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A Grain Structure Model based on Voronoi polygon of Non-oriented Electrical Steel in Blanking Process

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Abstract. World-wide there is a trend to develop higher permeability grades, thin thickness and coarse grain of non-oriented electrical steels, a core function material of motors. Blanking is the most popular technique for producing the motor laminations. However, the deformation of material is significantly influenced by grain size. In this paper, Voronoi polygon is used for generate the random microstructures of the studied non-oriented electrical steel. Finite Element (FE) model considering grain size is thus established to analysis the blanking process. The material behaviour of grains is derived from the widely accepted surface layer model. Compared to the conventional model without considering the grain size, the novel model shows good matching with the experimental results.

1. Introduction

Due to the energy and environmental protection, non-oriented electrical steel with higher permeability grade, thin thickness (0.3-0.6mm) and coarse grain (50-150μm) becomes the major product. In order to producing the motor laminations efficiently, blanking is the most popular manufacturing technique. Plenty of prior studies show that the deformation is significantly influenced by grain size. Therefore, how to study the blanking process with considering grain size is of great importance.

The grain size effect on polycrystal material is generally expressed by the famous surface layer model. Peng et al. [1] and Fu et al. [2] used the surface layer model to study the flow and deformation behaviours, which is widely accepted in many micro-scaled forming processes. In order to modeling the micro grain structures of polycrystal materials, Cao et al. [3] and Gao et al. [4] adopted the Voronoi method for investigating the plastic deformation in microforming process.

Grain size effect in blanking process was mainly investigated via experiments. Xu et al. [5] innovatively investigated the grain size effects in micro-blanking test and established a grain size phenomenological model of blanking process. However, grain size effect in blanking process using FE method need be paid more attention.

Therefore, this paper aims at addressing this issue via development of a grain structure model. To realize this thought, the Voronoi polygon and surface layer model are used to establish the grain structure model. The simulation and experiment results are compared and the proposed grain model is verified.

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2. Grain Structure Modelling

2.1. Material

High-grade non-oriented electrical steel B30AHV1500 (Baosteel Co., Ltd, Shanghai, China) is selected for the study. The chemical composition is shown in Table 1. With the help of Baoteel Company, some samples in different anneal stages (800℃,900℃,950℃,1000℃) are obtained. The metallographic images across the sheet thickness section and in-plain section are shown in Fig.1.

Table 1. Chemical composition of the investigated non-oriented electrical steel.

Element	Si	Al	Fe
Mass Fraction(%)	3.3	0.7	96.0

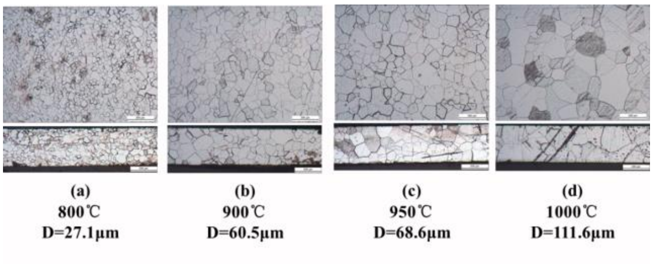


Figure. 1. Metallographic structure of non-oriented electrical steel samples under different anneal stage: (a)800℃ (b)900 ℃ (c) 950℃ (d)1000 ℃.

According to the hypothesis of surface layer model, the polycrystalline metal sheet is considered to consist of surface and internal grains, the flow stress can be represented as follows:

$$\begin{cases} \sigma_{sm}(\varepsilon) = \eta\sigma_s(\varepsilon) + (1-\eta)\sigma_i(\varepsilon) \\ \sigma_s(\varepsilon) = \mathrm{m}\tau_R(\varepsilon) \\ \sigma_i(\varepsilon) = M\tau_R(\varepsilon) + k(\varepsilon)\cdot D^{-1/2} \\ \eta = N_s/N \approx D/t \end{cases} \quad (1)$$

In Eq.(1) $\sigma_{sm}(\varepsilon)$ and N are the flow stress and grain number of the specimen, $\sigma_s(\varepsilon)$ and N_s are the flow stress and number of the surface grains, $\sigma_i(\varepsilon)$ is the flow stress of internal grains, D is the grain size, t is the thickness of metal sheet, $\tau_R(\varepsilon)$ is the critical shear resolved stress of single crystal, $k(\varepsilon)$ is the locally intensified stress needed to propagate general yield stress across the polycrystal grain boundaries, m and M are the orientation factors of the surface and internal grains. M is known as 3.06 and m is known as 2.0 for BCC material based on Taylor's Model [2].

To identify the flow stress curves of the surface and internal grains, the flow curves of the different samples at room temperature are first obtained by uniaxial tensile tests, then the hypothetic equation of $\tau_R(\varepsilon)$ and $k(\varepsilon)$ can be calculated using the least square fitting method. Fig.2 shows the results of surface layer model.

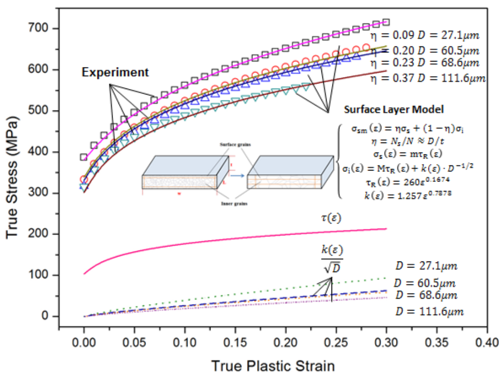


Figure 2. Results of surface layer model

2.2. FE model

In this paper, according to the average grain size, the Voronoi polygon is generated via a code in software Matlab to model the grain structure. Through the software interface, the geometric model was introduced into ABAQUS/CAE using python language (Fig.3). Different material properties of grains are assigned to geometric parts according to the hypothesis of surface layer model. A compared conventional model without grain structure is also established.

