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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.

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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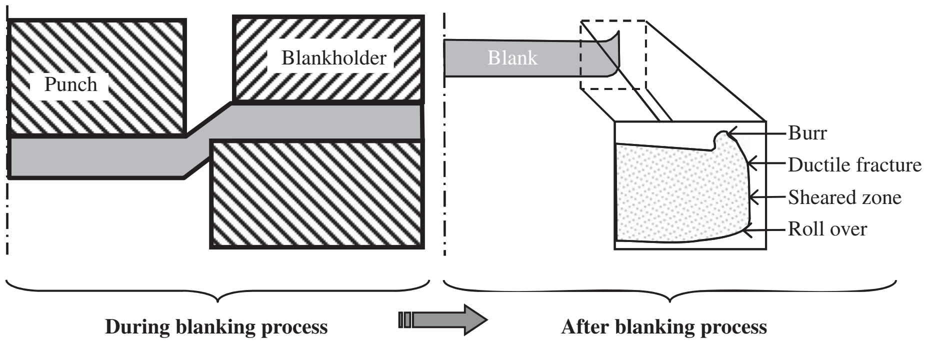

Fig. 1. Schematic description of the blanking process.

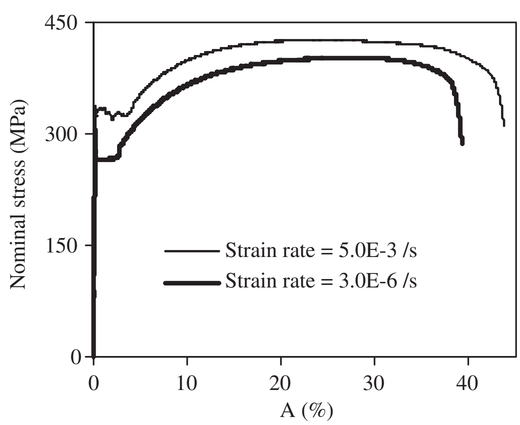

Fig. 2. Tensile test with two strain rates.

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 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 μm.

Table 1
Average mechanical properties of NO Fe-(wt.3%) Si measured with a monotonous uniaxial tensile test.

E (GPa)	σ_e^{max}(MPa)	σ_e^{min}(MPa)	L_p (%)	σ_m (MPa)	A (%)
180–200	293 ± 5	279 ± 8	3–3.5	410 ± 10	35–40

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 (σ_e^{min}) and a maximum (σ_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, σ_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]:

$$\sigma_y = k\bar{\varepsilon}_p^n \left(\frac{\dot{\bar{\varepsilon}}_p}{\dot{\bar{\varepsilon}}_{p0}} \right)^m \quad (1)$$

where σ_y is the yielding stress, $\bar{\varepsilon}_p$ the plastic strain and $\dot{\bar{\varepsilon}}_p$ the plastic strain rate. k, n and m are the parameters representing material strengthening. $\dot{\bar{\varepsilon}}_{p0}$ 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]:

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

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-