# EXPERIMENTAL, NUMERICAL AND ANALYTICAL ANALYSIS OF THE FORCE DURING IF STEEL CUP DEEP DRAWING

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***Abstract.*** *The deep drawing is one of the most important sheet metal forming processes. In this present work, different methods of analysis, such as, analytical, numerical and experimental have been used to evaluate and to verify the evolution of force related to the punch displacement. Moreover, the maximum deep drawing force can be determined. For the experimental stage, a set of tool rack was constructed, to carry through the cup deep drawing using a 100 mm diameter and 1.78 mm thick IF steel blank. The analytical stage was lead from the different analytical relations suggested by different authors and used to calculate the deep drawing force. The numerical stage was lead using the finite element method of Ls-dyna commercial software. This software was used to verify the shell element influence in the evolution and attainment of deep drawing force. The results of these different methods, analytical and numerical, have been compared to the experimental results, in order to verify the coherence and the applicability of the same ones.*

***Keywords:*** *Deep drawing, Redrawing, Ironing, Finite-Element Method, Formability.*

## 1. Introduction

In spite of the metal forming process to be extensively used in the industry, the production processes and the tool rack, they are still strongly based on empiric results. The development of the numeric simulation enabled to objective evaluation of the formability and the stress and strain distribution objectively in different stages of the drawing work. This has been able allowing the optimization of prototypes manufacture, the tool rack tuning and the possibility of reducing stamping trials during assessment process (Natarajna et al., 2002; Lei et al., 2001; Palaniswamy et al., 2004).

The theoretical analysis of the cup deep drawing is defined in the literature in several works. During the cup deep drawing, they happen cup wall thickness variations foreseen theoretically and verified experimentally. The Hosford and Caddell (1993) theoretical works of they foresee the cup wall thickness variations with cup bottom thinning and cup flange top thickening (cup edge). The Figure 1(a) schematically represents the cup wall thickness variation.

This cup wall thickening carries to the ironing condition at the end of the cup deep drawing process, since the punch-die clearance is not enough. This condition is similar to the wire drawing process condition. This cup wall thickening in the deep drawing stage will influence the cup deep drawing force during the punch displacement. The Figure 1(b) represents the cup deep drawing total force variation for the deep drawing initial condition without thickening as much as for the ironing final condition with thickening, indicating the occurrence of two maximum relative total force variations to each condition (Hosford and Caddell, 1993).

The objective on this work is the construction of cup deep drawing tool rack with the fixed blankholder and the evaluation of the deep drawing total force during punch displacement. This evaluation was carried experimentally through the constructed tool rack and theoretically through modeling and computer simulation with the LS-DYNA licensed application program. The maximum cup deep drawing force is evaluated through analytic methods proposed in the literature and described in the section 3 (Hosford and Caddell, 1993; Fereshteh-Saniee and Montazeran, 2003; Barata da Rocha and Ferreira Duarte, 1992). The computer numeric results were compared with experimental results and with those obtained through analytic methods.

