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# Material characterization of blanked parts in the vicinity of the cut edge using nanoindentation technique and inverse analysis

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## ABSTRACT

Sheet metal blanking is widely used in various industrial applications such as automotive and electrical rotating machines. When this process is used, the designer can be faced with several problems introduced by the change of the material state in the vicinity of the cut edge. In general, blanking operations severely affect mechanical and physical properties of blanked parts. To take into account these modifications during the part design, it is important to assess the influence of the process parameters on the resulting material properties. Previous experimental and numerical investigations of blanking process have been carried out, leading to the development and the validation of a finite element model that predicts the shape of the cut edge and state of the material. The study presented in this paper makes use of nanoindentation technique to improve the validation of the previously cited model. To this end, nanoindentation tests were combined with inverse identification technique to approach some of the characteristics of material state like work hardening near its cut edges. Indentation tests were carried out in the vicinity of several parts of cut edges. Based on the corresponding load versus penetration curves, the evolution of the yielding stress resulting from the material work hardening was estimated and compared to the predictions obtained from the numerical simulation of blanking process. These comparisons show good agreement between the measurements and the predictions from finite element model.

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## 1. Introduction

Sheet metal blanking is a complex operation by which material separation is obtained through a shearing process (Fig. 1). It combines plastic flow and ductile fracture of the blanked material. The phenomena involved in the blanking process are well known since the leading work of Johnson and Slater [1]. The main issues related to this process are the global behavior related to the punch load versus the punch penetration curve and the shape of the cut edge like size of the sheared zone, roll over and burr height. The first issue is important for the design of the blanking tool and machine while the second is imperative in the quality of the blanked part.

Given the blanking specification like part material, sheet thickness and part shape, corresponding parameters for the blanking operation are for example punch shape, clearance and friction. The evaluation of the influence of those parameters is generally based on the empirical knowledge. However, over the last decade, several researches were devoted to the modeling of the process and its numerical simulation; therefore it is difficult to give a comprehensive literature survey on this subject. Nevertheless, the interested reader can refer to some recent works like Husson et al. [2] for numerical simulation and Klingenberg and Singh [3] for analytical models.

When sheet metal blanking is used for manufacturing electromagnetic core devices like electrical rotating machines, there is another important issue to be addressed. It relates to the material state in the vicinity of the cut edge. In fact, it is well known that magnetic properties of blanked ferromagnetic steels are severely affected by the blanking [4,5]. Consequently, the design of reliable rotating electrical machines requires correlations between the mechanical state of the material near the cut edge and the degradation of the magnetic properties like the loss of magnetic permeability. For this purpose, some researches were conducted on the correlation between a material stress/strain state and its magnetic properties.

This paper focuses on the investigation of the blanking effect on the state of material in the vicinity of cut edge. The investigated material is a fully process non-oriented (NO) Fe-(3 wt%) Si alloy commonly used for the manufacturing of rotor/stator of core motors and electrical machines. Several axisymmetric blanking tests were carried out. Then, nanoindentation tests were performed in the

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Fig. 1. Schematic description of the blanking process.



Fig. 2. Tensile test with two strain rates.

vicinity of the cut edge. The nanoindentation measurements (load versus penetration curves) were used to compute the evolution of yielding stress near the cut edge using inverse identification method. The first finite element model was developed for simulation of blanking test. To compute the appropriate cost function and its gradients for inverse identification with the nanoindentation tests, another finite element model was used for the simulation of this test.

The results obtained from the nanoindentation measurements and inverse identification methods were then compared with the predictions from the simulation of the blanking tests for validation purposes. This paper is devoted to the material characterization near the cut edge with the help of the nanoindentation test and its inverse analysis. Thus, this work completes the previously published works [6–8] where the validation is limited to the prediction of punch force and the shape of the cut edge.

In the first section of this paper, the material which was studied is briefly presented and previous experimental results are reviewed. In the second section, the experimental aspects of this work, concerning blanking and nanoindentation tests are presented. The third section is devoted to the performed numerical investigations. In the fourth section, the predictions are compared with the experiments for validation purposes. The comparison is made between evolution of yielding stress and equivalent plastic strain in the vicinity of the cut edge (work hardened zone).

