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INFLUENCE OF THE MECHANICAL FATIGUE PROGRESS ON THE MAGNETIC PROPERTIES OF ELECTRICAL STEEL SHEETS

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Abstract – **In electrical machines, different types of mechanical loads affect the electrical steel packages magnetically. Cyclic mechanical stresses due to centrifugal forces or electromagnetic forces lead to material fatigue process within the steel packages as well. This paper studies the consequences of different cyclic stress states and number of cycles on the magnetic properties of electrical steel sheets by measuring pre-loaded electrical steel sheet specimens in a single-sheet-tester. An influence of the stress level and number of stress cycles on the magnetic properties can be observed.**

I. INTRODUCTION

The effect of static mechanical stresses is in the focus of current research activities. Due to the Villari effect, magnetic properties change while loaded by mechanical stress [1]. In electrical machines, mechanical stresses appear with static and periodic or cyclic behaviour. For example, cyclic mechanical stresses are caused by fluctuation in the speed of the rotor or periodic electromagnetic forces on the rotor surface or stator teeth. Electrical steel packages fatigue mechanically dependent on the number of cycles and the amplitude of the stress. Material fatigue causes a variation in the magnetic properties [2, 3]. This effect is used as non-destructive-testing method in some applications [3].

During operational life of constructions or machines, the cyclic mechanical loading of steel parts can lead to an accumulation of fatigue damage. In order to avoid that the fatigue damage process ends in a sudden fracture or significant change in the machine's operating characteristics due to involved alterations of magnetic properties, it is vital to assess the material degradation. Particularly, in rotating electrical machines, this effect can influence the magnetic flux path or the iron losses after a certain time of operation.

Due to the microstructural dependence of the magnetic behaviour of electrical steel grades, standardised magnetic techniques are appropriate for non-destructive evaluation.

In this paper, the change in magnetic parameters is determined at several interruptions of the cyclic loading. The results show a variation in the magnetic properties dependent on the number of cycles and the level of mechanical stress.

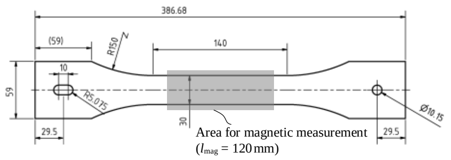

Fig. 1. Shape of the specimens with area for magnetic measurement.

II. CYCLIC STRESS

Stressing a specimen in a cyclic way causes material fatigue. This material degradation process starts with slip and agglomeration of dislocations, followed by nucleation and growth of micro cracks that lead to the coalescence of cracks and finally the formation and propagation of a dominant crack, eventually leading to final failure [4]. Due to the magneto-mechanical coupling, the material fatigue has an influence on the magnetic properties.

A. Investigated material

To analyse the effect of cyclic stress on the magnetic properties of electrical steel sheet, sheets of type M270-35A cut by a CO_2-laser are used. Examining the determined stress-strain curve of the studied material, the mechanical data of the material is given in Tab. I. Only specimens in rolling direction are studied. The shape of the specimens for applying cyclic loads is shown in Fig. 1.

B. Cyclic load

For analysing the variation of the magnetic properties due to a fatigue evolution, specimens are stressed at different stress levels and different numbers of cycles. For the conduction of the experiments, a hydraulic testing machine is used. To avoid cracking of the specimens, the maximum number of cycles is reduced for a high mechanical stress level (see Tab. II). The chosen stress levels correspond to $0.23\sigma_y$, $0.46\sigma_y$ and $0.69\sigma_y$, respectively. σ_y reports the yield strength (Tab. I).

TABLE I
MECHANICAL PROPERTIES OF STUDIED MATERIAL.

Description	Symbol	Value
Yield Strength	σ_y	361 MPa
Young's Modulus	E	210 GPa
Tensile Strength	σ_{TS}	471 MPa

TABLE II
STRESS LEVELS AND NUMBER OF CYCLES.

Stress Level σ_{max}	Maximum Number of Cycles N_{max}
83 MPa	500,000
165 MPa	500,000
249 MPa	100,000

The cyclic load has a sinusoidal shape with a frequency of $f = 20$ Hz. To avoid compressive stresses on the specimen, the pre-load has a minimal value of $\sigma_{min} = 1.6$ MPa.

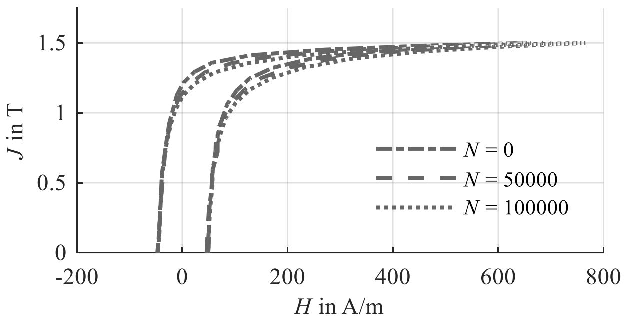

Fig. 2. Hysteresis curves (upper part) of stressed samples for $\sigma_{max} = 249$ MPa, $f = 50$ Hz and $J_{max} = 1.5$ T.