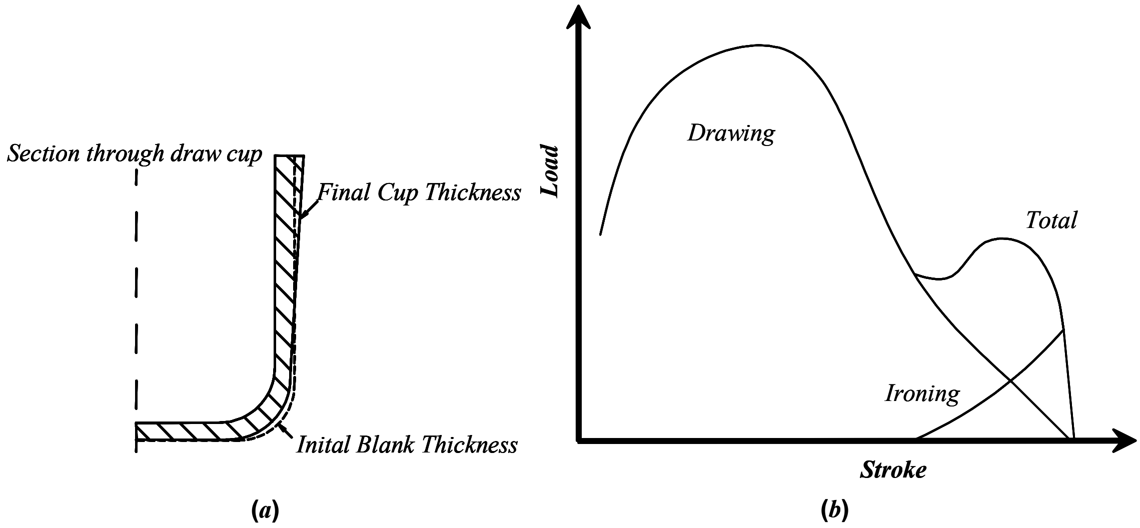


Figure 1. (a) Schematic profile of the wall thickness variation for cup deep drawing. (b) Variation of the deep drawing total force associated with the drawing and ironing conditions.

## 2. Experimental methodology

The tool rack was built for the deep drawing and ironing laboratory execution thought the hydraulics presses as much as the mechanical trial universal machines. This tool rack can be seen in Fig. 2. The tool rack is constituted of two bases, to make possible the assembly in presses with holed tables or mechanical trial machine. Generally, they possess table without hole. The die can make the deep drawing and insert the ironing rings. The fixed blankholder fastened to the die for four Allen M20 screws. Three centralization pins of blank, that also to make distance between the fixed blankholder and the die. The centralization disc for the cup punch. The cup punch with 48.30 mm diameter, 150 mm length and 10.0 mm profile radius.

The deep drawing trial had been carried through mounting it described tool rack previously, using three pins that had supplied to the 2.00 mm distance between the fixed blankholder and the die, in the Kratos mechanical trial universal machine, with 490.5 kN compression module capacity. The machine is equipped with the data acquisition computer system that it possesses as transducers, the 245.25 kN load cell with 49.5 N resolution and the 500 mm LVDT with 0.1 mm resolution.

The used material in the work was the free interstitial elements steel with the 1.78 mm thickness and one galvanized face. The plate had been cut five blanks of 100 mm diameter for the trial. These blanks had been deep drawing with 0.8 mm/s speed of punch displacement, using the grease based for molybdenum disulfide lubricant between the plate and the die. They were also cut 15 specimens from a sheet for taking away the flow curves and the anisotropy coefficients at 0º, 45º and 90º to the rolling direction.

## 3. Analytic relationships

There are several techniques to the drawing process. However, four important relationships for prediction of the deep drawing maximum force will be described in this text. In an analytic method, it is essential to simplifying assumptions. In the theory described by Hosford and Caddell (1993), the simplifying assumptions were adopted:

- The total energy process is used to forming the cup flange. The work due to the friction forces and to bend and unbend the sheet have been initially neglected, and these will be considered in the final stage process with the introduction of deformation efficiency factor, $\eta$;
- The material does not work harden ($n$=0);
- The cup thickness stays constant during the processing;
- The sheet material has been the planar isotropy and the normal anisotropy, according to Eq. (1);
- Later it will be assumed that angular variations can be handled by using the average strain ratio;
- The yielding is described by 48 Hill's anisotropy plasticity theory.

