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Magnetic Properties of Non-Oriented Electrical Steels under Compressive Stress Normal to Their Surface

***Abstract**. Magnetic properties of non-oriented electrical steels are measured under a compressive stress up to 28 MPa normal to their surface. It is shown that the perpendicular stress changes their permeability and magnetic losses along their circumferential direction. The variations in magnetic properties are discussed in terms of changes in magnetic domains due to the stress.*

***Streszczenie.** Zbadano wpływ naprężeń ściskających na niezorientowane blachy elektrotechniczne. Stosowano naprężenia do 28 MPa normalne do powierzchni. Stwierdzono że naprężenia prostopadłe powodują zmiany przenikalności i strat w obu kierunkach. (**Właściwości magnetyczne blach elektrotechnicznych niezorientowantych poddanych naprężeniu ściskającemu normalnemu do powierzchni**)*

Keywords: Electrical steel sheet, Stress effect, compression, magnetic loss
Słowa kluczowe: blachy elektrotechniczne, naprężenia mechaniczne.

Introduction

Electrical steel sheets used in motor cores are subjected to external stresses in manufacturing process of motors. Difference in the magnetic properties between before and after the fabrication is a problem in the design of recent motors with high performance. The effect of stresses on strip-shaped non-oriented electrical steels [1, 2], and ring-shaped ones [3, 4] have been studied. These studies have mainly focused on the stress parallel to the magnetizing direction, although the stress can be applied in various directions when electrical steels are used for electrical machines. There are a few studies on the effect of compressive stress which is normal to the surface of electrical steel sheets [5, 6], but more studies are needed to clarify the magnetizing process of electrical steel sheets under the perpendicular compressive stress.

In this study, we focused on the effect of a compressive stress perpendicular to the surface of electrical steel sheets on their magnetic properties. Results are discussed in terms of stress-induced changes in magnetic domains.

Experimental

The samples under investigation were non-oriented electrical steel sheets, 50A1300 and 50A290, and both of the samples had a thickness of 0.5 mm. They were cut into rings with outer and inner diameters of 80 and 60 mm, respectively. As shown in Fig. 1, each sample was placed between two rings made of acryl. Each acryl ring had a thickness of 8 mm and 24 grooves having a depth of 3 mm for both a magnetizing coil and pick-up coil.

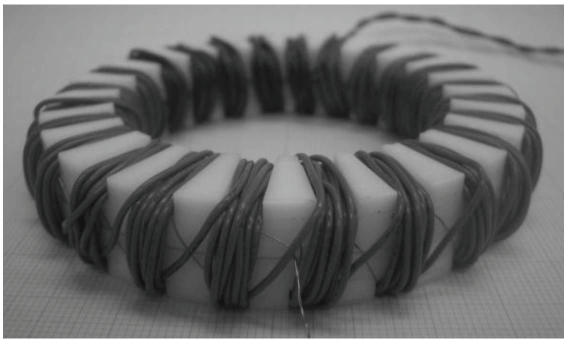

Fig. 1. Magnetizing winding around an electrical steel ring.

The compressive stress was applied normal to the surface of the samples using an oil-pressure jack. Fig. 2 shows stress patterns on force detecting films when the stress of 4 MPa and that of 20 MPa were applied. According to this result, this system is able to apply the stress almost uniformly to the samples.

a) b)

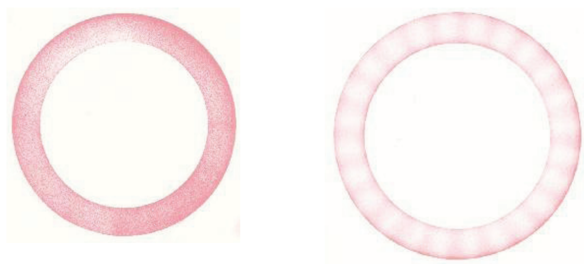

Fig. 2. Patterns on force detecting films after (a) 4 MPa and (b) 20 MPa stress application, where each film has different stress detecting range.

The sample rings were magnetized along their circumferential direction. Magnetic flux density was measured using a 240-turn pick-up coil.

Magnetizing current was controlled to make the induced voltage in the pick-up coil sinusoid, with distortion less than ± 2 %, and its form factor was 1.1107 $\pm$ 0.5 % [7]. The deviation of maximum magnetic flux density was controlled to be less than $\pm$ 0.2 %.

Results and discussion

Fig. 3 shows magnetization curves of the 50A1300 sample magnetized at a frequency of 50 Hz under a compressive stress. When a compressive stress of 8 MPa was applied to the sample, its permeability increased, and the maximum magnetizing field H_m decreased at all magnetic flux densities B_m. On the other hand, compression of more than 16 MPa resulted in a decrease in the permeability in high B_m regions. For example, the permeability of the sample under 16 MPa compression was increased for $B_m \leq 0.7$ T, but decreased for Bm > 0.7 T.

