Optimum blanking clearance choice method by an approach coupling experimental trials and simulations

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Abstract. Blanking process of sheet metal is accomplished by a shearing action on a thin plate placed between two sharp cutting edges, known as “punch” and “die”. The main problem of this sheet metal cutting technology, that causes major shutdowns of the press machine, is the punch wear. Among all blanking parameters, the clearance set between the punch and the die has the major influence on tool wear. In this context, our study focuses on identifying the optimum blanking clearance that guarantees a maximum abrasion and chipping wear reduction for different sheet metal materials and different blanking operations. The developed approach combines experimental blanking tests and numerical simulation of blanking processes. Based on assumptions made in this paper, links are established between the stripping force and the abrasive wear behaviour of punching tools and also between the maximum pressure on the face of the punch and the risk of chipping. Using these links, criteria have been developed allowing to propose an optimum blanking clearance for all the configurations tested in this paper. A next step of this study consists on applying the optimum punch-die clearances in a variable way along a complex blanking shape and realizing experimental tests to compare the results (tool life and edge quality) with a constant blanking clearance.

1. Introduction

The mechanical blanking process on a press is commonly used by manufacturers in sheet metal cutting operations. The high productivity rate of this process allows it to intervene at different stages of the sheet metalworking process: at the beginning of the process to blank the sheet or pierce the pilot holes, during the process to prepare for bending or drawing operations and at the end of the process to trim or separate the part from the strip. Tool life is a primary concern for manufacturers in order to guarantee the quality of the manufactured parts while maintaining the productivity, and among all the sheet metal cutting operations, the blanking operation induces the most significant tool wear which is the primary cause of press shutdowns.

The main consequences of wear formation on blanking tools are listed below:

- Dimensional variations or distortions of parts,
- Increase in the size of the burrs on the part produced,
Increased blanking forces and more particularly the so-called “stripping” force (Figure 1) which strongly contributes to the wear of the punch [1].

![Figure 1. Blanking force during punch travel [1]](image)

Among all blanking parameters, the clearance set between the punch and the die has the major influence on tool wear formation. Several studies had been carried out on the subject. Bell [2] and Högman [3] worked on the influence of the blanking clearance on the punch wear for the blanking of a 1 mm Dual Phase high strength steel. The results of their experiments showed that small clearances cause galling while high clearances cause chipping risks due to high bending stresses in the blanked edge. Thus, they found that there was an optimum clearance that minimises the punch wear formation. Another study implementing variable blanking clearance was reported by Högman for the blanking of a 1 mm thick DP800 sheet metal [4]. This study has shown that variable blanking clearances can be efficient in reducing tool wear formation. An increase of 10% in the clearance on the corner of the square punch results in an increase of 45 000 strokes to 200 000 strokes in the tool life. To improve the choice of an optimum clearance on the local punch shape, Subramonian et al. used a numerical method that consists of analysing the stresses developed at the punch corner during blanking operation and thus applying a more uniform stress distribution on the punch [5]. This method has been validated by experiments and the results show that punch life has increased from 126000 strokes to 350 000 by using a variable clearance. More recently Bohdal et al. [6] and Yousefi et al. [7] reported extensive studies on tool wear processes in nibbling and punching. The authors combined numerical simulation and experimental investigations to analyse the wear formation mechanisms.

Our study focuses on identifying the optimum blanking clearance that guarantees a maximum abrasion and chipping reduction for different sheet metal materials. We will analyse more particularly the abrasion wear that takes place on the sides of the punch. Different simple shapes of blanking were used to evaluate their influences. The method used is based on experimental trials combined with a simulation campaign carried out in order to choose a blanking clearance providing resistance to chipping wear. An analysis is then carried out with the prospects for further actions.

2. Experimental aspects

The experiments were carried out on a 200T crankshaft press equipped with a blanking tool. This blanking tool, presented on Figure 2, is provided with guiding columns on which the blank holder is also connected to ensure proper centering of the whole set (the punch, the guiding bush and the die). We also observe on Figure 2, the pretensioned load washer on the top of the punch.
The blanking process has been characterised by the following measurements:

- **Displacement – Load – Time curve** of the blanking process. A load washer on the top of the punch allows measuring the blanking force and a displacement wire sensor between the bed and the ram of the press allows measuring the displacement of the ram. Figure 3 illustrates a displacement – load – time curve measured with this set-up. With this method, it is possible to link the load with the displacement of the ram through the synchronisation made.

- **Variation of the blanked edge dimension** after extraction of the punch. This variation is due to the springback of the hole blanked edge [1] and is measured with calibrated rods whose diameter varies with a step of 0.01 mm. The precision of the calibrated rods diameter is equal to ± 3µm.

