FINITE ELEMENT SIMULATION OF THE SHEARING MECHANISM IN THE PUNCHING OF THICK SHEET

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Abstract. *Thick sheet punching is a process used during the production of chassis and bodies for the trucking, cars and tractors industry. Define the proper process and tools parameters is important for the quality of the punched hole, but identification of these parameters is usually the result of a series practical experiments that consume much time and cost. In recent years, numerical simulations of the shearing process of sheet metals has been made based on the finite element method. Besides reducing the time and cost for production of numerical simulation can be a useful tool to improve processes, describe the material elastic-plastic behavior during the process and evaluate modifications to the tool. The aim was to evaluate the formation of roll-over and a burnished surface, and crack initiation and propagation, using a ductile fracture criterion from a commercial finite element code. The experiments will be for steel plates with thicknesses LNE38 between 2 and 8 mm. Different clearances between the punch and the die, blank holder force and the shape of the sheared edge are observed. The results show that finite element simulation can be a useful tool for choosing appropriate parameters of the process and tool.*

Palavras-chave: finite element simulation, punching, crack propagation, shear angle, LNE38 steel.

1. INTRODUCTION

The punching process in the metallic sheets is used into the metal-mechanic industry, mainly at the production of bodies of automobiles trucks and tractors. It consists in the cutting of a metallic sheet by the application of shearing stresses via punch action against a rigid die. The searing originates in the sheet region in contact with the side of the punch and the side of the die. The punch penetration inside the sheet, results in the propagation of the cracks until they meet with each other, causing the material failure and the expulsion of the scrap.

One of the most important aspects of the shearing process is the quality of sheared surface (Fig. 1), in which is affected not by material characteristics only, but also by process parameters as the clearance between the punch and the die, blank-holder force and angle between the punch and the die. Until now, the effect of these parameters at the shearing characteristics, has been investigated mainly by empiric means (JIMMA, 1965; KONDO, 1965). The choose of the most suitable process and tool parameter values is crucial to the good result in the process, but, according to Al-Momani and Rawabdeh (2008), the empiric approach makes this process expensive in time and costs. Recently, numeric simulations of the shearing process has been made via Finite Element Methods (FEM). Hatanaka et al.(2003) and Husson et al. (2008) show the possibility of using FEM simulations to reduce the number of experiments that has to be conducted and give an increased understanding concerning the influence of process parameters. Husson et al. (2008) using FEM simulations noted that high clearance or a high tool wear or a high friction affects the quality of the predicted sheared edges. Soares et al. (2011) studied the influence of the clearance between punch and die and noted that clearances between 2% and 10% are most suitable for ductile materials because produce a smaller punch force without burr. According to Hambli (2002) clearances up to 10% are suitable to minimize the cutting forces; otherwise, clearances up to 5% are desirable because the fracture angle and depth developed in the cutting region are minimized.

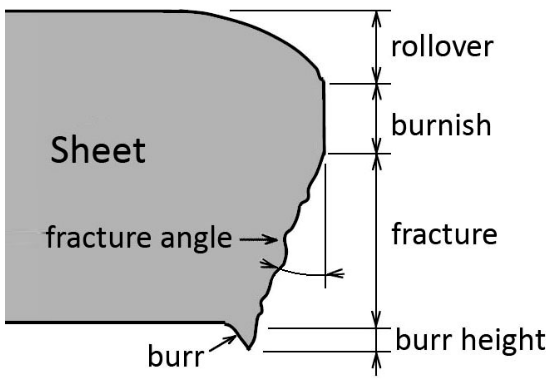


Figure 1. Detail of a typical sheared surface.

At the present work, the metallic sheets punching process, i.e., the formation process of a rollover region and a burnished surface, in simulated using a commercial software package. It was used a criterion of ductile damage assuming that when this criterion is met to the element, the crack begins and propagates. The goal of this work is to present how the shearing mechanism at the different stages.

It was made simulations considering a LNE38 steel sheet with 8mm in thickness and holes with 10mm in diameter. It were used different clearance values between the punch and the die and blank-holder forces, so the quality of the sheared edge and the crack propagation behavior were observed.

2. MATERIAL AND PROCEDURE EXPERIMENTAL

2.1. Material and simulation condition

The punched sheet material is the LNE38 high resistance steel (NBR 6656) with 8mm in thickness. The mechanic properties of the material are shown at the Table 1. In the simulation, it was assumed that the material was homogeneous, isotropic and followed the Von Mises yield criterion (assumes the material properties similar in all directions). Due to the fact of the obtained data from the conventional tensile test do not fully represent the total steel plasticity, the power law ($\sigma = K\varepsilon^n$) was applied to the tensile-strain curve in order to adequate the tensile-strain data for the simulations.