$$\overline{R} = \left(R_0 + 2R_{45} + R_{90}\right)/4 \tag{1}$$

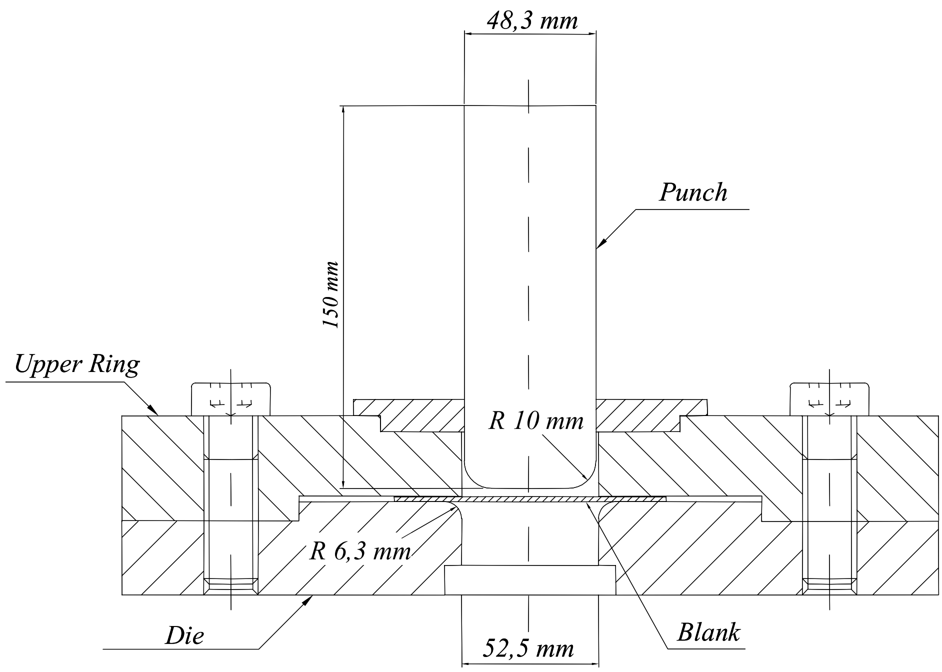


Figure 2. Schematic illustration of tool rack.

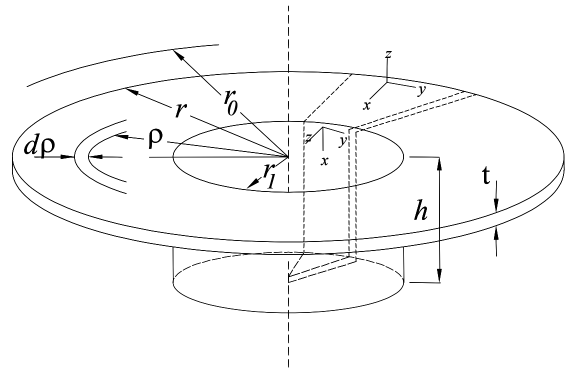


Figure 3. Schematic illustration of a partially drawn cup showing coordinate system (Hosford and Caddell, 1993).

Considering the flange strain, Fig. 4, and assuming the condition of plane strain, the volume dilatation of sheet implicates in the following relationship, according to Eq. (2).

$$\pi\rho^2 + 2\pi r_1 h = \pi\rho_0^2 = cons\tan te \quad (2)$$

In that, $\rho_0$, $\rho$, $r$ and $h$ are defined in the Fig. 4. Differentiating the Eq. (2) and considering $d\varepsilon_y = d\rho / \rho$ is obtained, according to Eq. (3).

$$d\varepsilon_x = -d\varepsilon_y = {-d\rho}/{\rho} = {r_1 dh}/{\rho^2} \quad (3)$$

In that $r_1$ is punch radius and $dh$ is the incremental distance by the punch displacement. Based on those conditions, the incremental work, $dW$, in an sheet element will be (Hosford and Caddell, 1993; Fereshteh-Saniee and Montazeran, 2003), according to Eq. (4).

$$dW = {2\pi rt\rho d\rho(\sigma_x - \sigma_y) r_1 dh}/{\rho^2} \quad (4)$$

Like this deep drawing force, $F_d$, should be the same to the total work for the incremental punch displacement, according to Eq. (5).

$$F_d = \frac{dW}{dh} = \int_{r_1}^{r} \frac{2\pi r_1 t\sigma_f d\rho}{\rho} = 2\pi r_1 t\sigma_f \ln\left(\frac{r}{r_1}\right) \tag{5}$$

The deep drawing force is major when $r = r_0$. Therefore, that maximum force is given by the Eq. (6):

$$F_{d(\max)} = 2\pi r_1 t\sigma_f \ln\left(\frac{r_0}{r_1}\right) = 2\pi r_1 t\sigma_f \ln\left(\frac{d_0}{d_1}\right) \tag{6}$$

In that $d_0$ is the blank diameter, $d_1$ is the punch diameter and $\sigma_f$ is the flow stress of the sheet material. The equation above is been worth for $\eta = 1$ and $\bar{R} = 1$. However, if it be considered the friction work, the normal anisotropy and the work to bend and to unbend the sheet through an deformation efficiency factor, η, that equation can be written as Eq. (7) (Hosford and Caddell, 1993).

$$F_{d(\max)} = \frac{2\pi r_1 t\sigma_f}{\eta} \ln\left(\frac{d_0}{d_1}\right) \tag{7}$$

