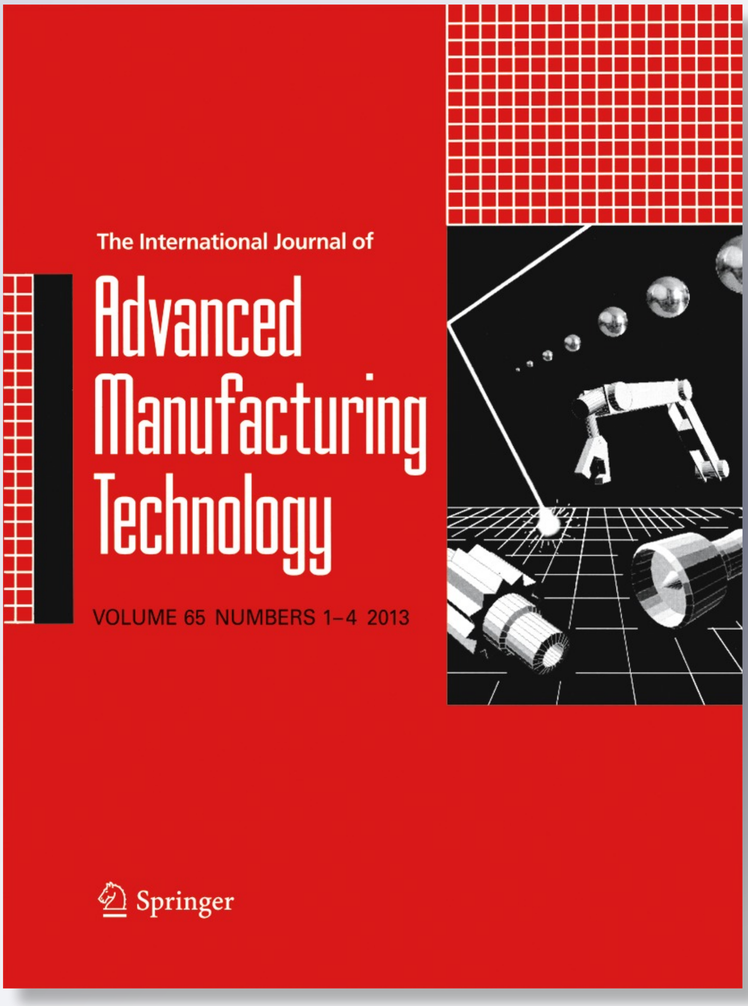
Study of the punch–die clearance influence on the sheared edge quality of thick sheets

J. A. Soares, M. L. Gipiela, S. F. Lajarin & P. V. P. Marcondes

The International Journal of Advanced Manufacturing Technology

ISSN 0268-3768
Volume 65
Combined 1-4

Int J Adv Manuf Technol (2013)
65:451-457
DOI 10.1007/s00170-012-4184-2



Int J Adv Manuf Technol (2013) 65:451–457
DOI 10.1007/s00170-012-4184-2

ORIGINAL ARTICLE

Study of the punch–die clearance influence on the sheared edge quality of thick sheets

J. A. Soares · M. L. Gipiela · S. F. Lajarin ·
P. V. P. Marcondes

Received: 13 October 2009 / Accepted: 18 April 2012 / Published online: 10 May 2012

Abstract Sheet metal punching is an important industrial process for forming mechanical parts. Aimed at generating holes on thick sheets, punching process has been considered as a promising solution for the heavy industrial sector. The correct punching parameters choice has a direct influence on the hole quality. Since there exists rarely an analytical expression describing the relationships between these process parameters, the forming variable choice follows a series of costly try-and-error procedures on the workshop floor. The numerical simulation is a powerful tool that helps the forming engineers at the try-and-error procedures. This work shows the possibility of using FE-simulations to reduce the number of experiments that has to be conducted propitiating an increased understanding concerning some punching process parameters influence. The aim is the study of the clearance influence on the punched holes quality, 8 mm LNE38 sheet metal. Clearances of 0.2% up to 15% between the punch and die were analyzed. The influence of the punch–die clearance on the crack propagation was also analyzed, and the results were in agreement with the literature, i.e., good results for gaps within the traditional ideal range and occurrence of burr for clearance of 15%.