# 2. Material

The investigated material is a fully process non-oriented Fe-(3 wt%) Si steel. The sheet thickness considered for this study

Table 1

Average mechanical properties of NO Fe-(wt.3%) Si measured with a monotonous uniaxial tensile test.

E (GPa)	$\sigma_e^{\rm max}({\rm MPa})$	$\sigma_e^{\min}(\text{MPa})$	$L_p$ (%)	$\sigma_m$ (MPa)	A (%)
180-200	$293\pm5$	$279\pm8$	3-3.5	$410\pm10$	35-40

is 0.65 mm. This bcc ferritic material exhibits a weak recrystallization texture. The grain structure is isotropic and the average grain diameter is 16  $\mu$ m.

Uniaxial tensile tests were carried out in various directions in the sheet plane in order to characterize its mechanical behavior. The average mechanical properties of the alloy are listed in Table 1. You can see an initial yield drop, characterized by a minimum ( $\sigma_e^{\min}$ ) and a maximum ( $\sigma_e^{\max}$ ) conventional yielding stress, followed by a Lüders strain plateau commonly exhibited by bcc alloys. The mechanical properties are nearly isotropic in the sheet plane. The tensile tests were also performed at different constant strain rates  $\dot{\varepsilon}$  with the help of video controlled tensile test techniques. For detailed description of such tests, the reader can refer to G'sell et al. [9]. Fig. 2 shows material sensitivity to strain rate.

Where  $L_p$  states for Lüders plateau,  $\sigma_m$  for the average maximum stress and *A* for the maximum elongation.

To take into account the strain rate effect, the following strain rate-dependent yielding stress is adopted [10]:

$$\sigma_{y} = k \overline{\varepsilon}_{p}^{n} \left( \frac{\overline{\varepsilon}_{p}}{\overline{\varepsilon}_{p0}} \right)^{m} \tag{1}$$

where  $\sigma_y$  is the yielding stress,  $\overline{e}_p$  the plastic strain and  $\dot{e}_p$  the plastic strain rate. k, n and m are the parameters representing material strengthening.  $\dot{\bar{e}}_{p0}$  is the reference strain rate at which the quasi static yield stress is measured. For the investigated material, the rate-dependent yielding stress is fitted to the tensile test data, resulting in the following equation [6]:

$$\sigma_y = 752\overline{\varepsilon}_p^{0.267} \left(\frac{\dot{\overline{\varepsilon}}_p}{10^{-5}}\right)^{0.0093} (\text{MPa})$$
(2)

### 3. Blanking process

### 3.1. Experimental procedure

In order to validate the predictive model for the blanking simulation, different blanking tests were carried out using one of the CETIM (Centre Technique des Industries Mécaniques) me-

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Fig. 3. Schematic description of the blanking system (CETIM mechanical presses).



Fig. 4. The investigated blanking test: (a) schematic representation and (b) initial and deformed mesh.

chanical presses (200 tons, 80 SPM: Strokes Per Minute) equipped with circular punching tool. On this machine, a piezoelectric sensor is located just above the punch (see Fig. 3); therefore only the cutting load (excluding the blank holder) is measured for each stroke. The tool is connected to a signal acquisition and processing system. This system is used to measure the punch load versus punch penetration during the blanking operation [8].

As mentioned in the introduction, the cut edge of the blanked parts is made of three zones (Fig. 1): a roll over zone, a sheared zone and a fracture zone. The shape and the distribution of these zones depend on the material properties, sheet thickness and the process parameters (such as clearance and punch velocity).

These investigations are used to measure the punch penetration at fracture zone. The so obtained measurements were used for the validation of the predictive finite element model [8].

#### 3.2. Numerical simulation

When dealing with the numerical simulation of sheet metal blanking, particular attention must be paid to three significant issues namely: (i) the load stepping algorithm for solving nonlinear global equilibrium equation, (ii) the mesh adaptivity that ensures solution reliability for high strain levels and (iii) the constitutive model of the metal sheet. To overcome the divergence problems caused by the high nonlinearities associated with the blanking process, non-iterative load stepping algorithms are preferred [11]. In this work, Abaqus/ Explicit software is used. The blanking tests are simulated using a solid axisymmetric finite element model. The punch, the die and the blank holder are considered as rigid bodies. The frictional contact is implemented with the help of the Coulomb friction model. The blanked sheet is appropriately meshed with four nodded axisymmetric solid elements (Fig. 4b).