Siebel (Barata da Rocha and Ferreira Duarte, 1992) using the plasticity theory proposed the following expression for the maximum deep drawing force, according to Eq. (8).

$$F_{d(\max)} = \pi d_m t_0 \Bigg( \underbrace{\left(1.1\sigma_{f1} \ln \frac{d_{F_{d(\max)}}}{d_m}\right)}_{A} \underbrace{\left(e^{\mu\pi/2}\right)}_{B} + \underbrace{\frac{2\mu F_N}{\pi d_{F_{d(\max)}} t_0}}_{C} + \underbrace{\sigma_{f2}\frac{t_0}{2r_D}}_{D} \Bigg) \tag{8}$$

In the Equation (8), A term corresponds to the work requested for homogeneous strain. The term B is due the friction energy in the die profile radius. The term C is due to the work to overcome the blank-die and blank-bankholder friction. The term D it is related to the energy to bend and unbend the sheet at the die profile radius. $d_m$ is the medium diameter and $d_1 - t_0$ is it $d_{F_{d(\max)}}$, that is the flange diameter when the deep drawing force becomes maximum. It is shown that $d_{F_{d(\max)}}$ is approximately equal the $0{,}77 d_0$, in that $d_0$ is the blank diameter (Fereshteh-Saniee and Montazeran, 2003). The blank thickness is $t_0$. The friction coefficient is $\mu$. The normal force on the blankholder is $F_N$ and the die profile radius is $r_D$. The medium flow tension in the flange is $\sigma_{f1}$ and the medium flow tension in the die profile radius is $\sigma_{f2}$. $\sigma_{f1}$ is approximately equal to $1{,}35\, S_u$, in that $S_u$ is the tensile strength of the sheet material. $\sigma_{f2}$ can also be determined using the Eq. (9) (Fereshteh-Saniee and Montazeran, 2003).

$$\sigma_{f2} = K\left(\ln\sqrt{1 + t_0/r_p}\right)^n \tag{9}$$

In that K is the strength coefficient, $n$ is the strain-hardening exponent and $r_p$ is the punch radius. To simplify the calculation of the maximum force, Siebel and Beisswanger (Fereshteh-Saniee and Montazeran, 2003) proposed the Eq. (10).

$$F_{d(\max)} = \pi d_m t_0 \left(\frac{1.1\sigma_{f1}}{\eta}\right)\left(\ln\frac{d_0}{d_1} - 0{,}25\right) \tag{10}$$

Oehler and Kaiser (Barata da Rocha and Ferreira Duarte, 1992) proposed the Eq. (11) for the calculation of the maximum deep drawing force for cylindrical pieces:

$$F_{d(\max)} = 5(d_1 - t_0)t_0\sigma_f \ln {d_0}/{d_1} \quad (11)$$

An empiric representation for the maximum punch force was proposed by Mielnik (Colgan and Monaghan, 2003), according to Eq. (12).

$$F_{d(\max)} = \frac{t_0 \pi \sigma_f d}{2\eta} \ln\left(\frac{d_0}{d_1}\right) \quad (12)$$

**4. Finite element method**

In the LS-DYNA computer application program of dynamic explicit approach, the plate will be modeled as anisotropy plastic material, considering $R_0$, $R_{45}$ and $R_{90}$ plastic anisotropy coefficients and Barlat's yielding criteria (Barlat and Lian, 1989). This approach is based in the dynamic equilibrium equations. The great advantage is no need to assembly and solution of the stiffness matrix, being obtained the time step solution more quickly than a static approach (Mattiasson et al, 1992). In Equation (13) is the global non-linear equation to estimate the nodal displacements (Mamalis et al, 1996; Owen and Hinton, 1986). It can be solved by the central difference method and if the damping coefficient matrix C is zero.

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + [K(u(t))]\{u(t)\} = \{F(t)\} \quad (13)$$

Where **M** is the mass matrix, u is the nodal displacement vector, **C** is the damping coefficient matrix, **K** is the stiffness matrix and **F**($t$) is the vector of the time dependent external forces.

For the plate, finite element discretization had been used 2,500 Belytschko-Tsay's shell square numerical elements with five integration points through the thickness. This numerical element type presents good results for the stress and strain distribution requesting smaller computational time (Belytschko and Tsay, 1983).