Keywords Punching of thick sheet · Clearance · Finite element · Ductile damage

1 Introduction

Stamping processes are widely used in the industry mainly at the heavy segment—automotive and petroleum refining manufacturers. The process parameter identification is mostly done by a large series of experiments which consequently are costly and time-consuming [1]. However, in the last years, the industries have been using numerical simulations to optimize the processes and describe the plastic behavior of formed sheets. Accordingly, the numerical simulation is a powerful tool that helps the forming engineers to maintain the product quality, avoiding or reducing common forming defects such as wrinkles, burrs, thickness reduction, and springback effect. In addition, numerical simulations can permit a better understanding of the material behavior during the sheet metal forming. Moreover, numerical simulations allow try-and-error procedure decreases and a previous evaluation of the drawbead, tools, blank holder pressure, and lubrication influences [2, 3].

In earlier work, reported by Li et al. [4], numerical simulation has been used to simulate the punching process with results close to the experimental. Simulations with ABAQUS/Standard FE-code and damage criteria have also shown results in compliance with the experiments [5].

Punching operations, basically, consist of a sheet metal cutting by mechanical induction of shearing tensions using a rigid punch and die. The shearing process develops from superficial cracks on the blank—placed between a punch and a die—and leads to the total sheet rupture [6].

Some studies have shown that sheet shearing processes have been improved by numerical simulation [1]. During the

J. A. Soares · M. L. Gipiela
Postgraduate Program in Mechanical Engineering (PGMEC),
Universidade Federal do Paraná,
Av. Cel. Francisco H. dos Santos, 210,
CEP 81531-990 Curitiba, Paraná, Brazil

S. F. Lajarin · P. V. P. Marcondes (✉)
Mechanical Engineering Department (DEMEC), Universidade Federal do Paraná,
Av. Cel. Francisco H. dos Santos, 210,
CEP 81531-990 Curitiba, Paraná, Brazil
e-mail: marcondes@ufpr.br

simulations, several process parameters such as tool geometry, lubrication, and clearance can be easily characterized or changed. According to Husson et al. [6], the clearance between punch and die is a very important parameter on the process showing a significant influence on the final hole quality. During the punching process, deformations occur on the sheet fibers—near the cutting areas—and these plastic strains can cause friction on the die walls. The friction hinders the slug expulsion and the punch withdrawal. To avoid this, usually, a clearance between the punch and die must be considered [4].

The clearance can also be used as a variable to control the occurrence of burrs on the perforated holes. Besides that, adequate clearances can allow tool life increases as well as the reduction of the strength needed to shear the sheet [7]. As the clearance between the punch and die gets larger, the blow-out effect increases, thus, fracture angle increases. Therefore, non-adequate clearances are the largest cause of tool damage [8].

Commonly, holes obtained by conventional punching did not show good cylindricity—tapered hole—also showing inferior dimensional and geometrical tolerances than holes obtained by the machining processes.

Mello [9] reported that the blow-out effect is aggravated with the material hardness and mainly with the sheet thickness increasing. When the blow-out occurs, the hole diameter at the end of the cutting process is larger than the diameter at the beginning of the punching. Therefore, the normal perforating solution for thick sheet could be a posterior machining by widening, broaching, holing, or laser cutting—for perfect cylindrical hole shape. Several experiments were carried out by Marcondes et al. [10] purposing precision improvements on the punched holes for thick sheets (8 mm). They reported the development of a new punching and broaching combo tool. This combo allies the advantages of the forming processes production and machining in only one process for heavy-duty jobs on thick metal sheets. The authors used a clearance between punch and die of 7.5%, producing perforated holes with good surface quality and perfect cylindricity after broaching.

The productivity and the quality of the sheet metal cutting process can be evaluated by the burr height after the shearing [1, 11, 12]. During the initial cutting stage, the sheet is pushed to the die and the material is elastically deformed. This process continues until the material yield happens, first at the sheet surface and, after that, in the material fibers between the punch and die. The plastic strain results on the sheet rollover, and, at this stage, the ductile fracture happens after the shearing.

