Size Effects at Laser Cutting and Mechanical Cutting on the Magnetic Properties of Fe-Si Steels

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***Abstract*—The deterioration of the microstructure near the cutting line and the appearance of residual stresses affect the magnetic properties of cut parts. In this paper, the differences in the resulting microstructure at mechanical cutting and laser cutting as well as the observed effects of the size of the samples on the magnetization behavior will be described and discussed. It will be pointed out that the underlying mechanism for the changes in the magnetic properties is different for mechanical cutting and laser cutting.**

***Index Terms*—Cutting process, Magnetic anisotropy, Magnetic deterioration, Silicon steel**

I. Introduction

It is well established that different cutting techniques affect the properties in the zone near the cut in a different way [1]–[8]. At mechanical cutting, plastic deformation becomes clearly visible near the cutting line, while laser cutting induces a thermal shock wave, which results in thermal stresses. As a consequence, the magnetic properties of the material near the cut are influenced. The changes in the microstructure at the cutting edge have been intensively investigated by micro-hardness measurements, by looking at changes in the grain morphology with for example optical microscopy and by the evaluation of variations of the crystallographic texture and of the occurrence of misorientation gradients by using Electron Backscatter Diffraction (EBSD) [1], [2], [4]. Also the flux magnetic distribution variation near the cutting edge was studied [3], [9]. Micro-hardness [4] and flux density variation [3] measurements near the cutting edge indicate much less deterioration of the magnetic properties after laser cutting compared to mechanical cutting. Much less attention has been paid to the deterioration of the resulting magnetic properties: i.e. magnetization behavior (permeability) and specific magnetic losses as a function of the size of the samples after applying different cutting techniques. In this paper, the differences in the resulting microstructure between mechanical and laser cutting as well as the observed effects of the sample size on the magnetization behavior will be described and discussed.

II. Experimental Procedure

The investigated samples comprise conventional Fe-Si steels with variable chemical composition and grain size as well as FeSi6.5. Strips of different width (5mm to 30mm) as well as rings with different inner radius R_i and fixed outer radius R_a, i.e. ($R_a - R_i$ = 15, 10, and 5 mm), were prepared by mechanical and by laser cutting. The microstructure was studied by optical metallographic investigations and by EBSD. The microhardness as a function of the distance from the cutting edge was measured using a Zwick® machine with a load of 0.2kg. The hysteresis loops were observed using a Brockhaus® magnetic measurement unit.

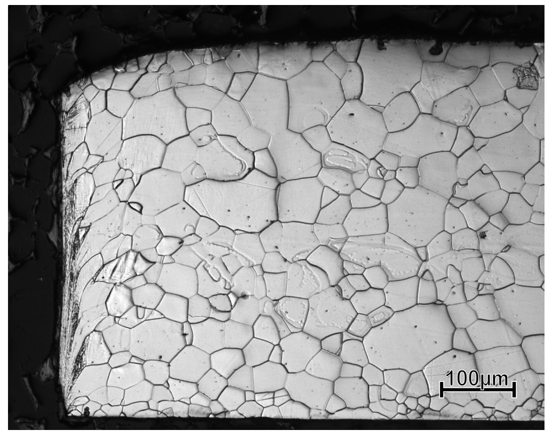

Figure 1. Optical micrograph of a Fe-Si steel with medium Si-content after mechanical cutting.

III. Results and Discussion

A. Microstructure

Fig. 1 shows the grain morphology of a Fe-Si steel with medium Si-content after mechanical cutting. As described in literature [1], [2], [4] the plastic deformation near the cutting line (left side of the figure) can be clearly seen. As is shown in Fig. 2, laser cutting does not induce any changes in the grain morphology in the area near the cutting line. This was also reported in literature [1], [2], [4].