- **Height of the burnished zone of holes**. The observation of the blanked edge is made using an optical microscope. The analysis and the measurement of the burnished zone is made through image post processing with a precision of ± 0.01 mm.
The blanking experiment was realized in dry conditions. Five samples have been blanked for each configuration.

A map experiment was carried out, varying the following parameters:

- Two tested materials: high strength steel HC380LA and stainless steel X2CrNi18-09, with 1 mm thickness.
- Six radial blanking clearances: 2.5; 5; 7; 10; 15 and 20 % of the initial thickness. The clearance has been transferred on the die.
- Three simple shapes (Figure 4), to represent the following localized geometry: straight edges and different values of fillet radius that we can encounter on complex shapes. A rectangular (18 x 15 mm) punch with a 1 mm radius and two circular (Ø8 and 16 mm) punches.

![Figure 4. Punches shape](image)

The measured outputs through these experiments are the blanking force, the dimensional variation of the blanked edges, and the distribution of the burnish zone of the hole. All values expressed in this article are averages of five measurements.

3. **Numerical aspects**

The various blanking tests carried out under this research program are simulated with the help of Abaqus software using a solid axisymmetric finite element model. The sheet metal is discretized using 3875 nodes and 3674 axisymmetric solid elements with reduced integration (CAX4R). The calculations involve three steps. In the first step, the blanking process is simulated using Abaqus/Explicit. The results are then transferred from Abaqus/Explicit to Abaqus/Standard for the subsequent calculations. In the second step, the calculations are achieved using Abaqus/Standard. The fracture line is then created, the slug elements are deactivated as well as the contact between the sheet metal, the die and the blank holder. This way, the blanked edge springback and the resulting pressure on the punch side are computed. In the third and final step, the contact between the sheet metal and the punch is deactivated and the blank edge geometric changes are computed. The calculations steps are illustrated in Figure 5.
Figure 5. Finite element model, (a) blanking simulation, (b) punch pressure due to spring back, (c) cut edge changes due to spring back

In all the calculations, the punch, the die and the blank holder are considered to be rigid while the sheet metal behaviour is described using a \( J^2 \) plasticity model. The material flow stress curve is described using Krupkowski strain-hardening law:

\[
\sigma = K (\dot{\varepsilon} + \varepsilon_0)^n
\]

where \( \sigma \) is the yielding stress, \( \dot{\varepsilon} \) is the equivalent plastic strain, \( K, \varepsilon_0 \) and \( n \) are material parameters. The material input data for the two investigated steels are reported in Table 1. To complete these data, the Young modulus \( E \) is equal to 210 000 MPa and the Poisson ratio \( \nu \) is equal to 0.3.

Table 1. Mechanical characteristics and data for hardening laws for the materials used

| Material     | \( Rp_{0.2} \) (MPa) | \( Rm \) (MPa) | \( A \) (%) | \( r \)  | \( K \) (MPa) | \( \varepsilon_0 \) | \( n \) |
|--------------|----------------------|---------------|-------------|---------|--------------|----------------|-------|
| HC380LA      | 383.3                | 510.2         | 22.8        | 0.5797  | 800.09       | 0.008          | 0.167 |
| X2CrNi18-09  | 292.9                | 678.9         | 52.6        | 0.773   | 1442         | 0.0252         | 0.404 |

The parameters of the hardening law are obtained from trials on a tensile test machine equipped with cameras and by performing a DIC (Digital Image Correlation) method.

In this article, the fracture is simulated when the penetration of the punch reaches the value of the penetration measured experimentally corresponding to the effective rupture. It should be noted that the fracture line is created based on experimental observation because the damage modelling in blanking process and in particular the damage model calibration requires significant effort [8]. But in the future, we plan to take damage into account with the help of simple models like other researchers [9] who successfully used a simple Cockroft-Latham model to investigate damage induced by shearing process. They showed that the model can be calibrated using blanking tests and finite element modelling.
4. Experimental results

An assumption has been carried out in this paper by considering that the most important abrasion wear occurs during the stripping phase of the blanking operation. The contact between the burnished zone of the blanked edge and the side of the punch (Figure 6) is considered to be the main mechanism of abrasion wear formation. That assumption supposes that this contact is established on the entire burnish zone [1].

![Figure 6. Presentation of the contact between the burnished zone and the side of the punch during punching](image)

As stated before, the characterised outputs of interest using this experiment are the stripping force, the dimensional variations of the blanked edge and the height of the burnished zone of this edge.

Figure 7 shows the normalised stripping forces as a function of the blanking clearance for both tested materials. The stripping force has been normalised by the blanked perimeter so comparisons between the samples can be held independently of the dimension of the blanked perimeter (relation (2)).

\[
f_{ns} = \frac{f_s}{P} \quad (2)
\]

\(f_{ns}\) is the normalised stripping force, \(f_s\) is the stripping force and \(P\) is the blanked perimeter.