According to Goijaerts et al. [13], the cutting process is not totally understood due to situations in which the material constantly alters its resistance, the process becoming too complex to adopt an analytical model. The major difficulty found in numerical analysis is the exact description of ductile damage beginning. Komori [14] studied the ductile damage in metallic sheets experimentally and by finite elements method. He has developed a computer finite element program which shows the crack growth behavior after the ductile fracture. According to Wu [15], at any moment of the analysis, the material tension vector is given by a scalar equation, assuming that the strain is given in the beginning of the damage. The equation is defined by the relation between the hydrostatic pressure (p) and the Von Mises tension (q). This model is based on the equivalent plastic strain value on the element integration point, and the failure is shown when the damage parameter (ω) exceeds 1.

According to Hambli [16], clearances up to 10% are suitable to minimize shearing forces; otherwise, clearances up to 5% are desirable because the fracture angle and depth developed in the cutting region are minimized.

The clearance being an extremely significant parameter on punching process, the aim of this research is the study of the clearance influence in the burr formation and fracture angle development on punched holes of thick sheets. The punching force profile was also evaluated. In this study, clearances between 0.2% and 15% were numerically simulated, and the modeling response was also validated with the results obtained by Marcondes et al. [10] on experimental punching data using clearance of 7.5%.

2 Experimental procedure

To assess the effective clearance, influence on the hole quality was numerically simulated the punching of 10-mm-diameter holes on 8 mm LNE38 sheet steel (NBR 6656). This steel has a low percentage of carbon (Table 1), high resistance, and good elongation (Table 2) and is used in heavy industrial applications. The simulations were carried out using ABAQUS/EXPLICIT 6.9 software and a computer with Sempron® 3100 processor and memory RAM of 512 MB.

The punching process was modeled with four bodies in an axisymmetric model (Fig. 1). The punch, die, and blank holder were assumed as solid/rigid structural elements. The sheet was modeled with axisymmetric quadrilaterals elements with four nodes and reduced integration (CAX4R)

Table 1 LNE38 chemical composition (percent in weight)

Material	C max	Mn max	Si max	*P* max	S min	Al min	Alloys elem.
LNE38 NBR 6656	0.10	1.10	0.035	0.035	0.03	0.02	Ti>=0.08

Table 2 LNE38 mechanical properties

Material	Yeild strength (MPa)	Tensile strength (MPa)	Elong. (%)	K (MPa)	*n*	Density (kg/mm³)	Poisson	Elastic modulus (MPa)
LNE38 NBR 6656	439	521	29	1,012	0.20	7.8E-6	0.3	210,000

K plastic resistance constant, *n* hardening coefficient

and with triangular elements with three nodes (CAX3) [17]. The proposed model uses a direct integration point condition in the structural dynamic equations. The direct integration point is suitable to highly dynamic problems with non-linear behavior as the simulation of fracture of metals. It was stipulated by only one step of simulation type Explicit/Dynamic. In this step, the punch moves into the opening period of the array with time of 0.01. This value was set after some preliminary tests to verify convergence.

Marcondes et al. [18] emphasize that the mesh density affects greatly the strain results in the simulations. Due to the high plastic strain gradient on the cutting area, enough dense mesh must be applied near the cutting area.

In earlier work, Söderberg [5] reported the influence of the mesh density on the cutting geometry and the cutting forces for the punching process simulation of thin sheets. In his work, he carried out simulations with different mesh conditions and concluded that meshes from 64 to 128 elements, defined in the sheet thickness, are good enough to evaluate the rupture force influence on the punching process.

In this work, 128 elements were applied in the sheet thickness just in the crack propagation region, i.e., where the plastic strains are concentrated. At the other regions, a broader mesh was applied to narrow the time demanded by the simulations. The clearance influences on the burr formation, on the cutting forces, and on the fracture angle were also evaluated.

