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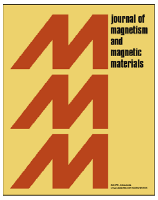

The influence of punching process on residual stress and magnetic domain structure of non-oriented silicon steel

Hongzhi Cao [a], Linpo Hao [a], Jingwen Yi [a], Xianglin Zhang [a,*], Zhonghan Luo [b], Shenglin Chen [b], Rongfeng Li [c]

[a] State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] National Engineering Research Center for Silicon Steel, Wuhan Iron and Steel Group Corp, Wuhan 430080, China
[c] Research and Development Center, Wuhan Iron and Steel Group Corp, Wuhan 430080, China

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ABSTRACT

The main purpose of this paper is to investigate the influence of punching process on residual stress and magnetic domain structure. The residual stress in non-oriented silicon steel after punching process was measured by nanoindentation. The maximum depth was kept constant as 300 nm during nanoindentation. The material around indentation region exhibited no significant pile-up deformation. The calculation of residual stress was based on the Suresh theoretical model. Our experimental results show that residual compressive stress was generated around the sheared edge after punching. The width of residual stress affected zone by punching was around 0.4–0.5 mm. After annealing treatment, the residual stress was significantly decreased. Magnetic domain structure was observed according to the Bitter method. The un-annealed sample exhibited complicated domain patterns, and the widths of the magnetic domains varied between 3 μm and 8 μm. Most of the domain patterns of the annealed sample were 180°-domains and 90°-domains, and the widths of the domains decreased to 1–3 μm.

1. Introduction

Non-oriented silicon steel with excellent magnetic properties is widely used for motor cores which are manufactured by shearing and punching process. It is well known that the residual stress produced on shear edge due to the punching process would deteriorate the magnetic properties of non-oriented silicon steel. Minimizing the stamping affected zone is an effective way to reduce the iron loss of motors [1,2]. Therefore, it is important to investigate the residual stress distribution after punching.

A variety of methods were introduced to measure residual stress: neutron diffraction [3], XRD method [4,5], hole-drilling [6], layer removal [7], Raman spectroscopy [8], ultrasonic [9], etc. However, these methods are somewhat restricted by accuracy, spatial resolution, and operational complexity in a practical situation. XRD and hole-drilling methods are mainly used in the residual stress measurement for silicon steel. However, for non-oriented silicon steel, the width of degraded area affected by punching process was confirmed to be less than 1 mm [10], which is comparable to or even smaller than the spatial resolution of both XRD and hole-drilling methods. Nanoindentation has been widely used to characterize various mechanical properties [11–13], such as elastic modulus, hardness, fracture toughness, etc. Recently, many achievements were made on residual stress estimation based on nanoindentation [14–16]. Zhang et al. [17] studied the residual stress in the 304 stainless steel by the nanoindentation method. In their research, the residual stress was 381 MPa, which was very close to that tested by the XRD method (350 ± 23 MPa). According to Zhu et al. [18], the measurement of the residual stress in quenched 1045 steel was based on nanoindentation as well. The calculated residual stress was -117 ± 20 MPa, while by XRD, it was -114 ± 32 MPa. In conclusion, nanoindentation is a promising method to measure residual stress.

In this research, the distribution of residual stress on the sheared edge of non-oriented silicon steel was determined by the nanoindentation method, taking advantage of its high resolution and accuracy. The relation between residual stress and magnetic domain is important for magnetic research of silicon steel, but little has been reported about it [19,20]. Hereby, we explored the effect of the punched stress on the magnetic domain structure. The domain structure was observed by Bitter method with Fe_3O_4 nanoparticle magnetic fluid.

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[*] Corresponding author.
E-mail address: hust_zxl@mail.hust.edu.cn (X. Zhang).

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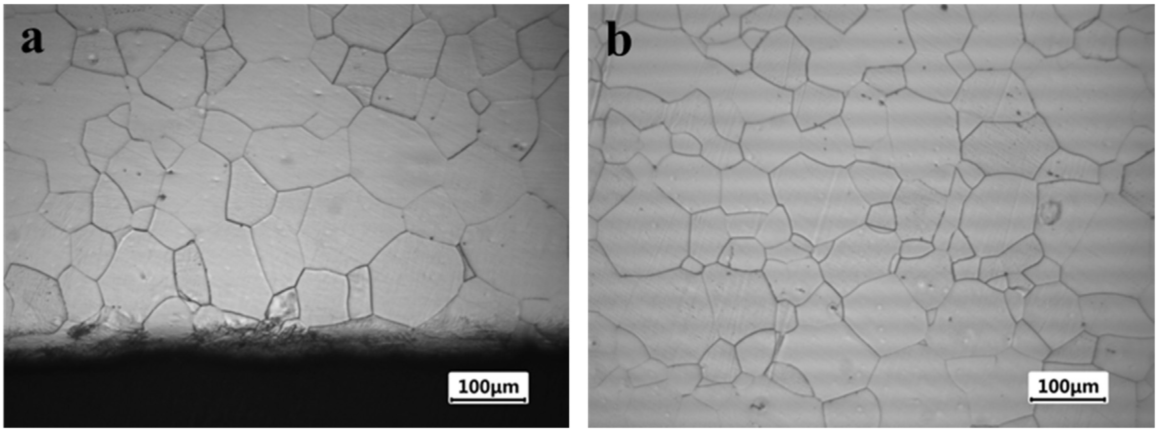

Fig. 1. Microstructures of 50WW470 (a) edge of the sample, (b) central of the sample.