Table 1. LNE38 mechanical properties

Material	Yeld Strength (MPa)	Tensile Strength (MPa)	Elong. (%)	K (MPa)	n	Density (Kg/mm³)	Poisson	Elastic Modulus (MPa)
LNE 38	439	521	29	1012	0,20	7,8E-9	0,3	210000

The simulations were conducted using the software package ABAQUS/Explicit 6.9. Fig. 2 shows the initial mesh of finite element model used for the simulation. It was defined an axisimetric model with four components. The punch, the blank-holder and the die were modeled as rigid structural components. The sheet was modeled with axisimetric quadrilateral with 4 nodes and reduced integration (CAX4R) and triangular elements with three nodes (CAX3) (ABAQUS, 2009). In order to observe the deformation behavior of the material during blanking process fine elements of about 0.031mm in side length - 256 elements in thickness - were used at the shearing region (between the punch tip and the die entrance). At the remaining regions under low stress levels, it was used a broader meshing in order to save computational time. The importance of the meshing refining was stated by Söderberg (2008). The contact between the rigid bodies (punch, blank-holder and die) and the sheet surfaces were defined by the penalty contact method (Coulomb model with 0.1 coefficient). It was used the ductile damage model (Lajarin et al., 2010).

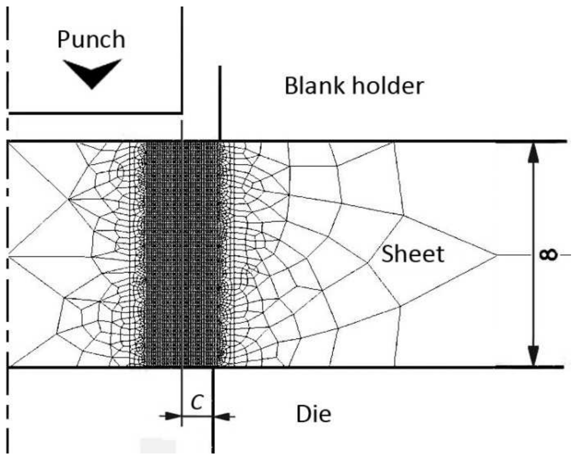


Figure 2. Initial mesh used in the simulation.

2.2. Experimental procedure

Punching experiments were carried out under the various conditions shown in Table 2. Were used cylindrical punches with plane tip with Ø 10mm. To analyze the variations at the shearing behavior, different clearances between the punch and die (0.2, 2, 5, 10 and 15% of the sheet thickness per side) and different blank holder forces (0, 10 and 30 kN) were defined.

Table 2. 3x5 Planning Matrix.

BHF (KN)	Clearance (% thickness per side)				
	0,2	2	5	10	15
0	x	x	x	x	x
10	x	x	x	x	x
30	x	x	x	x	x

3. RESULTS AND DISCUSSION

To validate the accuracy of the result of the FEM model, the punch geometry was changed and the model was used to simulate an innovative combined broaching-punch tool for comparison with experimental results obtained. The results were quite consistent and showed the good response of the model.

3.1. Fracture criterion and crack propagation model

The shear originates in the region of the sheet in contact with the edge of the punch and the edge of the die. When the punch penetration depth is increased, cracks occur at the tool edges where the material undergoes large shearing deformation. The determination of the damage initiation criteria after the ultimate tensile strength (UTS) was obtained as follows: It was chosen the ductile damage initiation criteria that predict the damage initiation due to nucleation, growing and coalescence of voids in ductile materials. The model assumes that the equivalent plastic strain at the failure beginning $\dot{\bar{\varepsilon}}_D^{pl}$ is a function of the triaxial stress and the strain rate $\dot{\bar{\varepsilon}}_D^{pl}(\eta, \dot{\bar{\varepsilon}}^{pl})$. In this case $\eta = -p/q$ is the triaxiality stress. The variable p is the pressure stress, q is the Mises equivalent stress and $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent plastic strain rate. The pressure stress p and the Mises equivalent stress q are represented by equations 1 e 2, respectively.