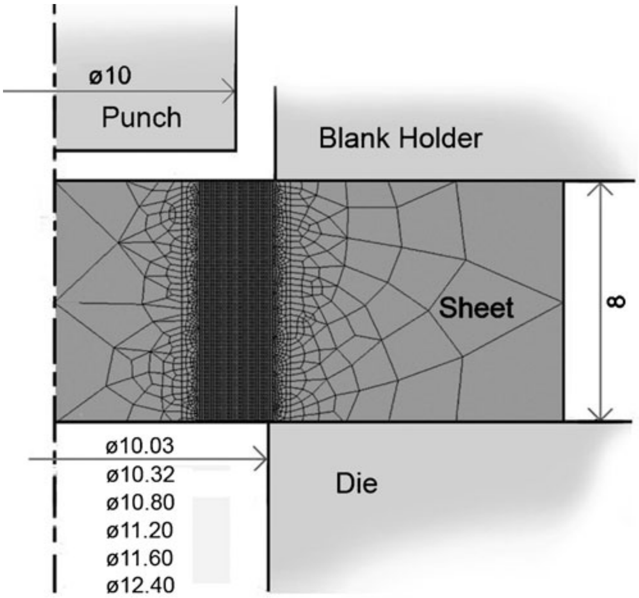


Fig. 1 Axisymmetric punching model showing the clearances analyzed (dimensions in millimeters)

Accordingly [19–22], clearances from 2% to 10% allow an acceptable cutting force and good finishing ratio on punching. In this work, clearances of 0.2% (ø10.03), 2% (ø10.32), 5% (ø10.80), 7.5% (ø11.20), 10% (ø11.60), and 15% (12.40) were evaluated (Fig. 1) (percentage of the sheet thickness per side). Additionally, clearances of 0.2% and 15% were also evaluated to verify the influence on the burr development.

Marcondes et al. (2008) carried out experiments showing the influence of lubrication on the punching and broaching process. They reported that the lubrication has little influence on the quality of the hole. Due to this reason, the contacts between the rigid bodies—punch, die, and blank holder—and sheet surfaces were defined by the penalty contact method using a friction coefficient of 0.1 (Coulomb's model). The load at the blank holder was of 10,000 N.

The material was modeled as von Mises isotropic hardening, assuming the material properties as 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 was applied to the conventional tensile–strain curve (Fig. 2a). The adequate true tensile–strain data for the simulations are shown in the Fig. 2b.

The damage initiation criteria, after the ultimate tensile strength (UTS), were chosen so as to predict the damage initiation due to the nucleation, growing, and coalescing 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 $\dot{\bar{\varepsilon}}_D^{pl}\left(\eta, \dot{\bar{\varepsilon}}^{pl}\right)$. In this case, the triaxiality stress η is given by $\eta = -p/q$. The variable p is the pressure stress and q is the von Mises equivalent stress. The term $\dot{\bar{\varepsilon}}^{pl}$ is the equivalent plastic strain rate. The pressure stress p and the Mises equivalent stress q are represented by Eqs. 1 and 2, respectively.