In the finite element simulation, using the Lagrangian formulation, an additional difficulty which may arise is the large distortions of the elements that make the solution unreliable. In this work, the ALE (Arbitrary Lagrangian Euleurian) technique is used for the mesh adaptivity [12].

For the sheet metal constitutive model, both plastic flow and ductile fracture need to be considered. For this purpose, the Gurson-Tvergaard-Needleman's model [13–15] is used to handle coupled damage and plasticity. In addition, it is combined with the rate-dependent yielding stress described in Section 2 in order to take into account the punch velocity effect (Eq. (2)).

Several blanking tests are simulated with the help of the previously described finite element model. The results are compared with the measurements for validation purposes. In Fig. 5, measured and predicted punch loads are compared, for the blanking test described in Fig. 4a.



**Fig. 5.** Punch force evolution during blanking (punch velocity=127 mm/s; clearance=7.69%).



Fig. 6. Definition of the distance from cut edge.



**Fig. 7.** Evolution of the equivalent plastic strain and the yielding stress in the vicinity of the cut edge.

The numerical results are in good agreement with the measurements. In addition, it should be noticed that the rate-dependent plasticity constitutive model improves the predictions.

The equivalent plastic strain and the yielding stress are computed on the top surface of the blanked part and their evolution with the distance from the cut edge, as defined in Fig. 6, is investigated. It should be noted that as the elements in the sheared zone experience high strain levels, the results for distances less than 100  $\mu$ m are not relevant.

Fig. 7 shows the evolution of the equivalent plastic strain and the yielding stress in the vicinity of the cut edge. It clearly appears that the material is subjected to work hardening in the vicinity of the cut edge, the size of the affected zone being about  $300\,\mu m$ 

around the cut edge. These results are qualitatively in good agreement with the experimental observations. Nevertheless, for quantitative validation, material characterizations in the vicinity of the cut edge are required. The next section is devoted to this issue.

## 4. Material characterization in the vicinity of the cut edge

## 4.1. Nanoindentation tests

Originally used for hardness measurement, nanoindentation tests are widely used nowadays for the calibration of various constitutive models. Most often, a nanoindentation curve (load versus penetration, Fig. 8) is used to identify isotropic material parameters with the help of analytical formula. On the other hand, an inverse analysis of the nanoindentation test can be combined with the additional measured data like residual deformation (imprint) to identify anisotropic constitutive models [16,17]. Moreover, this technique is used to investigate complex constitutive models with time and strain rate dependency [18], kinematic work hardening effect [19], or pressure sensitive plasticity [20].

The determination of the mechanical properties from nanoindentation data (load versus penetration) is briefly reviewed in this section. The instrumented nanoindentation is characterized by an indenter penetrating into a homogeneous solid where the indentation load P and the indenter penetration h are continuously recorded during one complete cycle of loading and unloading (Fig. 8).

Two mechanical properties frequently measured by nanoindentation are hardness H and Young's modulus E. A simple method has been developed by Oliver and Pharr [21] that allows measurement of these properties. This method is appropriated for the majority of ceramic and metallic alloys that do not exhibit pile-up, creep, viscoelasticity and work hardening. H and E can be determined generally within  $\pm 10\%$  margins, sometimes better.

The fundamental relations used to determine H and E are:

$$H = \frac{L}{A}$$
(3)

where L is the maximum load applied during the test and A the contact area.

$$E^* = \frac{S}{2} \sqrt{\frac{\pi}{A}} \tag{4}$$



Fig. 8. Schematic representation of the indentation curve.