$$p = \frac{1}{3}(\sigma 1 + \sigma 2 + \sigma 3) \tag{1}$$

$$q = \frac{1}{\sqrt{2}}\,[\,(\sigma 1 - \sigma 2)^2 + (\sigma 2 - \sigma 3)^2 + (\sigma 3 - \sigma 2)^2]^{1/2} \tag{2}$$

The criterion for the damage initiation is met when the following condition is satisfied (eq. 3), where ϖ_D is a state variable that increases monotonically with plastic strain. At each increment during the analysis the incremental increase in ϖ_D is computed as (eq. 4).

$$\varpi_D = \int \frac{d\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_D^{pl}(\eta, \dot{\bar{\varepsilon}}^{pl})} = 1 \tag{3}$$

$$\Delta\varpi_D = \frac{\Delta\bar{\varepsilon}^{pl}}{\bar{\varepsilon}_D^{pl}(\eta, \dot{\bar{\varepsilon}}^{pl})} \geq 0 \tag{4}$$

In the simulations is assumed that the stiffness degradation is associated with each ductile damage mechanism and can be modeled applying a scalar damage variable. The data considered to define the ductile damage mechanism can be obtained as follow: for the uniaxial stress, $\sigma 2 \neq 0$, $\sigma 1 = \sigma 3 = 0$ the triaxial stress factor value is obtained replacing the values $\sigma 2 \neq 0$, $\sigma 1 = \sigma 3 = 0$ in the equations 1 and 2 and $\eta = 0.272$ is obtained. For the biaxial stress, is assumed that $\sigma 1 = \sigma 2$ and $\sigma 3 = 0$ and $\eta = 0.667$ is calculated. For shearing, $\sigma 1 = -\sigma 2$ e $\sigma 3 = 0$ and $\eta = 0$ is obtained. Furthermore, it was determined the damage evolution criteria, i.e., parameter that defines how the material degrades after damage initiation criteria are met.

3.2. Formation of roll-over and a burnished surface

Figure 3 shows the emergence and the spread of the crack. In this case, the clearance between punch and the die is 10% of sheet thickness per side. It is observed in these results that the roll-over and burnished depths grows with increasing of the punch penetration. When the punch reaches about 1.5 mm stroke, a crack already exists from the edge of the punch; from 2 mm in penetration, it is possible to observe a crack from the edge of the die. With the advancement of the punch, the cracks increases and around 2.5mm (1/3 thickness) they met, causing the collapse of the material.