General trends are observed for both tested materials:

- The normalised stripping force decreases when the blanking clearance increases,
- The normalised stripping force increases when the size of the punch decreases,
- The normalised stripping force is relatively small for a punch shape mostly made of straight edges (rectangular punch).

Figure 8 shows the dimensional variations expressed as a function of the blanking clearance. The dimensional variation of the hole has been expressed using the diameter of the punch and the obtained value has been divided by two in order to obtain springback value of the blanked edge of the hole. On Figure 8, \(D\) is the measured diameter and \(D_{\text{nominal}}\) is the diameter of the punch. For comparison purposes, the straight edges could be considered as circles with an infinite radius. The results in Figure 8 show that an increase in the blanking diameter led also to an increase in the springback of the sheet. Indeed, there is more springback on straight edges because the deformation
is not hindered, unlike the curved edges where the deformation closes the hole and is therefore limited by shrinkage.

On the contrary, the results in Figure 8 for the two circular punches show that the springback is higher for a smaller diameter. This result can be explained by the fact that the springback depends also from the distribution of the elastic stresses generated during the blanking of the edges which is higher for smaller punching diameter.

In Figure 9, the burnish zone of the blanked edges is expressed as function of the blanking clearance. It is observed that the burnish zone decreases with an increasing blanking clearance (this observation is in agreement with the rules of the blanking profession). And finally, by characterising the different shapes by their radius of curvature, the burnish zone is found to have an increasing trend when the radius of curvature decreases.

![Figure 7. Normalised stripping forces as a function of blanking clearance, (a) HC380LA steel, (b) X2CrNi18-9 steel](image7)

![Figure 8. Dimensional variation as a function of blanking clearance, (a) HC380LA steel, (b) X2CrNi18-9 steel](image8)
5. Numerical results

In addition to the experimental tests, numerical simulations of the blanking operation were carried out in order to deduce the following measures:

- Maximal pressure on the face of the punch (Pmax),
- Contact surface and the side pressure of the blanked edge on the side of the punch.

Each simulation has been evaluated through a comparison with the experimental maximum blanking force. The calculation parameters have been adjusted so as to minimise the differences between the maximum blanking force obtained experimentally and numerically. Figure 10 shows an example of a comparison made to evaluate the simulation of one tested configuration. In that evaluation, it can be estimated that the difference between the two forces is acceptable and the analysis of the pressure is therefore allowed.

Figure 10. Validation of the simulation through the maximum blanking force (HC380LA, thickness 1mm, Ø8 mm, clearance=20 %).

Figure 11 shows a typical example of the distribution of the pressure on the face of the punch expressed as a function of the radius of the punch. This value is extracted just before rupture.
Figure 1. Pressure distribution on the face of the punch as a function of the radius of the punch (HC380LA, thickness 1mm, Ø8 mm, clearance=2.5%).

Figure 1 shows that the maximal pressure is located close to the blanking edge. Its position coincides with the initiation of the chipping which is shown as an example on Figure 12. Within the scope of this article, none chipping case has been met during the experiments.

Figure 12. Example of chipping on the blanking edge of the punch (CETIM results met outside the presented work)

Based on the results obtained from Figure 11 and 12, one can assume that the risk of chipping is related to the maximum pressure on the face of the punch.

Figure 13 shows the numerical maximum pressure on the punch as a function of the blanking clearance.

The following trends are observed:

- The maximum pressure decreases when the blanking clearance increase regardless of the shape of the punch except for the case of stainless steel with clearance of 20% (Figure 13b).
- The maximum pressure decreases when the diameter of a circular punch increases with the same exception said in the line above.
- The maximum pressure increases with the maximum tensile strength of the material.
Figure 13. Predicted maximum pressure, (a) HC380LA steel, (b) X2CrNi18-9 steel

Figure 14 shows an example of a contact between the side of the punch and the simulated blanked edges, in which the contact doesn’t seem to apply on a surface but on two lines instead. This result contradicts the rubbed length assumption made in the forth paragraph which considered that the entire burnish zone was in contact with the side of the blanking tool. Nevertheless, this contradiction could be explained by the fact that the simulation doesn’t take into account neither the evacuation of the slug, and therefore the springback of the blanked edge, nor the stripping of the punch.

Figure 14. Contact example between the punch and the blanked edge during a punching operation (HC380LA, thickness 1mm, Ø8 mm, clearance=2.5%).

The blanked edge springback and the pressure on the punch side obtained after the second step of the calculations (Figure 5b) haven’t been analysed because of aberrant results which need an improvement of the numerical model.