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

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

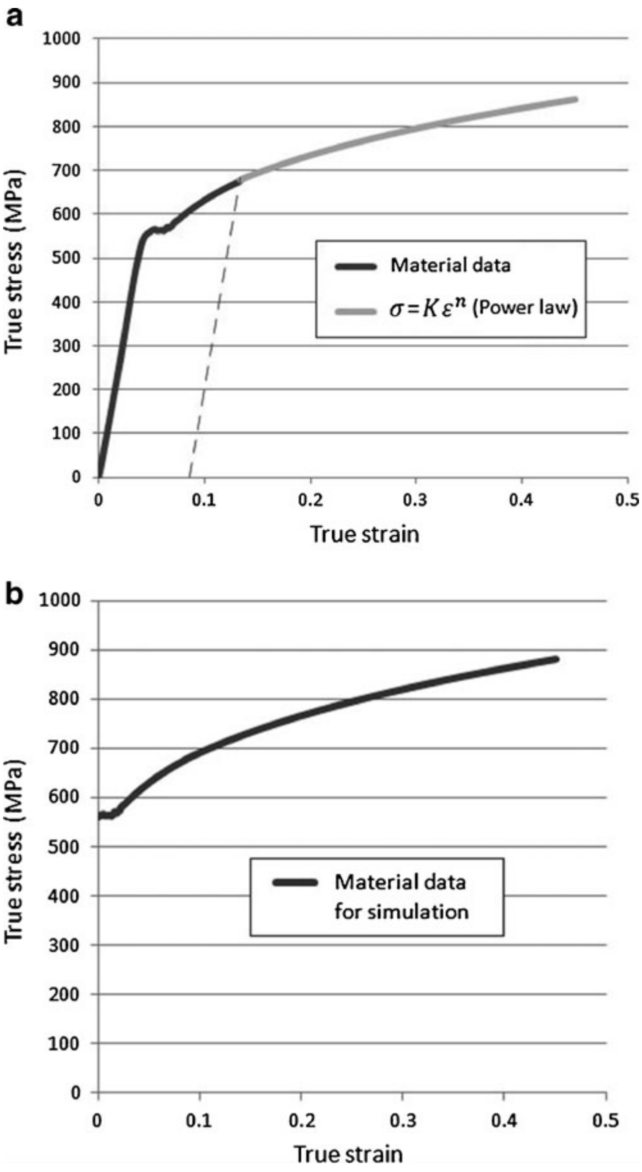


Fig. 2 LNE38 true tensile–strain curves: **a** material data with power-law fitting−material data+power law and **b** treated experimental data used for simulation

The criteria for the damage initiation is achieved when the following condition is satisfied (Eq. 3), where ϖ_D is a state variable that increases monotonically with plastic strain. At each increment, the incremental growth in ϖ_D is computed as (Eq. 4).

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

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

During the simulations, it was 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 follows: 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 Eqs. 1 and 2, and $\eta = 0.272$ is obtained. For the biaxial stress, it is assumed that $\sigma 1 = \sigma 2$ and $\sigma 3 = 0$ and $\eta = 0.667$ are calculated. For shearing, $\sigma 1 = -\sigma 2$ and $\sigma 3 = 0$, and for this case, $\eta = 0$ is obtained. Furthermore, it was determined the damage evolution criteria—the parameter that defines how the material degrades after the damage initiation criteria—are found.

3 Results and discussion

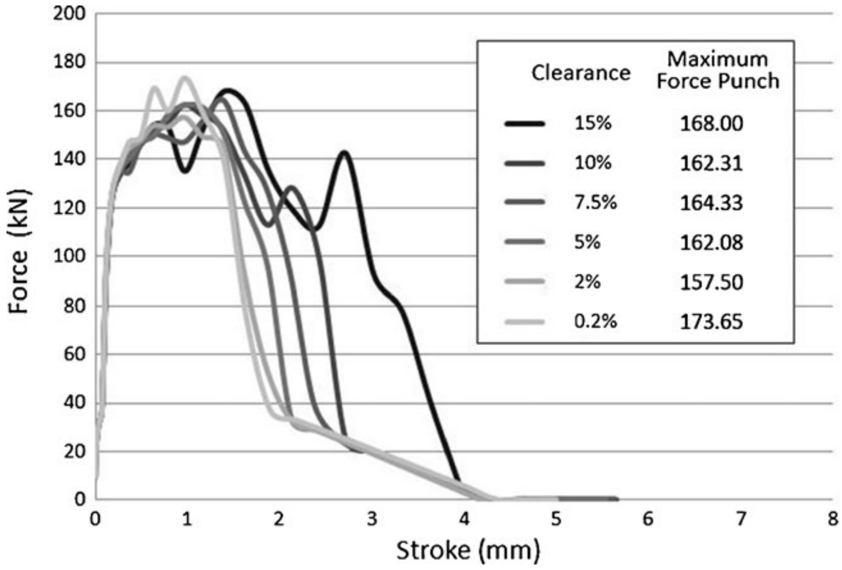
In order to evaluate the damage behavior induced by the punch forces in the sheet thickness, the finite elements (FE) simulations have been carried out considering the ductile damage initiation criteria (DUCTCRT). This ductile damage initiation criterion indicates that the material region that exceeds $\varpi_D > 1$ (Eq. 3) was plastically deformed beyond its resistance. As the elements will degrade, they were being eliminated from the model. The degradation started in the region in contact with the edge of the punch and matrix—giving the onset of cracks—which has been propagated to produce the complete shear.

