Journal of Magnetism and Magnetic Materials 392 (2015) 126–133

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Investigation of the influence of different cutting procedures on the global and local magnetic properties of non-oriented electrical steel

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ARTICLE INFO

Article history:
Received 10 February 2015
Received in revised form
17 April 2015
Accepted 12 May 2015
Available online 14 May 2015

Keywords:
Magneto-optical Kerr-effect
Influence of cutting
Magnetic properties
Non-oriented electrical steel

ABSTRACT

The process of manufacturing iron cores for electric machines out of electrical steel sheets can strongly affect the magnetic properties of the material. In order to better understand the influence of cutting on the iron losses, a characterization of the magnetization behavior near the cutting edge is needed. The local magnetic properties of the material are modified by the cutting process which leads to an increase in the iron losses measured for 5 mm wide ring core samples by nearly 160% at low inductions. We present investigations on the effect of cutting by observation of the magnetic domain structure of 0.35 mm thick non-oriented electrical steel. By using the magneto-optical Kerr-effect on a ring samples the local magnetic properties of the material after processing are characterized in the form of domain wall displacements under an applied external ac-field. The influence of various cutting techniques on the magnetic properties was studied before and after stress relief annealing. This method allows a quantitative analysis of the influence of different cutting techniques on the micro-magnetic properties of non-oriented electrical steel for rotating machines.

1. Introduction

For stator and rotor cores in rotating machines non-oriented electrical steel is used for flux conduction. In order to shape these cores electrical steel sheets have to be cut in laminations. Various cutting operations like punching, laser cutting and spark erosion can be used, which induce stresses inside the material close to the cutting edge. Due to these stresses the magnetic properties of the material are deteriorated which can be determined by an integral measurement of the magnetization curve of the bulk material. Previous works tried to identify the local magnetic properties near the cutting edges by using needle probes [1–3]. Local magnetic properties after punching have also been investigated with spatially resolved measurements [4] or using a single-sheet-tester with repeatedly cut sheets to determine the influence of the cutting length in relation to the sample volume [5,6]. The effect of punching and shearing was investigated by imaging the domain structure by using the magneto-optical Kerr effect [7]. In other works [8,9] the authors observed additionally the domain wall movement by applying an ac-field to a processed lamination, but without particularizing the discreet manner how the field is applied into the sample.

In this paper the authors will present fundamental investigations on the effect of different cutting procedures using microscopic analysis and integral measurements of the magnetic properties. In order to analyze the local magnetic properties of the cut specimen near the edges a method was developed using the magneto-optical Kerr-effect (MOKE) [10]. The aim is to visualize the local influence of cutting on the magnetization behavior in form of magnetic contrast. Several cutting techniques have been compared with respect to their magnetic contrast before and after stress relief annealing. The results of the microscopic investigations are compared with integral measurements of electrical loss. The investigations were made on a fully processed commercial electrical steel grade (as used for stator and rotor cores of electrical machines in electrical and hybrid vehicles), and will therefore be useful for optimization of the manufacturing process and reduction of loss in electrical machines.

2. Experimental procedure

Fully processed non-oriented electrical steel with a thickness of 0.35 mm was used for this study. The specimens were taken from neighboring parts in the center of a mother coil to guarantee constant material properties. The most important metallurgic parameters for the magnetic properties are as follows: average grain size of 96 μm and chemical composition with 2.8% silicon,

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http://dx.doi.org/10.1016/j.jmmm.2015.05.031
0304-8853/

0.4% aluminum and 0.2% manganese content.

A CO_2 laser was used to cut the material at a power of 1500 W, a speed of 20 m/min and a N_2-gas stream of 10 bar. The punching machine was operated at 100 cuts/min with a lift of 44 mm using sharpened blades and a clearance of 0.02 mm. Reference samples showing magnetic properties not affected by heat or mechanical deformation have been produced by electrical discharge wire cutting (spark erosion). The spark erosion was performed using a brass wire at a diameter of 0.25 mm placed in a water quench. To recover the original material properties after the cutting process, stress relief annealing was performed under nitrogen atmosphere at 820 °C for three hours with a cooling phase of two hours.