The modeling and the numerical simulation had been considered the punch, the blankholder and the die as rigid material. The 0.8 mm/s punch speed was along of the 60 mm stroke. The Coulomb friction coefficients were adopted: punch-plate interface equal to 0.30, die-plate interface equal to 0.12 and blankholder-plate interface equal to 0.06. The Young's modulus equal to 210 GPa and Poisson ratio equal to 0.3.

**5. Results and discussion**

In this work, the IF steel plate characterized by the values of the anisotropy coefficients $R_0$ = 1.48, $R_{45}$ = 1.61 and $R_{90}$ = 2.02, yield strength $S_0$ = 160 MPa and for the Hollomon's equation $\sigma = 508.7\ \varepsilon^{0.242}$ obtained for tensile specimens cut from 45$^o$ to the rolling direction in the sheet.

The Figure 4 display a forecast of the values obtained by simulation through the LS-DYNA computer application and the experimental curve associated to the force during the punch displacement.

During the deep drawing it happens the blank thickening in the flange area and in the near die profile radius. This thickening happens due to the existent clearance between the die and fixed blankholder to be of 2.00 mm and the blank thickness to be of 1.78 mm and also because it blankholder doesn't offer any restriction to the increase of blank thickness in the area of the die profile radius. It was verified experimentally that the cup flange thickness was of 2.05±0.03 m. The Figure 5 represents the thickness variation with the punch displacement in LS DYNA simulation for a numeric element located in the blank periphery. It is in good agreement with those results.

In the flange areas near die profile radius, the blank will be subject the circumferential compression stress, which generate buckling in the form of small undulations. The flange with those small undulations will present larger difficulty to the bending and unbending and will make contact with blankholder and the die. As the thickening process, the contacts intensify and the deep drawing force increases in this stage of the process. In the Figure 4, it can be observed that the experimental value of the force increases smoothly to the maximum value, reached for a punch displacement of 37.4 mm. Soon after the force falls very smoothly until the end of the contact between the fixed blankholder and flange. Later it happens strong fall associated to the end strain at the die profile radius. After that moment, the force falls smoothly until zero. That soft final fall is related to the small undulations that were formed and that originate contact forces. Those forces were significant due to the small difference between the die-punch clearance (2.10 mm) and the cup top thickness (2.05 mm).

In the Figure 4 it can be observed that the simulate results of the force increase to a level as the punch displacement. This stage of the simulation is associated to the cup forming. Soon after, it happens a strong variation of the force. We believed that this strong variation of the force is related to a strong contact of small wrinkles that they were formed with blankholder. A strong fall happens after the end of the contact with blankholder, for a punch displacement of 40 mm, soon after a soft fall associated to the strain is observed edgewise in the die profile radius. The final stage was characterized by a force level of 15 kN. This level can be justified for the contact force between the cup and the die due to the die-punch clearance to be of 2.10 mm and the cup top thickness to be of 2.04 mm approximately. This analysis can be verified by the diagrams represented in Fig. 6 and 7.

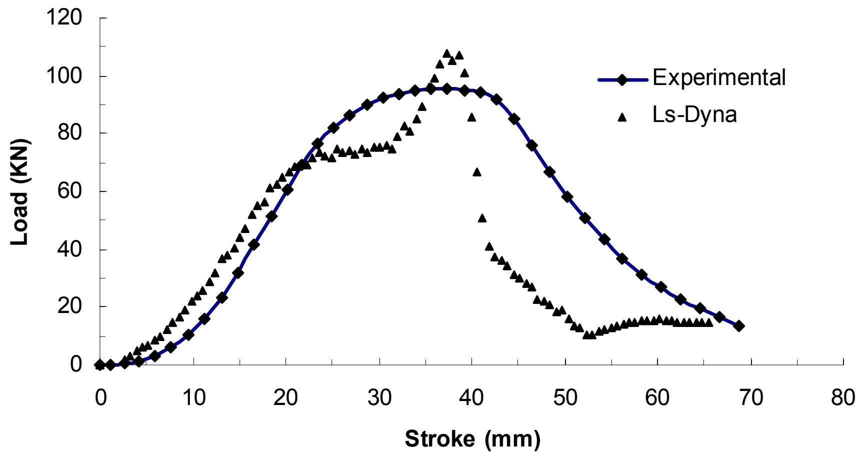


Figure 4. Values simulated by LS-DYNA of the force during the punch displacement and the experimental curve.

