ_h). It is noted that the suitable lubricant for the holder/blank friction is the fluid lubricant. When the coefficient of friction between holder/blank (μ_h) is increasing, the average value of the thickness distribution is slightly stable. But the thinning of the cup grows with increasing the coefficient of friction between holder/blank (μ_h).

Fig. 26 shows the maximum residual stresses with different values of the coefficient of friction between holder/blank (μ_h). Again it is noted that the suitable lubricant for the holder/blank friction is the fluid lubricant. When the coefficient of friction between holder/blank (μ_h) is rising, the maximum residual stresses are decreasing.

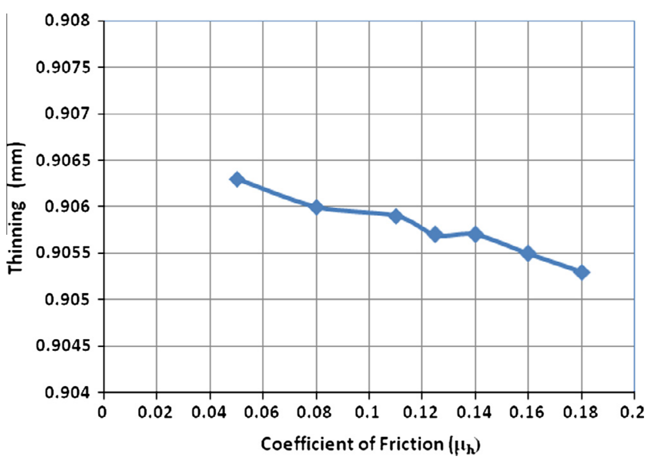

Fig. 25. Variation of the sheet metal thinning with different values of the coefficient of friction between holder/blank (μ_h).

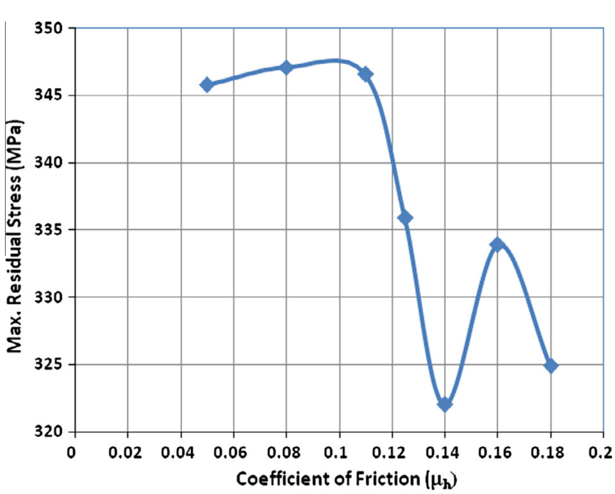

Fig. 26. Variation of the maximum residual stresses in sheet metal with several values of the coefficient of friction between holder/blank (μ_h).

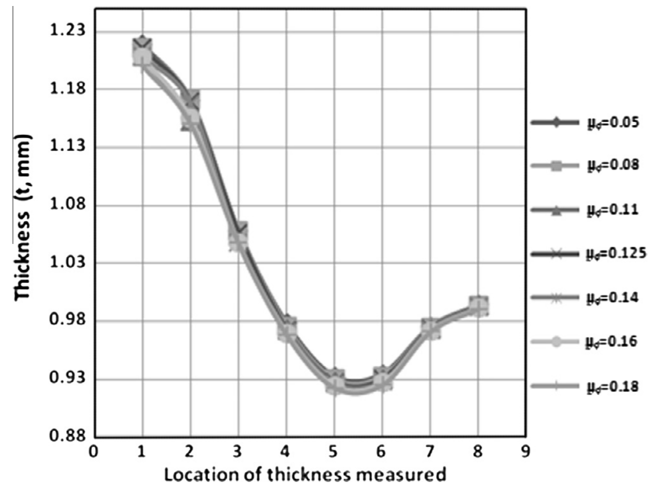

Fig. 27. Distribution of sheet metal thickness with different values of the coefficient of friction between die/blank (μ_d).

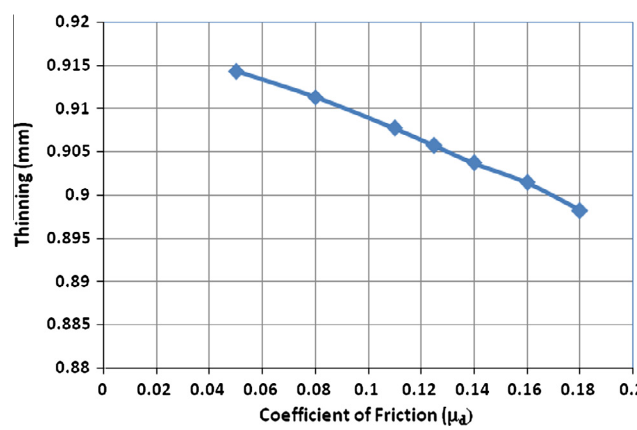

Fig. 28. Variation of the sheet metal thinning with different values of the coefficient of friction between die/blank (μ_d).