Figure 3 shows the punch force versus punch displacement curves obtained with ABAQUS/Explicit. The CPU processing time was of 4 h in average.

The punch force versus punch displacement curve obtained with clearances inside the ideal range suggested by Altan, Klingenberg and Singh, Peng et al., and Vaz and Bressan [19–22] shows that the crack initiation occurs between the sheet thickness of 1 and 2 mm, and the maximum punch force observed was 161 kN. The smallest clearance (0.2%), typical clearance used for fineblanking processes, caused the crack initiation at the same range of thickness. The maximum punch force observed was 173.65 kN, and the blow-out effect was near 40 kN. Otherwise, the largest clearance (15%) caused the crack initiation near the thickness of 2 mm, extending the crack propagation longer and moving the blow-out effect for the thickness of 4 mm (Fig. 4b), suggesting more plastic strain before the blow-out effect (around 5 kN). The maximum punch forces were observed with 0.2% and 15% clearances which are out of the reported ideal range of clearances.

According to Hambli [16], in an ideal punch process, the punch stroke should be around 1/3 of the sheet thickness, before the blow-out effect. In this work, the closest of this condition was observed for the clearance of 7.5% which agrees with the experimental data obtained by Marcondes

Fig. 3 Punch force vs. displacement numerical curves obtained for LN32 steel



et.al. [10]. Figure 4a shows the detailed crack propagation behavior under this condition. The curve for the clearance of 5% was the one that showed the smoothest behavior without peaks and valleys alternation that characterizes plastic strain and cracks propagation, respectively.

The characteristic features of the sheared holes have been plotted with respect to die–punch clearance variation (Fig. 5). Burr size near 1.5 mm was observed just when the clearance of 15% was simulated. For all other simulations, considering 0.2%, 2%, 5%, 7.5%, and 10%, it no burr occurrence was observed at all. These results for thick sheets obtained by numerical simulation are in agreement with the experimental results for thin sheets observed by other authors [23, 24], which stated that the use of larger clearances results in larger burrs.

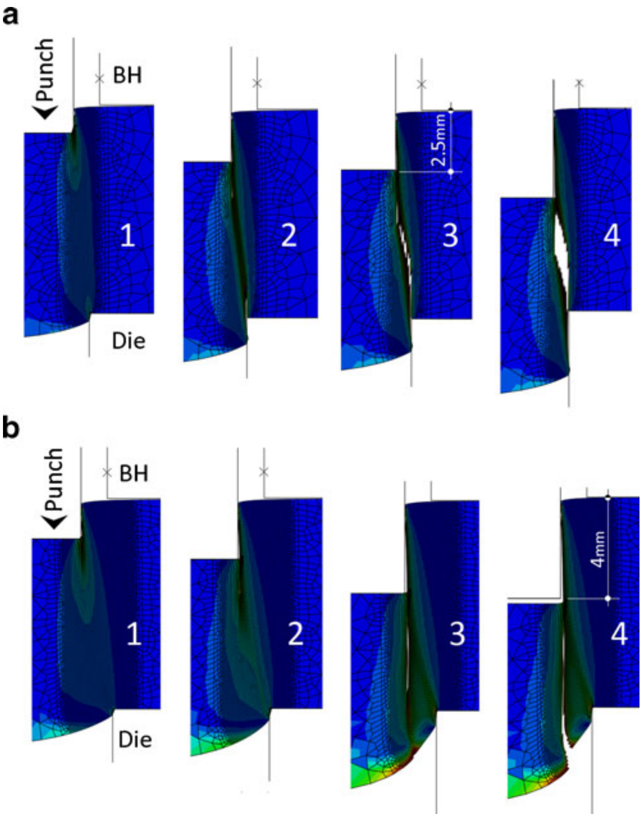


Fig. 4 Detailed crack propagation with the punch–die clearance variation: **a** 7.5% and **b** 15%