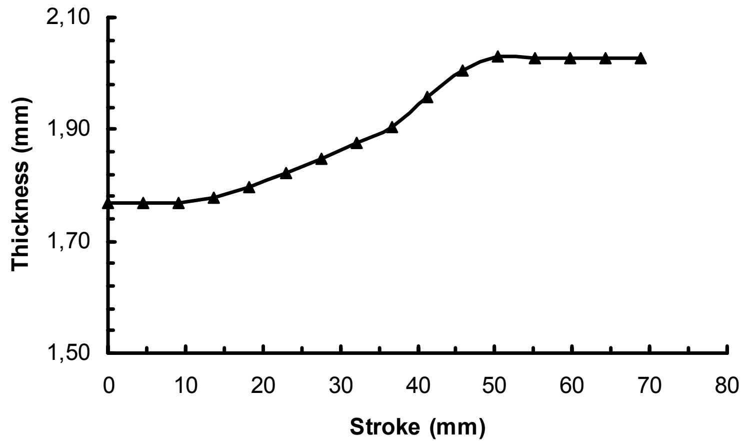


Figure 5. Variation of the blank thickness with the punch displacement in LS DYNA simulation for a numeric element located in the blank periphery.

The Figure 6 represents a forecast of the values obtained through the LS-DYNA computer application considering three simulation conditions and the experimental curve associated to the force during the punch displacement. The experimental curve and the simulate with experimental parameters were already presented previously in Fig. 4. The die-punch clearance was reduced for 1.95 mm and the force-punch displacement curve associated presented a secondary maximum of force related to the ironing stage for this clearance, when the punch displacement reached 50 mm (Huang and Chen, 1996). This forecast of the application is in agreement with the conditions of the process with die-punch clearance reduced. For reduction of the blankholder-die clearance for 1.95 mm, the curve force-punch displacement associated presented the largest maximum force probably related to the more severe friction conditions. With significant approach, the maximum of force happened for the punch displacement between 35 and 40 mm in all the treated cases, according to Fig. 6.

The Figure 7 represents a forecast of the values obtained through the LS-DYNA computer application considering three simulation conditions associated to the sheet thickness for a peripheral numeric element during the punch displacement. Considering the clearance associated to the experimental parameters and the reduced clearance of 1.95 mm so much for the die-punch as blankholder-die clearance, the simulations accomplished in each case they resulted in thickening significantly close to the verified experimentally. Probably the conditions and simulation parameters were appropriate for the simulate forecast of the thickness for the punch displacement. In the Figure 7 it is verified for the displacement among 35 and 40 mm, that the thickness is of 1.89 mm and the sheet is to leave of the blankholder-die area. However, for the simulate condition of punch-die clearance equal to 1.95 mm, it was possible to verify the increase of the force during the punch displacement associated to the ironing condition. Nevertheless, it was not possible to verify the correspondent thickness reduction in the ironing condition. This impossibility is related to the sheet numeric element used in the simulations (Belytschko et al, 1984).