Fig. 3 demonstrates the texture evolution starting from an area near the cutting edge for a sample prepared by laser cutting by making use of the φ_2=45° section of an Orientation Distribution Function (ODF) obtained by EBSD. The same sample as shown in Fig. 2 was measured and ODFs were calculated starting at the cutting edge including all grains for a distance of 50μm (region A) and 140μm (region B) as well as inside the material. Although the statistics are rather poor, because of the small number of grains in the area affected by laser cutting, it was observed that in the A and B area orientations appeared that were away from the gamma fibre

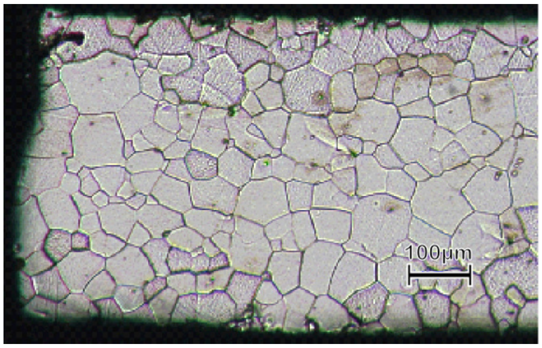

Figure 2. Optical micrograph of a Fe-Si steel with medium Si-content after laser cutting.

({111}<uvw>). The intensity lines on the ODFs of region A are mainly concentrated along the {h11}<1/h,1,2> fibre. The extension of the zone with different orientations compared to the orientations inside the material is smaller than 200 μm. The effect of these changes in the orientation seems to be not relevant for the magnetization behavior compared to the effect by the induced internal stresses at laser cutting. Also mechanical cutting gives rise to many changes in the crystallographic orientations near the cutting line. Due to the heavy cold deformation, it appeared to be very difficult to obtain an acceptable quality of indexation of the diffraction patterns during EBSD measurements. This was reported in similar work by M'Saoubi and Ryde [8]. Therefore, no details could be retrieved from these measurements on local orientation changes and gradients. The limited data that became available from the measurements revealed that the extent of the region with orientation changes was similar to the case of laser cutting.

B. Microhardness

Fig. 4 a and b show the microhardness (Vickers) as a function of the distance from the cutting line for the same Fe-Si steel after mechanical and laser cutting. While there is an increase of the microhardness in the area near the cutting line for mechanical cutting, the microhardness is more or less constant after laser cutting. Similar observations have been realized for quite different steels in [2], [4], [8]. We observed that the zone with increased values of the microhardness after mechanical cutting may go up to 1000 μm or even higher [4]. This observation can be correlated with the fact that the cold deformation remains present after mechanical cutting, while laser cutting is a high temperature process that does not inflict a higher hardness on the material.

C. Magnetic Measurements

Fig. 5 represents the hysteresis loops for the laser cut rings of conventional Fe-Si steel with different inner radius R_i and fixed outer radius R_a, i.e. ($R_a - R_i$ = 15, 10, and 5 mm) and an Epstein strip cut by laser with a width of 30mm of the same material. Fig. 6 shows the hysteresis loops for strips of FeSi6.5 also cut by laser with a width of 30, 15,