The blanking process is assumed to be plane strain situation and the finite element code ABAQUS/Standard is used to simulate the blanking operation in 2D. The blanking region is set to 0.30 mm×0.30 mm and the mesh of the region is defined very dense (element size: 0.005 mm). The right of blanking region is constrained against movement in any direction and the left is symmetrically constrained. 4-node bilinear plane strain quadrilateral elements with reduced integration (CPE4R) and hourglass control are used. A coulomb friction model is used to represent the contact between the plate and the tools with a friction coefficient value equal to 0.1. The punch and die are assumed to be rigid bodies. The punch-die clearance is set to 0.045 mm, which is same with the experiment. The Arbitrary Lagrangian Euleurian (ALE) technique is used to avoid element distortion in the sheared section. Then the FE model based on the Voronoi polygon is established (Fig.3b).

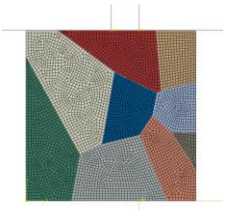


Figure 3. FE model based on the Voronoi polygon

2.3. Fracture Strain

In order to simulate the fracture of blanking process, Digital Image Correlation (DIC) method is adopted to measure the fracture strain more precisely. Fig.4a shows the strain distribution just when the crack occurs and the equivalent fracture strain is 0.241. From Fig. 4b, the fracture mode of the studied non-oriented electrical steel is transgranular fracture. Therefore, it is assumed that the fracture strain in uniaxial tensile test can also be suitable in blanking process. In the FE model, element suicides when the strain reaches the critical fracture strain.

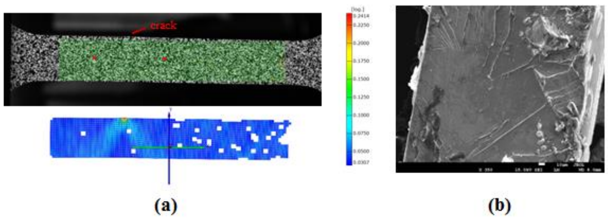


Figure 4. Fracture analysis: (a) DIC test; (b) SEM image.

3. Results and discussion

3.1. Verification of FE model

Grain structure model based on Voronoi polygon are first analysed by uniaxial tensile simulation. By controlling the displacement of the edge in the FE model, the total elongation of the whole grain structure model and the total reaction force on the edge are respectively calculated. Then the flow curve of the whole grain structure model can be obtained.

Fig.5 shows the comparison between the simulation and experiment. The simulation results coincide well with the experimental data, which verifies the fine feasibility of the Grain structure model.

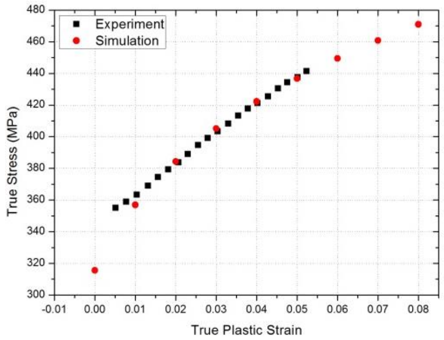
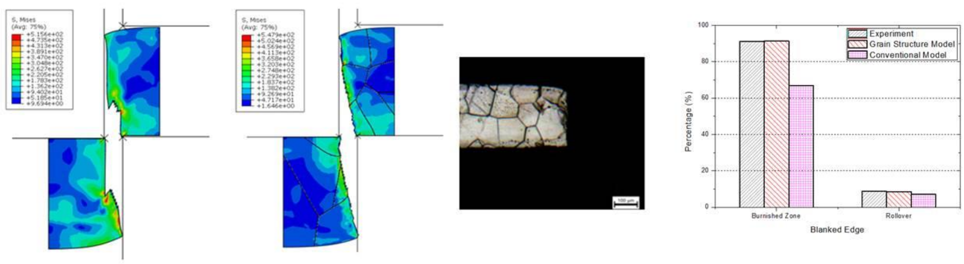


Figure 5. Comparison between the simulation and experiment

3.2. *Blanking process*

The simulation of blanking process is conducted using the grain structure model and the conventional model. The simulation and experiment results are shown in Fig.6, it is found that the fracture mechanism is transgranular fracture due to the coarse grain. The blanked edge is flat and without tensile fracture. The grain structure model can clearly predict the real blanked edge and the conventional model is not suit for the situation.



(a) **(b)** **(c)** **(d)**

Figure 6. Simulation and experiment results: (a) Conventional Model (b) Grain Structure Model; (c)Experiment result; (d)Distribution of blanked edge

4. Conclusion

In this paper, the FE simulation and experiments are conducted to investigate the blanking process. It can be concluded that when the scale of grain size is close to the punch-die clearance, the conventional FE model is no longer suit for blanking prediction. A grain structure model based on Voronoi polygon can be adopted in FE simulation. The good match with experiment results demonstrates the feasibility of the novel model.

5. Acknowledgements

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