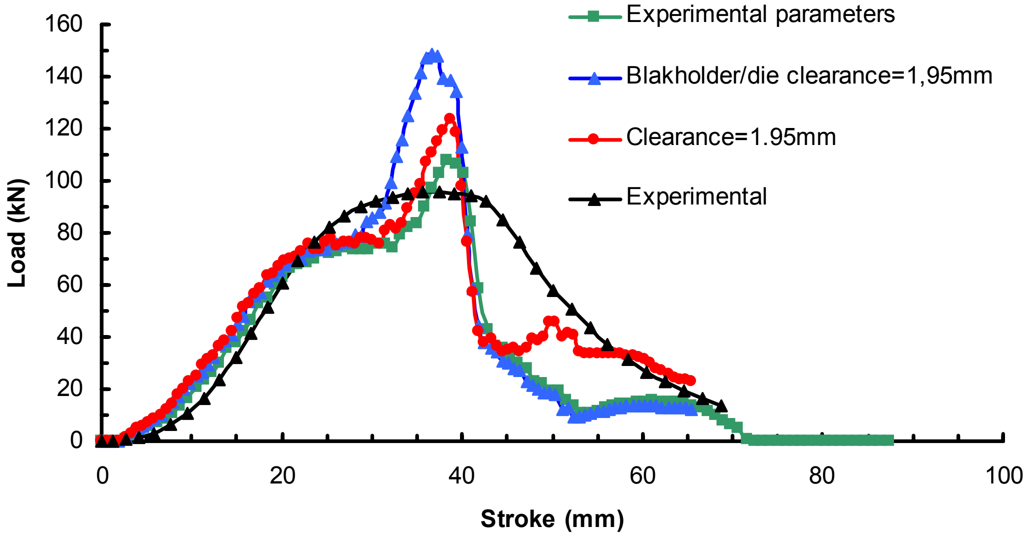


Figure 6. Simulated values for LS-DYNA for three clearance conditions and the experimental curve.

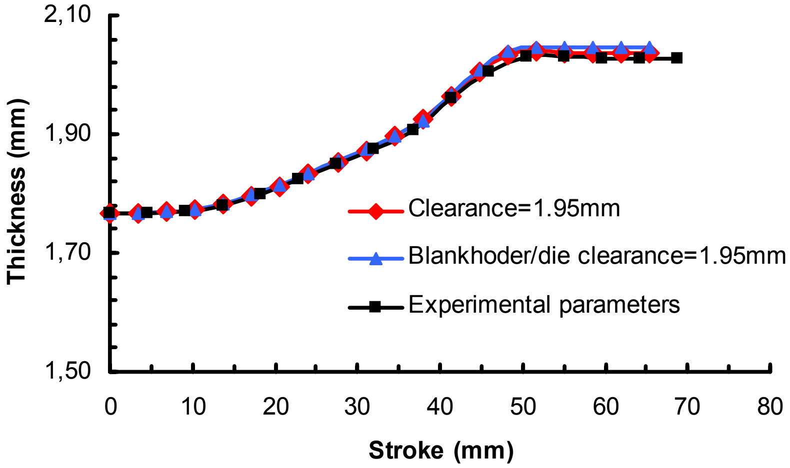


Figure 7. Simulated thickness values for three clearance conditions.

In the Table 1 the obtained maximum deep drawing force are shown through methods analytic, numeric and experimental. The analytic values are associated to the interval of values of the deformation efficiency coefficient, η, defined for the different researchers.

Table 1. The maximum deep drawing force obtained by from different methods.

| Method | Maximum Force, ( $F_{max}$ ), [kN] | Deformation efficiency coefficient |
|---|---|---|
| Experimental | 95,40 | -------- |
| Numeric | 107,59 | -------- |
| Hosford e Caddell, Eq. (7) | $93{,}57 < F_{max} < 99{,}89$ | $0{,}74 < \eta < 0{,}79$ |
| Siebel e Beisswanger, Eq. (10) | $79{,}85 < F_{max} < 111{,}78$ | $0{,}50 < \eta < 0{,}70$ |
| Oehler e Kaiser, Eq. (11) | 121,95 | -------- |
| Mielnik, Eq. (12) | $122{,}77 < F_{max} < 139{,}93$ | $0{,}74 < \eta < 0{,}79$ |

Through the Table 1 it is verified that the experimental value is contained in the range foreseen for Hosford and Caddell (1993) and for Siebel and Beisswanger (Fereshteh-Saniee and Montazeran, 2003). The simulate numeric value through LSDYNA is contained in the range foreseen by Siebel and Beisswanger. The experimental and numeric values are significantly close.

## 5. Conclusions

Each analysis method presents your own advantages and disadvantages. Some of the analytic relationships and the simulate results for finite elements presented in this very close of the experimental results healthy work. The analytic relationships are obtained at a low cost while the numeric simulations need great expenses with software, but they can supply a great wealth of details of the process. In spite of the costs associated to the experimental research they be the highest, the experimental results are indispensable in the wide research strategy in metal forming.

The analytic results for the forecast of the maximum force through the proposed formulation Hosford and Caddell (1993) they were significantly important for your simplicity and agreement with the experimental results in a narrow interval of values for the process considered in this work.

The numeric sheet element was shown appropriate to the accomplishment and evaluation of the sheet forming process developed in this work.

The conception and the project of the experimental apparatus with fixed blankholder they were shown consistent and appropriate to the accomplishment of stamping operations in presses of simple effect. With this experimental apparatus with fixed blankholder they were obtained experimental results that allowed the evaluation of the simulate and analytic approach.

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