Fig. 9. Indentation points in the vicinity of the cut edge.

and *A* is obtained with the following equation:

$$A = C \left( h - 0.75 \frac{L}{S} \right)^2 \tag{5}$$

The contact stiffness S is obtained by the initial slope of the unloading curve

$$S = \frac{dP}{dh}(h = h_{\max}) \tag{6}$$

The reduced Young's modulus  $E^*$  is defined by:

$$\frac{1}{E^*} = \frac{1 - v_{ind}^2}{E_{ind}} + \frac{1 - v^2}{E}$$
(7)

where  $E_{ind}$  and  $v_{ind}$  are, respectively, the Young's modulus and the Poisson ratio of the indenter while E and v are, respectively, the Young's modulus and the Poisson ratio of the indented material. In this work, a diamond conical indenter is used. Its elastic constants are  $E_{ind}$ =1140 Gpa and  $v_{ind}$ =0.07. The half-included angle of the cone is 70.3° and the tip radius is 27 nm.

In Eq. (5), *C* is an adjustable shape factor that depends on the indenter geometry. The nanoindentation instrument used in this work was calibrated by indenting fused silica with  $E^*$ =69.6 GPa leading to a shape factor *C*=24.51 while the theoretical value was kept at *C*=24.56.

## 4.1.1. Experimental procedure

Nanoindentation tests are based on a well-defined experimental procedure. Equally spaced indentations are performed starting from the cut edge. Distance between two adjacent indents is 25  $\mu$ m (Fig. 9). The indentations are performed at a constant loading rate. According to the principle of geometric similarity and the results reported by Lucas et al. [22], it could be shown that these experimental conditions correspond to a constant strain rate experiment of  $0.05 \text{ s}^{-1}$  while the maximum penetration depth is about  $3 \mu$ m. With these indentation test conditions, the strain rate influence is taken into account by shifting the obtained yielding stress according to Eq. (2). The quasi static yielding stress  $\sigma_{qs}$  is computed from the measured yielding stress  $\sigma_{mes}$  as follows:

$$\sigma_{qs} = \frac{\sigma_{mes}}{\left(\frac{0.05}{10^{-5}}\right)^{0.0093}} = \frac{\sigma_{mes}}{1.082} \tag{8}$$

Because of the sensitivity of nanoindentation to surface shape (burs, lack of flatness, etc.), the first indent is located at a distance of  $100 \,\mu$ m from the cut edge.



Fig. 10. Load versus penetration curve of nanoindentation tests for different distances from the cut edge.

The measured loads versus penetration for different distances from the cut edge are illustrated in Fig. 10.

The measurements shown in Fig. 10 are used in a finite element inverse analysis of the nanoindentation test in order to estimate the mechanical parameters, characterizing state of material near the cut edge, as for example material work hardening. This model is described in the following section.

## 4.1.2. FE model for the nanoindentation analysis

For simulation of the nanoindentation tests, a solid axisymmetric finite element model is used. To reduce the error on the cost function and its gradients, accurate predictions from the finite element model are required. To meet these requirements, Abaqus/Standard software is used instead of Abaqus/Explicit. The indenter is assumed to be a rigid body and the material Young's modulus is supposed to be the equivalent elastic modulus given by (Eq. (7)).

The size of the discretized domain is  $20 \times 20 \,\mu$ m. This domain is meshed with four-nodded solid axisymmetric elements (Fig. 11).

Because of high gradients near the indenter tip, the mesh is adequately refined. The typical element size in the refined mesh area is about  $0.10 \,\mu$ m. To prevent severe mesh distortion that affects the solution accuracy, the adaptive mesh option is used.

#### 4.2. Inverse identification

The inverse analysis problem is generally formulated as the minimization, with respect to the unknown material parameters, of a suitable cost function that quantifies the overall discrepancy between the measured response and the computed response from the finite element model. In this work SiDoLo software is used for the optimization task. The inverse identification procedure is described in the flow chart given in Fig. 12.

## 4.3. Results

The measurements obtained from the nanoindentation tests were combined with the inverse identification technique to compute the evolution of the yielding stress in the vicinity of cut edge. As the nanoindentation tests were performed at a constant low strain rate, the material behavior is described by a rate-independent elastoplastic constitutive model. Strain rate sensitivity is not required for this analysis because the



Fig. 11. Finite element mesh for the nanoindentation simulation.