4.2.2.3. Coefficient of friction between die/blank (μ_d). In this case the aim of lubrication is to achieve a minimum coefficient of friction with minimum wear. Even excessive lubrication of the sheet metal surface on the die side normally does not create a problem. Only on parts with large surface areas and a high percentage of stretch drawing, such as car body parts can excessive lubricant quantities lead to unacceptable deviations in form [25].

Fig. 27 shows thickness distribution with different values of the coefficient of friction between die/blank (μ_d), while Fig. 28 shows thinning of the blank with the variation of the coefficient of friction between die/blank (μ_d).

These results show that the proper lubricant for the die/blank friction is the fluid lubricant. In addition, the average value of the thickness distribution is reduced with increasing the coefficient of friction between die/blank (μ_d). Furthermore, the thinning in the drawn cup is increasing with increasing the coefficient of friction between die/blank (μ_d).

Fig. 29 shows the maximum residual stresses with different values of the coefficient of friction between die/blank (μ_d). These results show that the proper lubricant for the die/blank friction is the fluid lubricant. In addition, the maximum residual stresses are decreasing with increasing the coefficient of friction between die/blank (μ_d) above ($\mu_d = 0.11$). But, before the previous value, the maximum residual stresses are not stable.

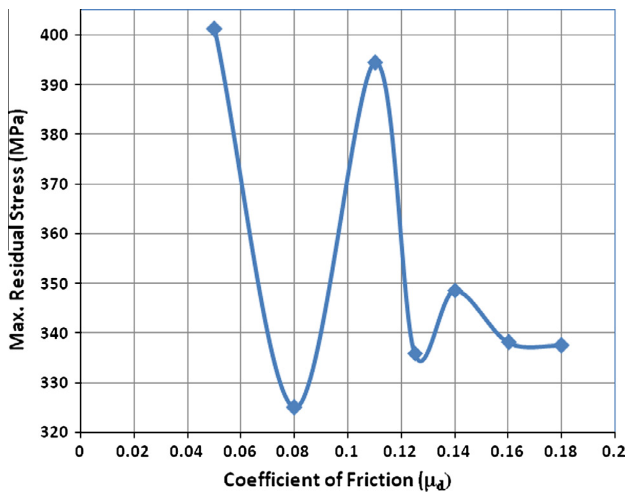

Fig. 29. Variation of the maximum residual stresses in sheet metal with several variation of the coefficient of friction between die/blank (μ_d).

To this end, tool designers and manufacturers can simulate their forming process in a virtual environment to save time and money spent on real pilot production or practical tests at the verification stage. In addition, simulation results provide useful information to address the feasibility of the actual production process. Product quality can also be improved. The risks of tool redesign and modifications are minimized.

On the product design side of the cup deep drawing, one is usually concerned with two main objectives. First is minimizing geometrical errors by reducing spring back effects on the cup geometry, and second is minimizing excessive thinning to maintain uniform thickness, integrity, and functioning of the product. Some design factors can be concluded to work nicely for both objectives [2]. To guarantee the proper functioning of the container, the product must be free from cracks or wall failures, and residual stresses should be controlled to avoid post production annealing processes. The design and operational factors involved are the die shoulder radius which should be at least 10 times the blank thickness, punch nose radius which should be at least 4 times the blank thickness, blank holder force which should be kept below a threshold value of 3.0 ton, slightly thicker blank thickness which reduces both excessive thinning and high residual stresses, and finally a redial clearance exceeding the sheet metal thickness. On the other hand the required coefficient of friction at the different mating interfaces would encourage ensuring the use of different lubrication regimes. For example the punch/blank interface requires relatively high friction coefficient of 0.3 which may be achieved by dry or solid lubricants and probably boundary lubrication with anti-wear additives. At the blank holder/blank interface fluid film with friction coefficient about 0.14 would help satisfying both objectives. The friction coefficient at the die/blank interface would encourage fluid film lubrication with μ_d about 0.125 for minimizing excessive thinning and residual stresses.

5. Conclusions

Successful deep drawing depends on many parameters (geometrical parameters and physical parameters). The finite element analysis simulation is used aiming at reducing time and trial and error efforts, and to cut many costly trials of production which is a common practice in the traditional production approaches.