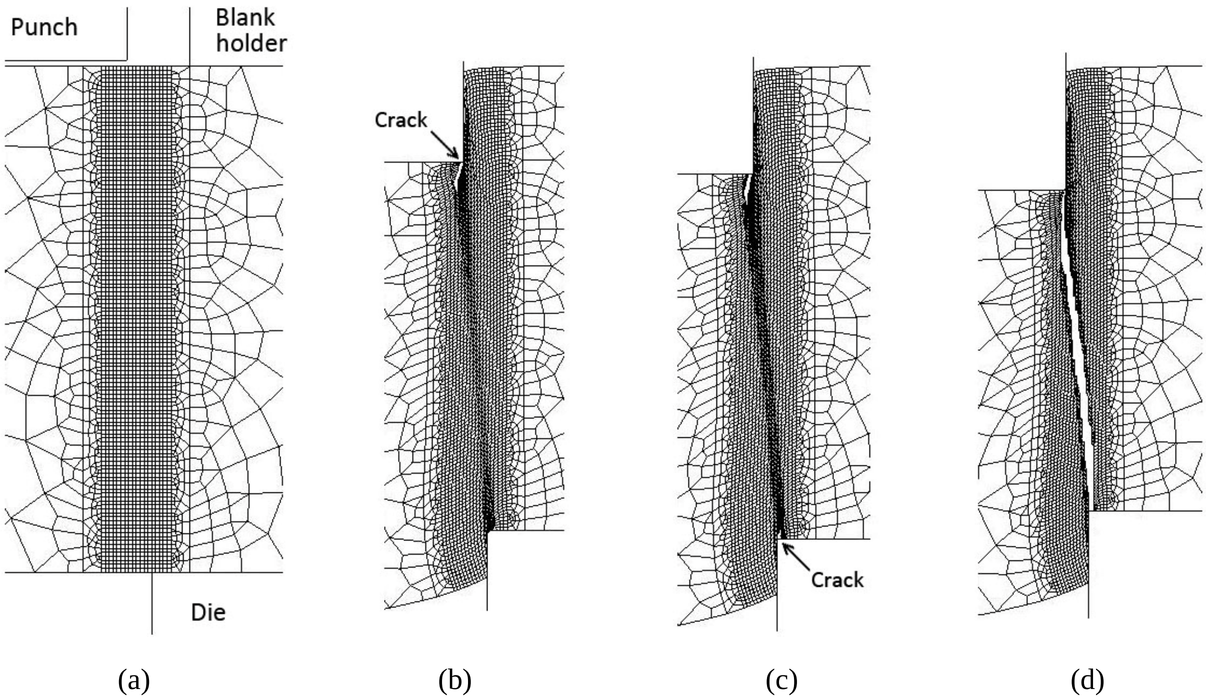


Figure 3 - Stages of deformation occurred on the sheet in the punching process

Figure 4 illustrates the clearance effect on increasing depth of the roll-over with the penetration of the punch. It can be observed that the roll-over depth increases with the progress of the punch penetration. However, the rate of increase in the roll-over depth becomes smaller as the punch penetration depths became bigger than about 0.6 mm and stabilized after 0.8 mm. It is observed that there were no major differences in the depth of the roll-over for different clearances as expected. Hatanaka et al. (2003) reported that with the increasing of the clearance depth, the roll-over also increases, and for large clearances, the roll-over increased depth continues increasing until the beginning of the crack. However, the fact that, at this present work, a different behavior occurred, may be due to the large sheet thickness used and the high resistance of the material that restricts the roll-over formation.

Normally is expected that larger clearances produce a larger roll-over, pushing material from the top edge down and consequently jeopardizing the roundness of the hole. Furthermore, Hatanaka et al. (2003) observed a big influence of the force applied on the blank-holders during the roll-over formation - a condition that was not observed in this study. The high strength and the big thickness also justified the absence of influence on the blank-holder force, so only the results of the condition with 10 kN of force applied at the blank-holders were shown (Fig. 4).

As can be seen (Fig.4) the roll-over growth rate changes near the penetration depth of the punch of 0.6 mm. This suggests that the transition from shear mechanism for a single-stage shear occurs around the depth of penetration of 0.6 mm.

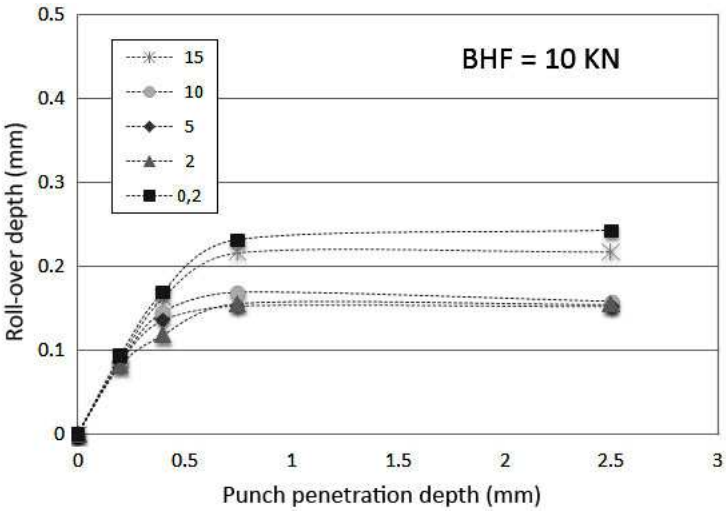


Figure 4. Effect of clearance on increase in roll-over depth.

Figure 5 shows the effect of the clearance in the burnished depth with the increase of the punch penetration. The burnished depth increases smoothly at the beginning of the punch penetration. The rate of increase in the burnished depth becomes greater when the clearance becomes smaller. Between 5 and 10% clearance, the results showed the smaller burnished depth, but after 10% clearance the burnished depth increased again. This increase is attributed to the large angle of fracture presented in this condition, coupled with the low roll-over value caused by high-strength steel.