To get a first impression of the effect of cutting the microstructure of the edge profiles of the cut samples was examined [11]. The integral magnetic properties, in particular core losses at 50 Hz and 400 Hz, hysteresis and magnetization curve, were determined using field-metric measurements on ring core samples as specified in DIN 50460 [12]. The cut laminations with an outer diameter of $D=55$ mm and an inner diameter of $d=45$ mm were stacked insulated from each other to a height of 5 mm. The magnetic field exciting the ring at the observed area was calculated according to Eq. (1), with $n=100$ for the number of windings, I for the applied current and l_m for the magnetic path length. To calculate the average magnetic field over the cross section of a ring the magnetic path length is calculated using Eq. (2).

$$H = \frac{n^*I}{l_m} \tag{1}$$

$$l_m = \pi\frac{D-d}{\ln\left(\frac{D}{d}\right)} \tag{2}$$

In order to analyze the micro-magnetic properties of the electrical steel near the cutting edge a method was developed using the magneto-optical Kerr-effect (MOKE). The domain observations were made using a Zeiss microscope with high stage stability equipped with a Hamamatsu image processing system. As specimens one lamination of the stacked rings used for the integral magnetic measurement was taken. These rings were embedded and primed. In order to get a smooth surface necessary for the Kerr-microscopy a final oxide polishing with colloidal silica was used to finish of the surface. For the introduction of a magnetic field the ring was cut out and coiled up with 100 windings, as shown in Fig. 1(a).

To determine the magnetic flux and field distributions inside the ring the setup was simulated using FEM. The whole flux goes through the ring because of the high permeability of the steel and no flux concentration could be observed.

Fig. 1(b) shows the domain structure of the punched specimen near the cutting edge in the demagnetized state obtained with the Kerr microscope from the observed surface, marked in (a). The domains can directly be observed even near the cutting edge (as seen in the box). This technique allows observing the domain wall movement in real time while applying an external magnetic field to the specimen. Under the conditions used here, the main contribution to the contrast originates from the longitudinal Kerr effect.

The aim of this investigation is to image the domains that have changed during an applied ac-field with specific field amplitude. In this way, regions of the sample may be identified where the magnetization reversal process has already started at the applied magnetic field. The difference image method [13,14] was used for this purpose. In this method a reference image is recorded by averaging 32 images while applying an external 50 Hz ac-field with given amplitude. After turning off the ac-field a demagnetized domain state is visible, from which the reference image is subtracted in the next step. The result is an image of the domains in regions where the contrast changed during ac-field application. The regions in which the contrast did not change show no contrast after subtraction of the reference image and appear gray. Fig. 2 shows a schematic representation of the subtraction procedure [10].

The investigations were made on several places close to the edges of the specimens; the figures show representative domain images. As a reference, domain structures inside the bulk of the material were obtained by imaging regions in the middle of the rings which are far away from the cutting edges to minimize the influence of the cutting process. Fig. 3 shows representative domain patterns of such unaffected regions.

3. Results and discussion

3.1. Examinations before annealing

First the microstructure of the cut specimen was examined. Optical micrographs of the cross sections of the cutting edges made after polishing and grain boundary etching with nital are shown in Fig. 4. The direction of cutting is marked, the edge is on the outer diameter. As expected, spark erosion (Fig. 4a) leaves no visible traces of deformation on the surface, the cut edge is straight due to the procedure. The punched edge (Fig. 4b) shows the typical burr (circle) and a zone of plastic deformation (arrow) on the other side [4]. Laser cutting with a CO_2-laser (Fig. 4c) leaves a smooth edge and no traces of plastic deformation are visible within the material. The observed profile of the laser cut edge can

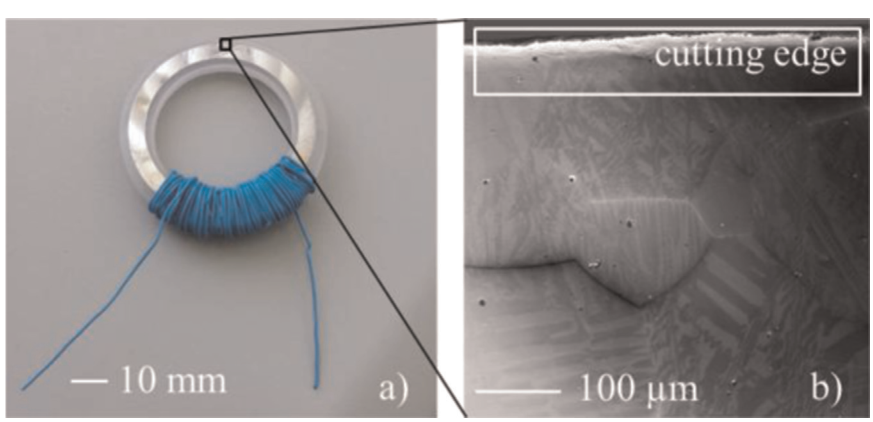

Fig. 1. (a) Primed and winded specimen used for the MOKE investigations and (b) domain pattern at the punched edge.