Fig. 4 shows the increment of the magnetizing field ΔH_m due to the compressive stress at various B_m. The lowest and the highest ΔH_m were observed at 4 MPa, 1.4 T and at 28 MPa, 1.5 T, respectively. Here, H_m changed between -15 % and 130 % due to the stress.

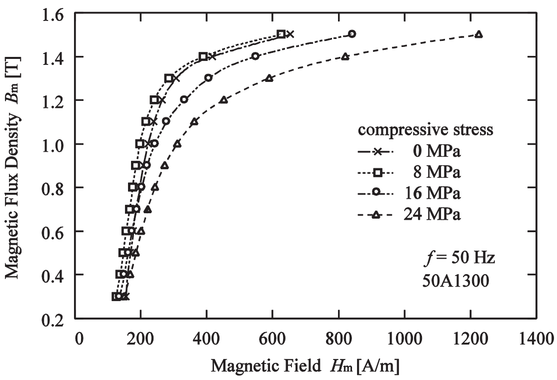

Fig. 3. B-H curves with/without compressive stress on 50A1300.

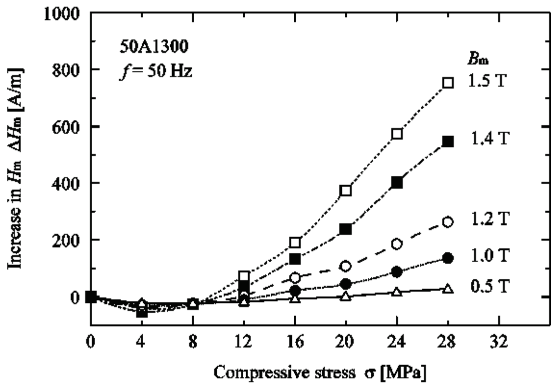

Fig. 4. Change of magnetizing field of 50A1300 sample due to compressive stress.

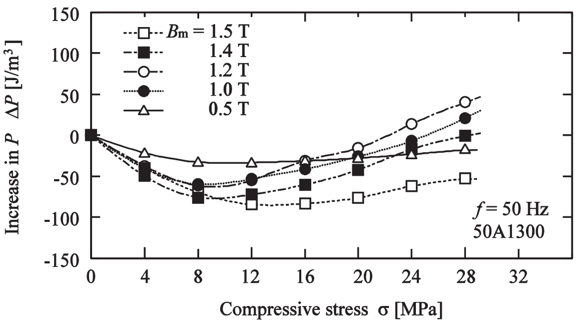

Fig. 5. Change of magnetic loss of 50A1300 sample due to compressive stress.

Magnetic losses P decreased on the 50A1300 sample due to the application of compressive stresses at most measured magnetic flux densities. Fig. 5 shows the changes of the magnetic loss ΔP versus the compressive stress. The minimum ΔP was observed at 8 MPa compression for all B_m but 1.5 T, and that for 1.5 T was observed at 12 MPa. Positive ΔP was also observed at B_m = 1.0 T, σ = 28 MPa, and B_m = 1.2 T, $\sigma \geq$ 24 MPa.

Fig. 6 and 7 show ΔH_m and ΔP versus the compressive stress on the 50A290 sample, respectively. The minimum ΔH_m and the minimum ΔP for 1.3 T were observed at 4 MPa and 12 MPa, respectively. No positive ΔP was observed in this sample.

When the magnetizing frequency f was increased, the magnetic loss P at 0.5 T increased. Linear relationships between f and P were observed in a frequency range between 50 Hz and 200 Hz as shown in Fig. 8(a) and at 1.0 T between 50 Hz and 200 Hz for 50A1300 sample. The linearity was also observed at 1.5 T between 50 Hz and 400 Hz as shown in Fig. 8(b). This relationship can be expressed as

(1) $$P = a f + b,$$

where both a and b are constants. The constant b represents hysteresis loss, and af denotes eddy current loss.

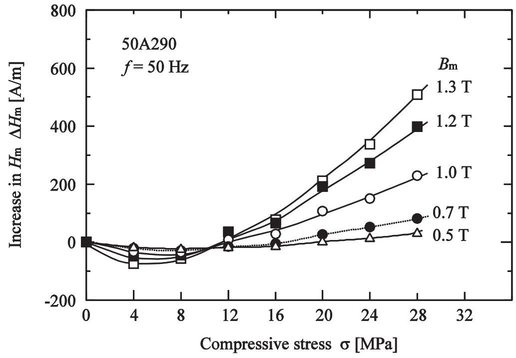

Fig 6. Change of magnetic field of 50A290 sample due to compressive stress.