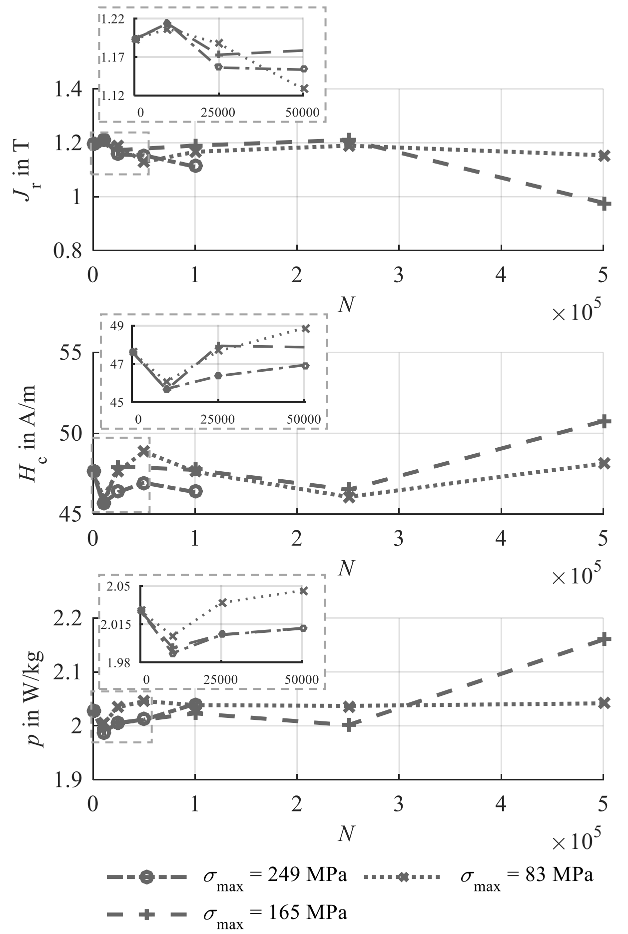

Fig. 3. Remanence polarisation, coercive field and specific losses at different stress levels for $f = 50$ Hz and $J_{max} = 1.5$ T with magnified region up to $N = 50{,}000$.

III. MAGNETIC MEASUREMENTS

A. Experimental setup

The middle part (see marked area in Fig. 1) of four specimens that were loaded mechanically with the same stress and number of cycles are merged and fixed by a non-magnetic adhesive tape to a sample with a width of 120 mm. For each stress level and number of cycles, one of these expanded specimens is measured magnetically with a single-sheet-tester (SST) constructed for samples with a width and length of 120 mm. The SST is incorporated into a computer-aided setup in accordance with the international standard IEC 60404-3. The samples are characterized using controlled sinusoidal magnetic flux density with a form factor error of less than 1 % in the frequency range from quasi-static to 1000 Hz.

B. Results

Fig. 2 shows the hysteresis curves of cyclically pre-stressed material samples for $\sigma_{max} = 249$ MPa dependent on the number of cycles. It is apparent that for an increasing number of cycles, the amount of magnetic field strength for reaching the same magnetic polarisation increases. Changes in the material microstructure influence the magnetic domain structure and thus the magnetic properties [5].

Fig. 3 depicts the trend of the different magnetic properties such as remanence flux density, coercive field and specific losses for different stress levels dependent on the number of cycles. A slight decrease of losses, i.e., decrease of coercivity and increase of remanence, seemingly due to the positive effect of small residual tensile stresses coupled to magnetostriction behaviour in RD is apparent. Subsequently, during the first percent of the fatigue life-time, the dislocation density increases which is indicated by an increase of coercivity, i.e., cyclic hardening occurs. In the second stage, approximately between 100,000 and 250,000 cycles, the magnetic properties remained almost on unchanged. Appearance of the last stage at a high number of cycles leads to reset of magnetic property variation. It is apparent that the results are strongly dependent on the level of tensile stress. A higher stress level affects the magnetic properties and their variation more intensively.

IV. CONCLUSIONS

In this paper, the effect of cyclic stresses on the magnetic properties of electrical steel sheet is studied. Particularly for a small number of cycles, the variation in the magnetic properties is higher compared to a high number of cycles. The stress level also has an influence on the intensity of variation for larger mechanical load.

Dependent on the state of electrical machine's operational life and its cyclic mechanical loads, the magnetic properties of electrical steel sheets can be altered which can influence the machine's magnetic flux path or the iron losses.

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