Fig. 12. Inverse identification using the nanoindentation measurements.

nanoindentation experiments have been performed at constant strain rate as highlighted in paragraph 4.1. The work hardening is assumed to be isotropic and the yielding stress is approximated by the following equation:

$$\sigma_y = k(\overline{\varepsilon}_p + \varepsilon_0)^n. \tag{8'}$$

To compute the yielding stress from the nanoindentation data (load versus penetration curve) the hardening exponent *n* and the material parameter *k* are assumed to be unchanged by the work hardening. These parameters have been determined from tensile tests (Section 2). The parameter to be calibrated is  $\varepsilon_0$  that represents the initial equivalent plastic strain due to the blanking process. Fig. 13 shows a comparison between the measured response and the computed one after calibration of  $\varepsilon_0$  for the first indent (100 µm from the cut edge). The obtained equivalent plastic strain is about 7.66%. For clarity, the starting response ( $\varepsilon_0$ =0) is also displayed on the same graphic. It should be pointed

out that different methods were proposed for extracting plastic properties from instrumented indentation experiments [23–25]. Compared to these methods, our procedure is very straightforward and it does not require any geometric measurement like imprint size or shape that is a difficult task in general. In addition, the proposed method can be used to calibrate material parameters of general and complex constitutive models.

The calibration is carried out with all data available from nanoindentation measurements to investigate the material work hardening evolution in the vicinity of the cut edge.

In Fig. 14, the evolution of  $\varepsilon_0$  in the vicinity of the cut edge is presented. It compares the results identified from the nanoindentation measurements and the predictions from the blanking simulation. This comparison shows a good consistency between the measurements and the predictions. It should also be noted that the affected zone is well predicted (about 300  $\mu$ m around the cut edge).



**Fig. 13.** Comparison between the measured response and the computed one after inverse calibration ( $100 \,\mu$ m from the cut edge).



Fig. 14. Equivalent plastic strain evolution in the vicinity of the cut edge.



Fig. 15. Yielding stress evolution in the vicinity of the cut edge.

The yielding stress near the cut edge is computed from the results previously described. Fig. 15 gives a comparison between the measured data and the predictions. These results show a significant increase of the yielding stress in the vicinity of the cut edge. Keeping in mind that the material fracture stress is about 410 MPa (Table 1), a good consistency is obtained between the predictions from the blanking simulation and the results from the nanoindentation measurements combined with the inverse identification. Thus they allow the validation of the inverse identification on the nanoindentation test and the predictions from the blanking simulation.

## 5. Conclusion

In this work, the nanoindentation technique and its inverse analysis are used to investigate the material state in the vicinity of the cut edge of blanked parts. The experimental and the numerical results are reported for a non-oriented fully process Fe-(3 wt%) Si alloy.

Some experimental and numerical investigations of the blanking process are carried out leading to the development and validation of a finite element model that predicts the shape of the cut edge and the material state in the vicinity of this area. For the sheet metal constitutive model, rate-dependent plasticity is combined with damage to take account of the ductile fracture of the material. With the help of the developed finite element model, some blanking tests are simulated and the obtained numerical results are compared with the measurements for validation purposes. In order to improve and to complete these validations, the comparisons between the predictions and the measurements are extended to parameters characterizing the material state, like work hardening in the vicinity of the cut edge. The measurements of such quantities are obtained with the help of a nanoindentation test and finite element inverse analysis. The results are then compared with the predictions from the blanking test simulation. These comparisons show a good consistency between the results from the nanoindentation test and the predictions made from the blanking simulation.

Future investigations could take into account a possible correlation between the predicted material state in the vicinity of the cut edge and the degradation of some of its physical properties, like the loss of its magnetic permeability. A predictive model could be developed that would be helpful to evaluate the blanking effect in the field of the design of rotating electrical machines.