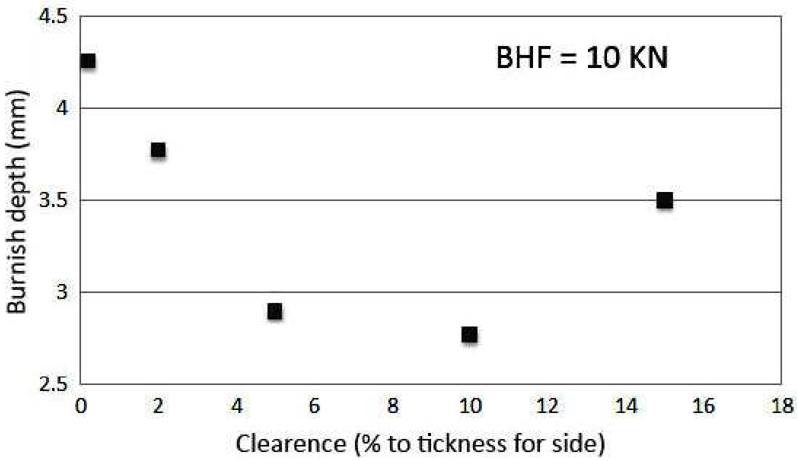
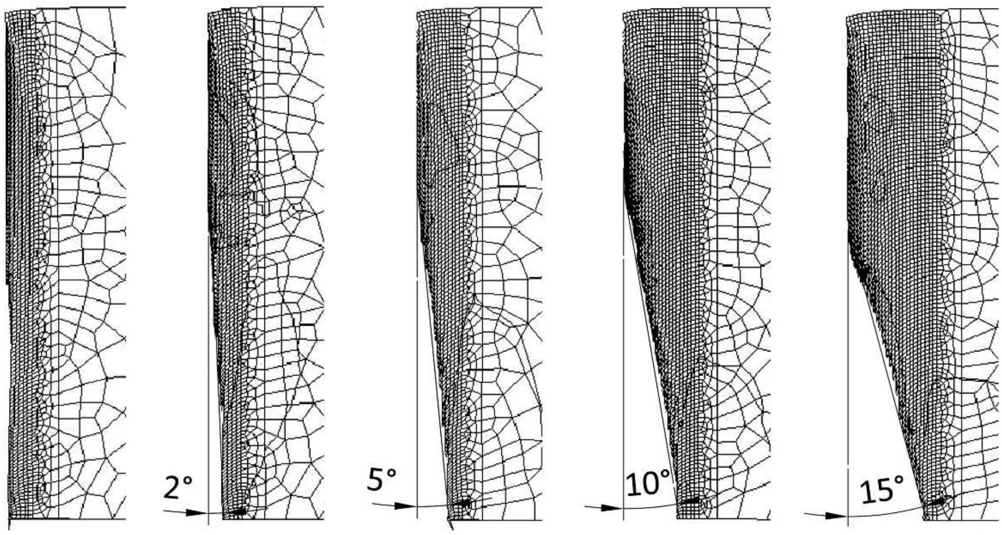


Figure 5. Effect of clearance on increase in burnished depth.

For this material and thickness it was observed a relationship between the clearance per side and fracture angle (Fig. 6). That is, $Fa = C$, where: Fa is the angle of fracture and C is the clearance per side.



0,2% 2% 5% 10% 15%

Figure 6. Effect of clearance on the fracture angle.

Figure 6 indicates the beginning of the crack for different clearance and blank-holder force conditions. The penetration depth of the punch at the beginning of the crack increases with the increase of the clearance up to 10% for all conditions of blank-holder force. However, after 10% clearance, the punch penetration depth decreases to the similar conditions with 0 and 30 KN.

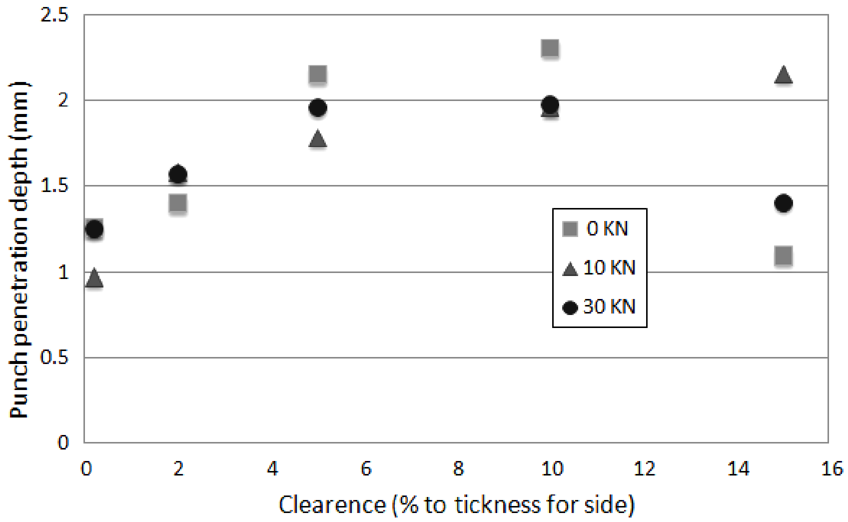


Figure 7. Effect of clearance on punch penetration depth at crack initiation from punch edge.