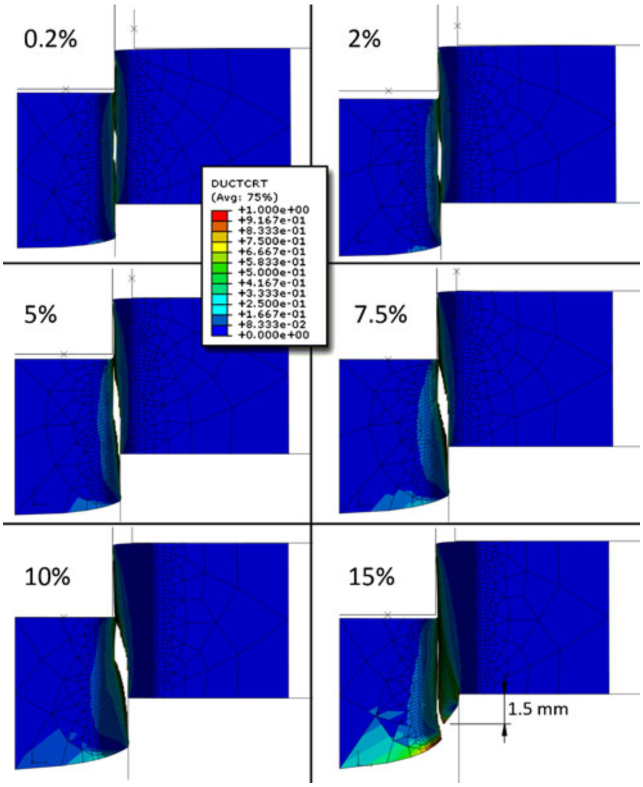


Fig. 5 Punching FE results using the ductile damage initiation criteria and several punch–die clearances

During the punch process, at the punch penetration step, the sheet is strongly deformed during the shearing process. At this stage, a die clearance increase allows an easier material flow between the punch and the die [6]. However, in this work, the die clearance did not show a strong effect on rollover, possibly due to the high sheet thickness effect and also, probably, because of the blank holder force influence, which is in agreement with Hatanaka et al. [2].

As expected, the fracture angle (Fig. 5) increases as the clearance also increases. This behavior is also in agreement with the experimental and numerical results in the literature [2, 3, 6, 13]. When the clearance is small, the cracks generated from the punch vicinity and die edges propagate along a straight line, connecting the cracking tips of the upper cracks and those under (Fig. 4a). Otherwise, when the clearance is larger, the crack propagates only from the punch side and widens. However, at 15% of clearance, the fracture path does not propagate from the under part of the punch corner and from the upper part of the die corner, resulting a fracture angle near 0º—a non-tapered hole. In this case, a primary crack occurs under the punch corner edge, so two paths of tension are shown: one to the die corner edge and other in a straight line that directs the crack propagation causing a hole profile without fracture angle, but with burr occurrence (Fig. 4b). Figure 3 emphasizes the non-simultaneous upper and under crack formation; it can be observed in two maximum peaks of punch forces for the clearance of 15%.

4 Conclusion

Sheet metal punching is an important industrial process for forming mechanical parts. It was shown that an accurate simulation of the process can lead to optimal forming parameter choice. In this study, the finite element analysis was applied for punching of LNE38 steel, a heavy-duty job on thick sheet.

The ideal clearance range for thick ductile materials is between 2% and 10%. However, the clearance below 5% can propitiate smaller punch forces.

The punching process was successfully simulated using the ductile damage initiation criteria. The 2% and 5% clearances showed the smaller peak of maximum punch force and the lower fracture angle. With the clearance of 5%, the smoothest force vs. displacement curve was observed. The optimized clearance between the punch and die was approximately 2% of the sheet thickness, but higher forces are needed with small clearances.

The rollover was inexpressive for all the conditions simulated. The hole's edge quality was investigated, and it was found that the fracture angle became larger when the punch–die clearance increases up to 15%. The use of a clearance of 15% showed an acceptable fracture angle profile but a large burr height. An option to the total fracture angle elimination, observed with the use of larger clearances, could be the use of the punching and broaching combo tool, as shown by Marcondes et al. [10].