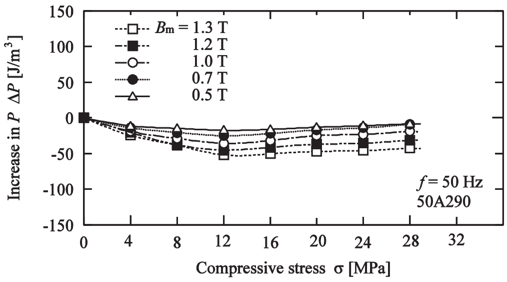

Fig. 7. Change of magnetic losses of 50A290 sample due to compressive stress.

a)

b)

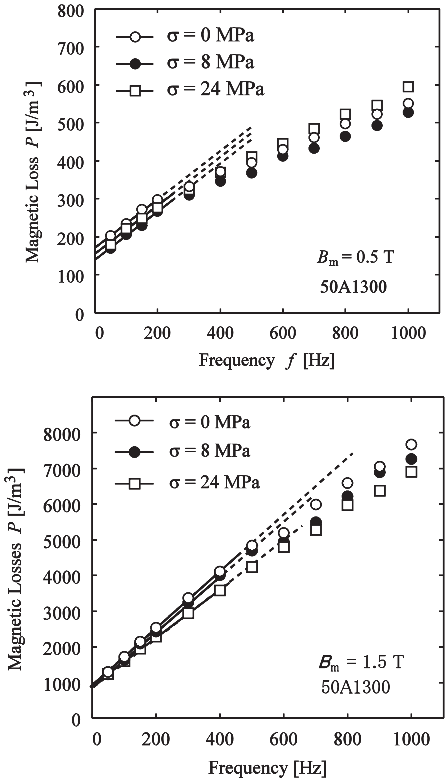

Fig. 8. Frequency dependency of magnetic losses in 50A1300 sample (a) 0.5 T and (b) 1.5 T.

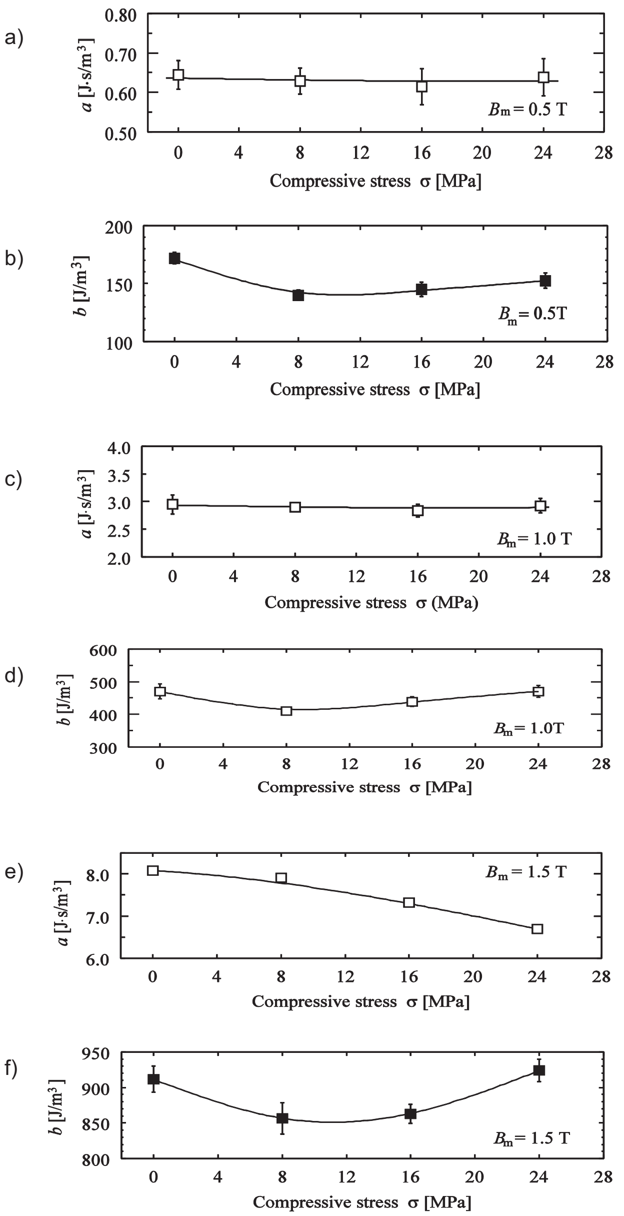

Fig. 9. Changes in constants of *a* and *b* of 50A1300 sample at (a), (b) 0.5 T, (c), (d) at 1.0 T, and (e), (f) at 1.5 T.