2. Experiments

2.1. Sample Preparation

The cold-rolled non-oriented silicon steel sheets (brand 50WW470) from WISCO (Wuhan Iron and Steel Corporation) were punched for circular shape of 20 mm in diameter. The clearance between punch and die was 8% of the thickness. Table 1 and Fig. 1 show the properties and the microstructures of 50WW470 respectively. Two samples with different post processing were analyzed. One was annealed at 750 °C for two hours and then furnace-cooled to relieve the residual stress, marked as AN-S. This sample was used as the baseline. No heat treatment was done on the other one (un-annealed), marked as UAN-S. The surfaces of both samples were mechanically grounded and polished to meet the surface roughness requirements of the nanoindentation experiment. Finally, all the samples were cleaned with ethanol.

2.2. Nanoindentation

2.2.1. Experimental process

The samples were measured by nanoindentor (TI750 TriboIndenter; Hysitron Corporation, USA) with the displacement and load accuracy of 0.2 nm and 3 nN, respectively. Berkovich indenter was applied in the experiment. Depth control was used to keep the maximum displacement constant as 300 nm. For each sample, 23 points were tested at same depth with 25 μm as an interval from the edge to the center, as shown in Fig. 2. In the center of AN-S sample, three random points were selected to test, and the average of the contact areas of the three points was used as reference (A_0).

2.2.2. Theoretical model

The Suresh theoretical model was utilized to calculate the residual stress with constant depth [21]. The measurement of residual stress is based on the calculation of the difference between the indentation contact areas of stressed and stress-free samples through analyzing the indentation load-depth data, as shown in Eqs. (1) and (2).

Table 1
The properties of 50WW470.

Element	Content	Mechanical properties	Value
Fe	> 97.4%	Thickness	0.5 mm
Si	2.0%	Density	7.70 Kg/dm^3
Mn	0.25%	Tensile strength	450 MPa
Al	0.25%	Hardness/Hv	155
P	≤ 0.02%	Iron loss/$P_{1.5/50}$	4.00 W/kg
S	≤ 0.005%	Intensity of magnetization/B_{5000}	1.64 T
C	≤ 0.007%	N/A	N/A

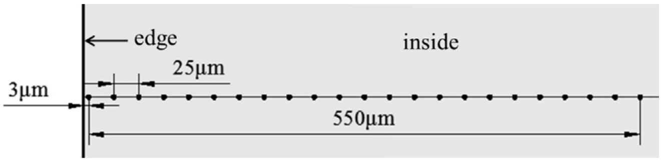

Fig. 2. Distribution of the points position.

$$\sigma^R = H\left(\frac{A_0}{A} - 1\right)$$

Equation for tensile residual stress (1)

$$\sigma^R = H\left(1 - \frac{A_0}{A}\right)\sin\alpha$$

Equation for comprehensive residual stress (2)

where A and A_0 are the indentation contact areas of the samples with and without residual stress, respectively. H is the hardness. α is the angle between indenter tip surface and sample surface. For a Berkovich indenter, $\alpha = 24.7°$.

In the nanoindentation experiment, the parameters for residual stress calculation were determined by the relations derived from the theory of contact mechanics and the Oliver–Pharr method [22]. The sign of the residual stress depends on the load-depth curves of indentation. Compared to the unstressed sample, the one with compressive residual stress requires larger contact load. Conversely, smaller contact load is required with tensile residual stress, in terms of constant depth [23].

2.3. Bitter method

The main reagents are $FeCl_3 \cdot 6H_2O$, $FeCl_2 \cdot 4H_2O$, NaOH, hydrochloric acid, sodium oleate and SDBS. Specialized equipment includes electronic balance, precise motor-driven stirrer, digital water bath with constant temperature, ultrasonic disperser and high-speed centrifuge.

Fe_3O_4 nano-magnetic fluid was prepared by coprecipitation method. $FeCl_3 \cdot 6H_2O$, $FeCl_2 \cdot 4H_2O$ and NaOH were used to prepare Fe_3O_4 nanoparticles. Magnetic nanoparticles tend to agglomerate due to large specific surface area, high surface energy and large magnetism. In order to avoid agglomeration, sodium oleate and SDBS (Sodium Dodecyl Benzene Sulfonate) were used as the