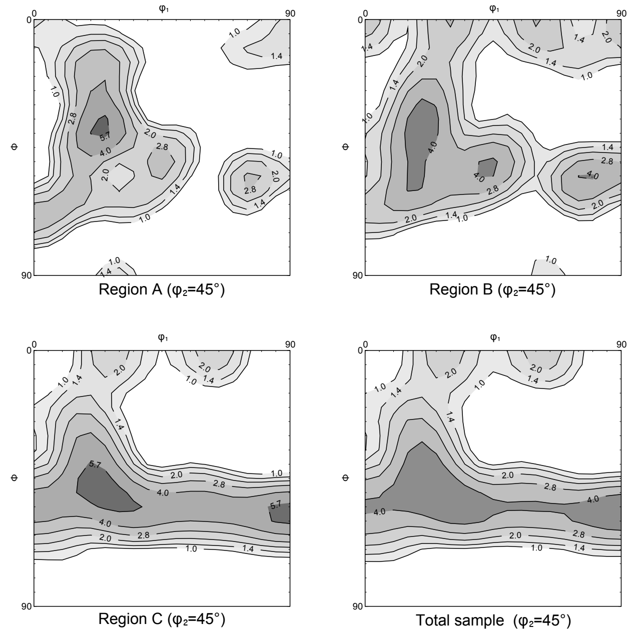

Figure 3. φ_2=45° section of ODF obtained by EBSD of a Fe-Si steel with medium Si-content after laser cutting as a function of the distance from the cutting edge: A - 50μm; B - 140μm; C - inside the material. Levels: 1.0 - 1.4 - 2.0 - 2.8 - 4.0 - 5.7.

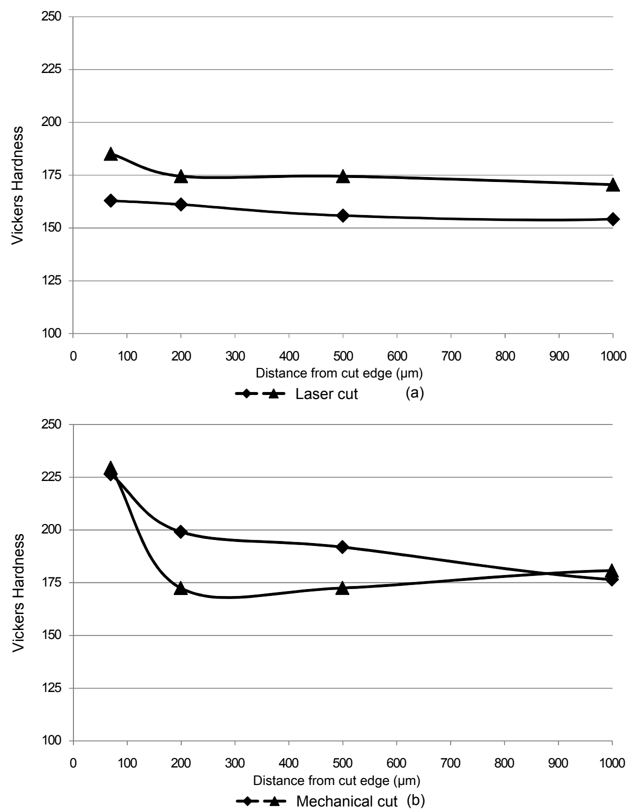

Figure 4. Microhardness of a Fe-Si steel with medium Si-content after laser cutting (a) and mechanical cutting (b).

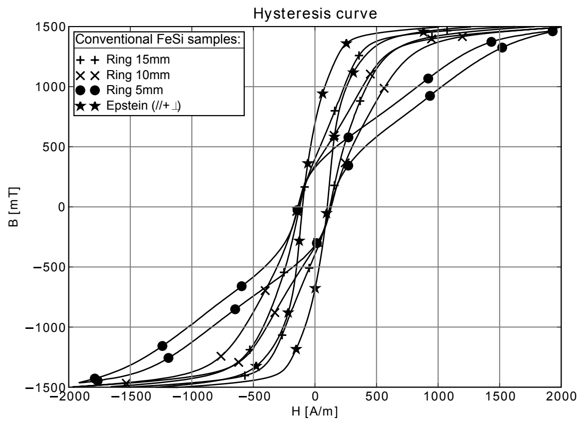

Figure 5. Hysteresis loops for laser cut rings of conventional Fe-Si steel with different inner radius R_i and fixed outer radius R_a. ($R_a - R_i$ =15, 10, and 5 mm); applied field strength up to 2000A/m.