Fig. 9 shows the changes in these constants due to the compressive stress. The application of a compressive stress of 8 MPa resulted in the minimum *b* for all B_m and *b* at 0.5 and 1.0 T was decreased due to the stress up to 24 MPa. These behaviors are very similar to that of ΔP shown in Fig. 5.

Domain structures in non-oriented electrical steels are very complex and are also very sensitive to their relating magnetic energy [8]; moreover, the loss generation process under stresses is very closely connected with the domain structure in the samples [9]. When the compressive stress normal to the sheet plane was applied, the <100> direction closest to the plane was energetically favored for magnetic vectors, in the demagnetized state, and the number of domain with 90° walls was reduced due to the compressive stress in the magnetizing process of low B_m. This 90° wall elimination reduces both coercive force H_c and *P* in low B_m. Fig. 10(a) shows *B-H* loops at the B_m of 0.5 T, and both H_c and *P* were reduced due to the stress. On the other hand, a complex magnetization process can occur in a medium-to-high B_m region, as observed in the case of the application of a strong tensile stress [10], thereby increasing *b* at 1.5 T, 24 MPa, as shown in Fig. 9(f) and also in Fig. 10(b).

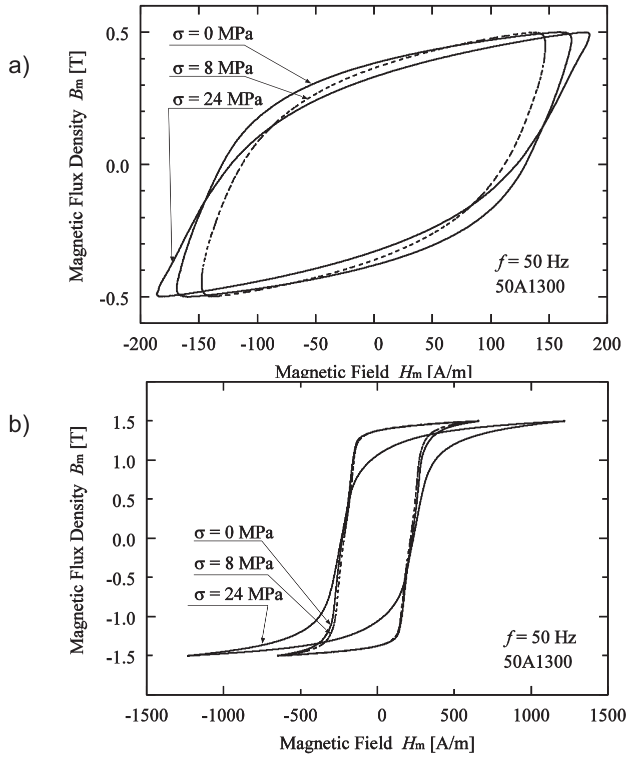

Fig. 10. *B-H* loops of the 50A1300 sample at (a) 0.5 T and at (b) 1.5 T.

As shown in Fig. 9(a) and (c), *a* did not change at 0.5 and 1.0 T. It decreased at 1.5 T due to the stress as shown in Fig. 9(e). Medium-to-high B_m can be achieved only by means of successive 90° rotation of magnetic vectors in each grain. Fig. 10 (b) shows *B-H* loops at 1.5 T. The difference in *B-H* loops between 0 MPa and 24 MPa indicates that the stress induces a large change in the rotational magnetization process. The reduction in *a* at 1.5 T shown in Fig. 9(e) relates to the eddy current loss owing to the magnetization changes which are perpendicular to the surface of the sample [11]. When the stress was applied in the direction which is normal to the surface of the sample, its direction becomes hard axis because of the magneto-elastic energy, and the reduction in quantity of the perpendicular magnetization change was made by the stress in the magnetization process. Above discussion has been based on the experimental results in frequency range between 50 and 200 Hz. When the frequency is higher than 200 Hz, different magnetizing process can occur as shown in Fig. 8(a).

These results show that a compressive stress normal to the surface of electric steel sheets can be used to reduce magnetic losses. Magnetic domain observation is required for more detailed discussion about the magnetizing process.

Conclusion

Effects of compressive stress perpendicular to the surface of non-oriented electrical steel sheets were investigated, and following results were obtained:

1. Increases in permeability were observed under a compressive stress up to 8 MPa. On the other hand, higher stress decreased the permeability.
2. Magnetic losses decreased due to the compressive stress at most measured magnetic flux densities.

These changes were analyzed by means of loss separation and were discussed in terms of changes in magnetic domains due to the stress.

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