3.2. Crack initiation and propagation

In the simulations, we assumed that when the fracture criterion given by equation (3) was met for an element a crack initiates and propagates. The effect of the clearance on the penetration depth of the punch at the beginning of the crack is shown in Fig. 7. It can be seen that the penetration depth of the punch at the beginning of the crack depends on the clearance between punch and die. The crack propagation was simulated in the element following the fracture criterion. For example, for 5% clearance with 10 KN of blank-holder force, the element located at the edge of the punch satisfies the fracture criterion with a penetration depth of 1.5 mm, as shown in Fig. 3. As the penetration of the punch increases, elements that satisfies the fracture criterion starts and propagates the crack. When the penetration of the punch has reached 2 mm, the element located on the edge of the matrix will also satisfy the fracture criterion. Therefore, the crack was also introduced into the edge of the die. This beginning of the crack edges of the punch and die continuously spreads and connects with each other at a punch depth of 2.4 mm. This leads to separation of the material.

3.3. Punching force

Fig. 8 shows a diagram punch force vs. punch stroke for different clearances between punch and die. The simulation results show that as the gap decreases the initial force reaches values slightly higher and the penetration depth with a maximum load becomes smaller. It can be seen in Fig. 8 that the crack occurs when the force of the punch begins to decrease. The decrease rate after the punching strength of the crack depends on the clearance; until 2%, the punching strength decreases rapidly, but for major clearances of 10 and 15% the rate of decline is not as fast and the force application remains until 3 and 4.2 mm respectively.

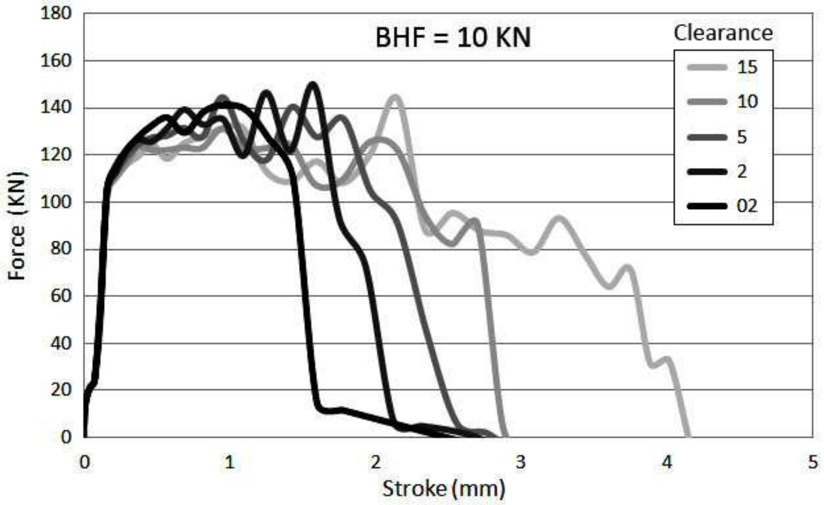


Figure 8. Clearance effect at the punching force

4. CONCLUSION

It was possible to observe through numerical simulation the various stages of deformation that occurs during a punching process. Different clearance conditions between punch and die and blank-holder force allowed studying the shear mechanism and its influences on sheared profile. The results are summarized as follows:

- The roll-over depth increases with the increasing penetration of the punch and clearance, but the roll-over depth almost ceases at a depth of penetration greater than 0.6 mm. Due to the high material strength and great sheet thickness the roll-over was not affected by the blank-holder force.
- The burnished depth increases slightly at the beginning of the penetration of the punch and the rate of increase in the depth of burnished becomes larger as the clearance becomes smaller, but after a clearance of 10% the burnished depth increases again.

- The penetration depth at the beginning of the crack depends on the clearance between the punch and die, the penetration rate in the thickness was 15% for small gaps of 0.2% and around 25% for higher clearances (from 5 to 10%).
- As happened with the burnished depth, the depth of the crack initiation has a increasing behavior up to a 10% clearance and begin to behave inversely towards a 15% clearance. This shows that the margin of 10% for this material thickness represents a transition point in the shear mechanism.

5. ACKNOWLEDGMENTS

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