10, and 5mm. In addition, Fig. 7 gives the hysteresis loops for a strip and a ring of FeSi6.5 both cut by laser and with a width of 5mm. All the loops have been measured in maximum fields up to 2000A/m as well as 5000A/m. The observed hysteresis loops indicate clearly a ”size effect”. There appears qualitatively no difference between ring and strip samples as shown in Fig. 7. The magnetizing behavior becomes increasingly worse, and the permeability decreases, at decreasing width compared to the Epstein strip in the induction range of 0.5T to 1.5T. The decrease of the permeability in the induction range of 0.5T to 1.5T is much smaller for samples of FeSi6.5 prepared by laser cutting. The coercive field strength when the maximum field goes up to 2000A/m is practically the same for all the ring samples despite the quite different widths as can be seen from Fig. 6. The same observation holds for the strip samples of conventional Fe-Si and of FeSi6.5 (Fig. 6 and Fig. 7). However, the value of B_r decreases with decreasing value of the width in both cases: i.e. for rings and strips. The lower values of B_r lead to lower values of the permeability, as observed. This may be attributed to the appearance of an additional magnetic anisotropy with a preferred axis perpendicular to the applied field direction. This may be originated by a semi macroscopic residual stress in the samples obtained by laser cutting. During laser treatment biaxial stresses: tensile as well as compressive stresses appear as was demonstrated elsewhere [10], [11]. The resulting stress-induced magnetic anisotropy is proportional to the magnitude of this residual stress and the value of the magnetostriction. The lower values of the magnetostriction for FeSi6.5 compared to the conventional Fe-Si steel materials may explain why the effect is much larger in the case of the conventional Fe-Si steels. This explanation is supported by the fact that we observed even larger effects for soft magnetic samples, which exhibit a larger value of magnetostriction compared to the Fe-Si steels.

Comparing the obtained results for mechanical cutting and laser cutting a quite different behavior is observed. While for the same Fe-Si material grade as in Fig. 5 after mechanical cutting and magnetizing the sample to 1.0T at 50Hz a decrease of the induction B in the area at the cutting line were observed in [3], no such decrease appears for laser cutting. The area, where a decrease of the induction B is observed after mechanical cutting correlates with the area of enhanced microhardness, which may originate from the elastic and plastic deformation at mechanical cutting. The observed decrease in permeability with decreasing value of the width of the strips, and the increase of the magnetizing field, in the range of 0.5T up to 1.5T after mechanical cutting of conventional Fe-Si steels [6], [7] show a clear dependence of the mean grain size of the material as shown in Fig. 8 [12].

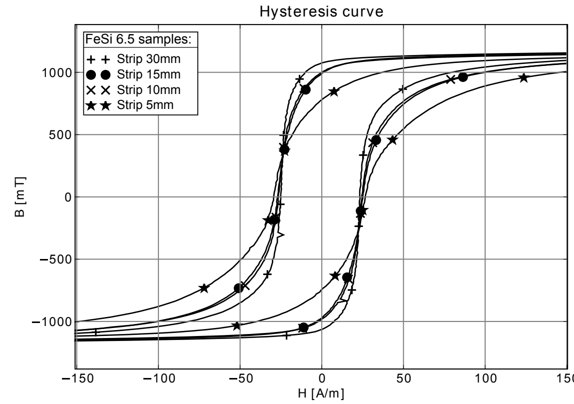

Figure 6. Hysteresis loops for laser cut strips of FeSi6.5 with a width of 30, 15, 10 and 5mm; applied field strength up to 2000A/m.

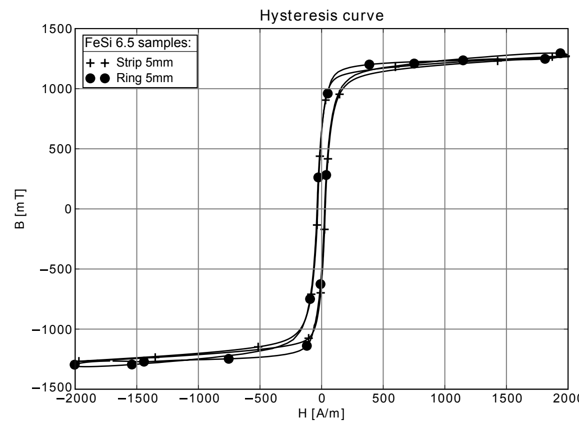

Figure 7. Hysteresis loops for a laser cut ring and strip of FeSi6.5 with a width of 5mm; applied field strength up to 2000A/m.