The results show that:

(1) The die shoulder radius is recommended to be about 10 times sheet thickness.
(2) The punch nose radius is recommended to be greater than 4 times sheet thickness.
(3) The thicker sheet metal is softer due to its increased volume which increases the thinning in sheet metal leading to increasing the maximum residual stresses.
(4) The radial clearance is recommended to be greater than the value of the sheet thickness [if the clearance is not large enough, ironing (thinning) will occur. Also, if the clearance is smaller than the sheet metal thickness (t), cup failure will occur].
(5) Blank holder force (BHF) is recommended to be less than 3 tons to avoid the increase in thinning and excessive increase in maximum residual stresses.
(6) The fluid lubricant with (μ_p = 0–0.3), is more suitable for friction between punch and blank, to reduce the thinning of the cup. But the solid lubricant with (μ_p = 0.3–0.7), is more suitable for friction between punch and blank to reduce the maximum residual stresses in the cup. So, the value of (μ_p) is recommended to be about (0.3).
(7) The fluid lubricant with (μ_h = 0.125–0.2), is more suitable for friction between holder and blank. (μ_h) should be about 0.14 to reduce the thinning and the maximum residual stresses of the cup.
(8) The fluid lubricant with (μ_d = 0.125–0.2), is more suitable for friction between die and blank. (μ_d) is recommended to be about 0.125 to reduce the thinning and the maximum residual stresses of the cup.

References

[1] Coles R, Kirwan MJ. Food and beverage packaging technology. London: Blackwell Publishing; 2011. p. 344.
[2] Zein H et al. Thinning and spring back prediction of sheet metal in the deep drawing process. J Mater Des 2014;53(2014):797–808.
[3] Colgan M, Monaghan J. Deep drawing process: analysis and experiment. J Mater Process Technol 2003;132:35–41.
[4] Demirci I, Yaşar H, Demiray K. The theoretical and experimental investigation of blank holder forces plate effect in deep drawing process of AL 1050 material. Mater Des 2008;29(2):526–32.
[5] Jawad WKh. Investigation of contact interface between the punch and blank in deep drawing process. Eng Technol 2007;25(3):370–82.
[6] Vladimirov IN, Pietryga MP, Reese S. Anisotropic finite elastoplasticity with nonlinear kinematic and isotropic hardening and application to sheet metal forming. Int J Plast 2010;26:659–87.
[7] Fereshteh-Saniee F, Montazeran MH. A comparative estimation of the forming load in the deep drawing process. J Mater Process Technol 2003;140:555–61.
[8] Lange K, Bruckner L. Deformation induced residual stresses and stress corrosion in deep drawn components of brass materials. Trans NAMRI/SME 1990:71–5.
[9] Danckert J. The residual stress distribution in the wall of a deep drawing and ironed cup determined experimentally and by finite element method. Ann CIRP 1994;43:249–52.
[10] Danckert J. Reduction of residual stress in deep drawing by modeling the draw die profile. Ann CIRP 1995;44(1):259–62.
[11] Fereshteh-Saniee F, Montazeran M. A comparative estimation of the forming load in the deep drawing process. J Mater Process Technol 2003;140:555–61.
[12] Brabie G. Residual stresses generated by materials transformation processes. Iasi (Romanian): Junimea; 2005.
[13] Hauk V. Structural and residual stresses analysis by nondestructive methods. Elsevier; 1997.
[14] Brabie G, Nanu N. Analysis of the stresses distribution in the case of drawn parts made from metal sheets. In: Int conf INETFORSMEP, Poznan; 2008. p. 86–90.
[15] Hearn EJ. Mechanics of materials. The mechanics of elastic and plastic deformation of solids and structural materials, 3rd ed., vol. 2. Butterworth-Heinemann; 1997.
[16] Crina A, Monica I. Determination of residual stresses distribution within the formed part. In: Fascicle of management and technological engineering, vol. VII (XVII), Bucharest; 2008. p. 54–8.
[17] Brabie G, Nanu N, Radu ME. The influence of the punch shape on the residual stresses distribution and springback in the case of conical drawn parts. In: NEWTECH 2009, GALATI, Romania, ISSN 1221-4566; 2009. p. 87–90.

[18] Meguid SA, Refaat MH. Finite element analysis of the deep drawing process using variational inequalities. Finite Elem Anal Des 1997;28:51–67.
[19] Abaqus analysis user's manual, vol. IV. Elements; 2011.
[20] Taylor LM, Cao J, Karafillis AP, Boyce MC. Numerical simulations of sheet metal forming. In: Makinovchi A, editor, Proceedings of 2nd international conference, NUMISHEET 93, Isehara, Japan; 1993.
[21] Suchy I. Handbook of die design. 2nd ed. McGraw-Hill Publishing; 2006. p. 383–400.
[22] Grote K-H, Antonsson EK. Springer handbook of mechanical engineering. Springer Science and Business Media; 2008. p. 617.
[23] David S, Jeff L, John G. Fundamentals of tool design, American Society of tool and manufacturing engineers. New Delhi: Prentice Hall; 2003.
[24] Marciniak Z, Duncan JL, Hu SJ. Mechanics of sheet metal forming. 2nd ed. Butterworth-Heinemann; 2002.
[25] Mang Theo, Dresel Wilfried. Lubricants and lubrication. 2nd ed. Weinheim: WILEY-VCH Verlag GmbH & Co. KGaA; 2007. p. 527–30.