Acknowledgments Financial support from CAPES Agency (Brazil) is acknowledged.

References

1. Al-Momani E, Rawabdeh I (2008) An application of finite element method and design of experiments in the optimization of sheet metal blanking process. J Mech Indust Eng 2:53–63
2. Hatanaka N, Yamaguchi K, Takakura N (2003) Finite element simulations of the shearing mechanism in the blanking of sheet metal. J Mater Process Technol 139:64–70
3. Hatanaka N, Yamaguchi K, Takakura N, Iizuka T (2003) Simulation of sheared edge formation blanking of sheet metals. J Mater Process Technol 140:628–634
4. Li JH, Du H, Niu YS, Fu XL (2002) Research of the plastic status parameter and instantaneous clearance of a punching without burr. J Mater Process Technol 129:305–309
5. Söderberg M (2006) Finite element simulation of punching. Dissertation, Luleå, Sweden: Luleå University of Technology: ISSN 1402–1617
6. Husson C, Correia JPM, Daridon L, Ahzi S (2008) Finite elements simulations of thin copper sheets blanking: study of blanking parameters on sheared edge quality. J Mater Process Technol 199:74–83
7. Fang G, Zeng P, Lou L (2002) Finite element simulation of the effect of clearance on the forming quality in blanking process. J Mater Process Technol 122:249–254
8. Lin JC, Lin WS, Lee KS, Tong JL (2008) The optimal clearance design of micro-punching die. J Achievements Mat Manuf Eng 29:79–82
9. Mello LB, Marcondes PVP (2006) Punching and broaching combos—a new stamping tool. J Braz Soc Mech Sci Eng 28:94–98
10. Marcondes PVP, Eto AM, Beltrão PAC, Borges PC (2008) A smart stamping tool for punching and broaching combination. J Mater Process Technol 206:188–193
11. Ahzi S, Daridon L, Correia JPM, Husson C (2008) Finite elements simulations of thin copper sheets blanking: study of blanking parameters on sheared edge quality. J Mater Process Technol 199:74–83
12. Hilditch TB, Hodgson PD (2005) Development of the sheared edge in the trimming of steel and light metal sheet. J Mater Process Technol 169:192–198
13. Goijaerts AM, Govaert LE, Baaijens FPT (2001) Evaluation of ductile fracture models for different metals in blanking. J Mater Process Technol 110:312–323
14. Komori K (2001) Simulation of shearing by node separation method. Comput Struct 76:197–207
15. Wu Tsu-Te (2008) A proposed methodology for strain-based failure criteria. ASME Pressure Vessels and Piping Division Conference July 27–31, Chicago, Illinois
16. Hambli R (2002) Design of experiment based analysis for sheet metal blanking processes optimisation. Int J Manufact Technol 19:403–410
17. ABAQUS/CAE (2009) User's manual, version 6.9. ABAQUS Inc.
18. Marcondes PVP, Lajarin SF, Magalhães JFS (2007) Influence of the mesh format, refinement and way of application on sheet forming simulation. 19th International Congress of Mechanical Engineering-COBEM 2007, Brasília/DF/Bazil

19. Altan T (1998) Metal forming handbook, Schuler. Springer-Verlag Berlin Heidelberg, New York, pp 281–282
20. Klingenberg W, Singh UP (2006) Further observations and review of numerical simulations of sheet metal punching. Int Journal Adv Manufaturing Technology 30:638–644
21. Peng L, Liu F, Ni J, Lai X (2007) Size effects in thin sheet metal forming and its elastic–plastic constitutive model. Mater Des 28:1731–1736
22. Vaz MJ, Bressan JD (2002) A computational approach to blanking processes. J Mater Process Technol 126:206–212
23. Taupin E, Breitling J, Wu W-T, Altan T (1996) Material fracture and burr formation in blanking results of FEM simulations and comparison with experiments. J Mater Process Technol 59:68–78
24. Hambli R (2002) Prediction of burr height formation in blanking processes using neural network. Int J Mech Sci 44:2089–2102