IV. Conclusions

The observed changes of the microstructure and the appearance of residual stresses affect the magnetizing behavior in quite a different way. Local changes of grain size and texture result in local changes of the critical field for domain wall movement. Stress induced magnetic anisotropy gives rise to changes of the remanent induction and the permeability at

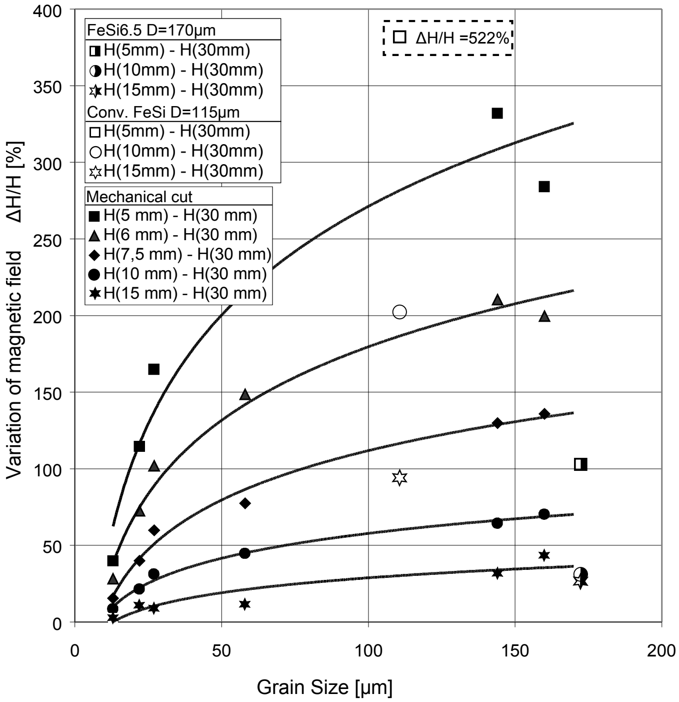

Figure 8. Increase of the magnetizing field ΔH to reach B =1T as a function of the grain size at mechanical cutting [12] and data for laser cut samples; $\Delta H = H_x - H_{30mm}$.

higher applied magnetic fields. The grain morphology of the samples of conventional Fe-Si prepared by laser cutting, as shown in Fig. 2, is the same in the area near the cutting line as inside the material (far away from the cutting line). Both FeSi6.5 and the regarded conventional Fe-Si steel exhibit nearly the same mean grain size. Despite this fact the observed decrease of the permeability, and the increase of the magnetizing field to reach a certain value of B, for samples using laser cutting is quite different for conventional Fe-Si and FeSi6.5, see Fig. 8. The decrease of the permeability, respectively the increase of the magnetizing field, with decreasing value of the width of strips in the range of 0.5T up to 1.5T is much larger for conventional Fe-Si steel compared to FeSi6.5. Compared to mechanical cut samples these facts point to different underlying mechanism of the deterioration of the magnetic properties for these two cutting techniques. In the case of mechanical cutting there is a clear region of changes in the grain morphology near the cutting edge due to elastic and plastic deformation. On the other hand there is no clear indication of a change of the grain morphology for samples obtained by laser cutting. Residual biaxial stresses due to the thermal shock wave at laser cutting may be therefore the origin of the observed changes of the remanent induction, respectively the decrease of the permeability at higher magnetic fields. The resulting stress-induced magnetic anisotropy is proportional to the magnitude of the residual biaxial stress and the value of the magnetostriction. The magnetostriction, itself depends on the silicon content.

The remarkable "size effect" (influence of the width of the samples) with respect to the deterioration of the magnetic properties demands for a different optimum choice of the material grade to reach a minimum of deterioration of the magnetic properties due to the different mechanism of deterioration of the magnetization behavior at mechanical cutting and laser cutting.

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