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## References

- Johnson W, Slater RAC. Survey of slow and fast blanking of metals at ambient and high temperatures. In: Proceedings of the International Conference on Manufacturing Technology, CIRP-ASTME 1967, p. 822–851.
- [2] Husson C, Correia JPM, Daridon L, Ahzi S. Finite elements simulations of thin copper sheets blanking: Study of blanking parameters on sheared edge quality. Journal of Material Processing Technology 2008;199:74–83.
- [3] Klingenberg W, Singh UP. Comparison of two analytical models of blanking and proposal of a new model. International Journal of Machine Tools & Manufacture 2005;45:519–27.
- [4] Kedous-Lebouc A, Cornut B, Perrier JC, Manfé Ph, Chevalier Th. Punching influence on magnetic properties of the stator teeth of an induction motor. Journal of Magnetism and Magnetic Materials 2003;255:124–6.
- [5] Loisos G, Moses A. Effect of mechanical and Nd:YAG laser cutting on magnetic flux distribution near the cut edge of non-oriented steels. Journal of Material Processing Technology 2005;161:151–5.
- [6] Marouani H, Ben Ismail A, Hug E, Rachik M. Rate dependent constitutive model for sheet metal blanking investigation. Materials Science and Engineering A 2008;487:162–70.
- [7] Marouani H, Ben Ismail A, Hug E, Rachik M. Numerical investigations on sheet metal blanking with high speed deformation. Material & Design 2009;30: 3566–3571.

- [8] Rachik M, Roelandt JM, Maillard A. Some phenomenological and computational aspects of sheet metal blanking simulation. Journal of Material Processing Technology 2002;128:256–65.
- [9] G'sell C, Jonas JJ. Determination of the plastic behavior of solid polymers at constant true strain rate. Journal of Materials Science 1979;14:583–91.
- [10] Peirce D, Shih CF, Needleman A. A tangent modulus method for rate dependent solids. Computers & Structures 1984;18:875-87.
- [11] Belytschko T, Liu WK, Moran B. Nonlinear finite elements for continua and structures. England: John Wiley & Sons LTD; 2001.
- [12] Schreurs PJG, Veldpaus FE, Berkelmans WAM. Simulation of forming processes, using the arbitrary eulerian-lagrangian formulation. Computer Methods in Applied Mechanics and Engineering 1996;58:19–36.
- [13] Gurson AL. Continuum theory of ductile rupture by void nucleation and growth: part I. Yield criteria and flow rules for porous ductile materials. Journal of Engineering Materials and Technology 1977;99:2–15.
- [14] Needleman A. Material rate dependence and mesh sensitivity in localization problems. Computer Methods in Applied Mechanics and Engineering 1988;67:69–86.
- [15] Tvergaard V. Influence of voids on shear band instabilities under plane strain condition. International Journal of Fracture Mechanics 1981;17:389–407.
- [16] Bocciarelli M, Bolzon G, Maier G. Parameter identification in anisotropic elastoplasticity by indentation and imprint mapping. Mechanics of Materials 2005;37:855–68.
- [17] Nakamura T, Gu Y. Identification of elastic-plastic anisotropic parameters using instrumented indentation and inverse analysis. Mechanics of Materials 2007;39:340–56.

- [18] Kermouche G, Loubet JL, Bergheau JM. Cone indentation of time-dependent materials: the effects of the indentation strain rate. Mechanics of Materials 2007;39:24–38.
- [19] Huber N, Tsakmakis Ch. Experimental and theoretical investigation of the effect of kinematic hardening on spherical indentation. Mechanics of Materials 1998;27:241–8.
- [20] Narasimhan R. Analysis of indentation of pressure sensitive plastic solids using the expanding cavity model. Mechanics of Materials 2004 633-45.
- [21] Oliver WC, Pharr GM. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. Journal of Materials Research 1992;7:1564–83.
- [22] Lucas BN, Oliver WG, Pharr GM, Loubet JL. Time-dependent deformation during indentation testing. Materials Research Society Symposium Proceedings 1997;436:233–8.
- [23] Casals O, Alcala J. The duality in mechanical property extractions from Vickers and Berkovich instrumented indentation experiments. Acta Materialia 2005; 53:3545–61.
- [24] Dao M, Chollacoop N, Van Vliet KJ, Venkatesh TA, Suresh S. Computational modeling of the forward and reverse problems in instrumented sharp indentation. Acta Materialia 2001;49:3899–918.
- [25] Kucharski S, Mroz Z. Identification of yield stress and plastic hardening parameters from a spherical indentation test. International Journal of Mechanical Sciences 2007;49:1238:1250.