6. Analysis and discussions

All results presented in the paragraphs 4 and 5 will be used, in the following, to choose an optimum blanking clearance that reduces abrasion and chipping wear. The assessment of abrasion wear is made by studying the variation of the stripping forces as a function of the blanking clearance. Indeed, an analysis of the parameters of the Archard Law [10] leads to conclude that the abrasion wear is linked to the normal stress, the friction coefficient, the hardness of the materials facing each other’s and the rubbed length. The study of the blanking clearance influence fixes the following parameters: the
coefficient of friction ($\mu$) and the hardness of the materials facing each other. In that case, we can compare the abrasion wear corresponding to several blanking clearances by establishing the following relation:

$$\frac{V_{c_1}}{V_{c_2}} = \frac{\sigma_{n_{c_1}} r_{l_{c_1}}}{\sigma_{n_{c_2}} r_{l_{c_2}}}$$

(3)

$V$ represents the wear volume, $c$ represents the blanking clearance, $\sigma_n$ represents the normal stress and $r_l$ represents the rubbed length.

$r_l$ is equivalent to the height of the burnish zone (hb). The normal stress $\sigma_n$ can be also expresses by the following relation:

$$\sigma_n = \frac{f_{ns}}{hb} \cdot \frac{1}{\mu}$$

(4)

Combining relations (3) and (4) leads to:

$$\frac{V_{c_1}}{V_{c_2}} = \frac{f_{ns_{c_1}}}{f_{ns_{c_2}}}$$

(5)

Knowing that this abrasion wear criterion doesn’t always allow to decide between several clearances, a criterion based on the quality of the blanked edge is chosen. This criterion is based upon the height of the burnish zone (hb). Indeed, in industry, a compromise between the tool life and the part quality is aimed.

The chipping risk of the punch blanking edge can be evaluated by comparing the yield strength of the tool steel to the maximum pressure which occurs on the punch. Thus, the criterion can be written as:

$$C \cdot P_{\text{max}} \leq R_e \left( \text{Tool steel} \right)$$

(6)

$C$ is a dimensionless security constant that includes the chipping risk by fatigue ($C<1$), $P_{\text{max}}$ is the maximum pressure in the blanking direction and $R_e$ is the yield limit of the tool steel.

While the abrasion wear criterion concerns the side of the punch, the chosen chipping risk criterion concerns the face of the punch pressed against the blank. This criterion indicates a minimal resistance of the tool to exceed and can integrate a fatigue limit.

From these different approaches, it is possible to establish recommendations on optimum blanking clearances to use on different simple shapes regarding the risk of wear and to temper these choices in the aim of respecting the quality of the edge. These optimum clearances are determined by an analysis of the abrasion wear risk and then controlled regarding the chipping risk. A table of recommended variable clearances is therefore proposed for both materials tested (Table 2).

| Table 2. Recommended variable blanking clearances |
|-----------------------------------------------|
| Ø16   | Ø8  | Straight Edge |
|------------------|-----|-------------|
| **HC380LA**      | 5 % | 10 %        | 5 %         |
| **X2CrNi18-09**  | 2.5%| 7.5%        | 2.5%        |

7. Conclusion
In the present paper, an optimum blanking clearance choice method by an approach coupling experimental trials and simulations has been investigated. This method has been applied to two materials and three blanking shapes to define an optimum blanking clearance that is aiming to reduce the tool wear. It was highlighted that the stripping force would be the major parameter used to identify an optimum blanking clearance for reducing abrasion wear. It was also found that this parameter has a
direct link with the Archard Law to estimate the wear volume. Also, the risk of chipping has been defined by a criterion involving the maximum pressure on the punch and the yield limit of the tool steel. Finally, the maximum pressure used to establish the previous criterion was obtained by a numerical simulation of the blanking operation. The next steps of this study are to apply the optimum punch-die clearances in a variable way along a complex blanking shape and realizing experimental tests to compare the results (tool life and edge quality) with a constant blanking clearance and to improve the numerical model by including damage modelling.

References
[1] Maillard A 1995 Proc. Int. Deep Drawing Research Group Conf. (Colmar)
[2] Bell T and Krause B 2005 Proc. Great Designs in Steel Sym. (Livonia)
[3] Högman B 2002 Proc. 6th Int. tooling conf. (Karlstad)
[4] Högman B 2004 Proc. Int. Conf. Recent Advances in Manuf. & Use of Tools & Dies (Olofström)
[5] Subramonian S and Ciocirlan B 2016 Proc. Int. Deep Drawing Research Group Conf. (Linz)
[6] Bohdal L, Kukielska L, Patyk R, Loska K, Chodor J and Czyrewski K 2022 Materials 15 107
[7] Yousefi M and Pervaiz S 2022 Simulation Modelling Practice and Theory 114 102415
[8] Basak S, Kim C, Jeong W, Jung Y I and Lee M G 2022 Int. J. Mech. Sci. 219 107109
[9] Han S, Chang Y, Wang C Y and Dong H 2022 J. Mat. Proc. Technol. 299 117377
[10] Archard J F 1953 J. Appl. Phys. 24 981