Electromagnetic assessment of welding processes for packaging of electrical sheets

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***Abstract*—In this paper, the effect of welding of thin electrical steel sheets is studied and evaluated by experimental magnetic measurements. Welding is a typical method of connecting iron stacks of electrical machines. However, this process deteriorates the magnetic properties of the said electrical sheets, thereby increasing the iron losses and decreasing the magnetization and efficiency of the magnetic core. Two methods of the welding process are assessed, namely spot and line welding. For this assessment an electrical sheet of grade 280-30AP is utilized. The effects of each welding method to the deterioration of the magnetic properties can be characterized in three main categories, namely magnetic short-circuiting of the ring core, thermal degradation and increase of the residual stress distribution inside the material. The results confirm that the eddy-current component of the iron loss is influenced at a different rate as the hysteresis component of the iron loss.**

***Index Terms*—welding process, ferro-magnetic lamination, electrical steel**

I. Introduction

Electrical steel sheets are mostly used for the guiding of the magnetic flux in electrical machines. Therefore, the optimization of such machine depends on the reduction of the iron loss and the increase of the magnetization of these electrical sheets. The manufacturing processes like punching, stacking and fixing of electrical sheets are well known to lead to significant magnetic deterioration of these sheets. Welding is one of the state-of-the-art methods, alongside interlocking and gluing, of fixing electrical sheet laminations. In this study laser welding by linear continuous welds and single spot welds is compared. The process of welding leads to a decrease of the magnetic permeability (magnetization) and an increase of the generated iron losses associated with the electrical sheets. These effects reduce the efficiency of the machine.

The effects of welding have been reported [1]–[3] to lead to a significant magnetic deterioration of the ring core. However, a comprehensive and systematic analysis of the welding process is lacking. This paper studies the effects of different welding methods on the iron losses and magnetization of the electrical sheets in view of optimizing the efficiency of electrical steel sheets.

II. Experimental Approach

A. Examined sample

Four ring core samples were manufactured for this work. The rings have inner D_i and outer D_o diameters of 60 mm and 48 mm respectively (Fig. 1).

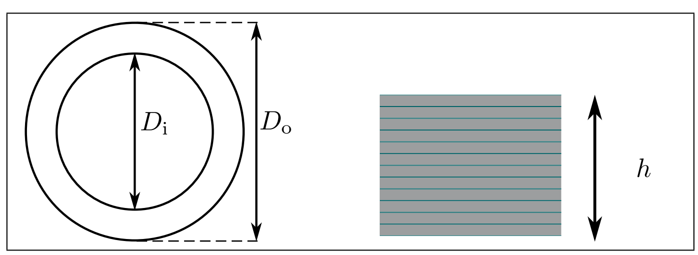

Figure 1: Geometry of the samples

The height of the examined samples is 9 mm, i.e. 30 ring laminations are connected together. The reference ring core is stacked with 30 rings without any connecting technique, so as to exclude the effects of the joining methods. The specific iron loss and magnetization emanating from this sample represents the electro-magnetic properties of the laminated stack. The

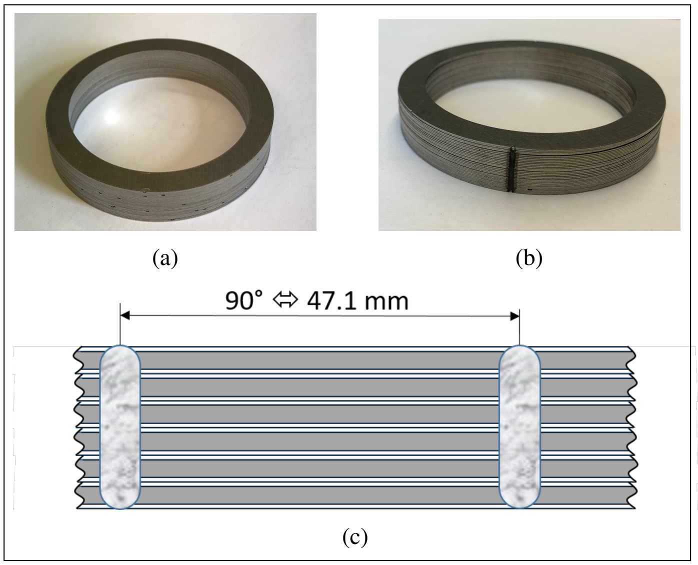

Figure 2: (a) Reference sample, (b) Line welding sample and (c) Illustration of the line welded point

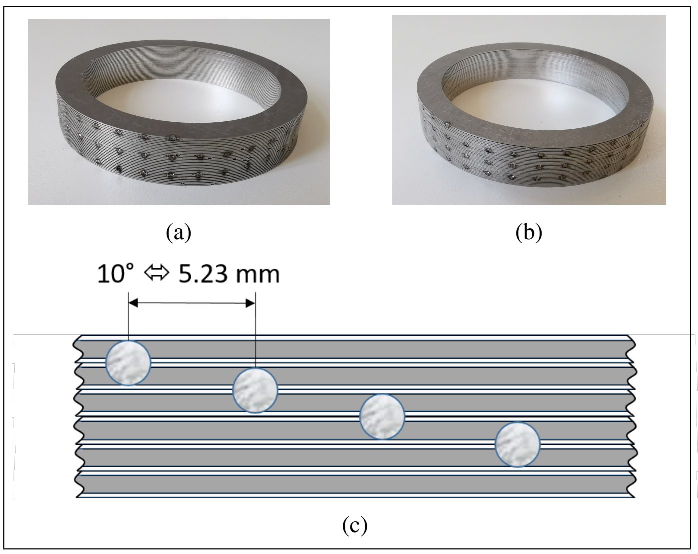

Figure 3: (a) spot welding Sample with 3 spots per ring, (b) spot welding sample 4 spots per ring and (c) Illustration and distribution of the spot welded point

individual rings are laser cut to the aforementioned dimensions. The reference ring core is compared with three welding concepts including line welding to connect all 30 rings with 4 continuous weld seams displaced by 90 degrees and spot welding to connect only two rings per spot (2b and 3). In 2c and 3c shows the illustration of the weld distribution of line- and spot welding respectively.

The spot welding is tested in two versions with three (Fig. 3 a) respectively four (Fig. 3 b) welds. The welding spots are distributed on the circumference of the rings with an offset of 120° for three respectively 90° for four welds to join two ring-lamellas each. Each following joining level is welded with an offset of 10° to the last level. According to investigation of [13] the compressive stress of the stacks was 0.1 N/mm² to avoid pores.

Both versions are welded with a single-mode fibre laser with a wavelength of 1070 nm and a fibre diameter of 35 µm creating a focal diameter of 70 µm. For both processes the working distance is 400 mm.

The spot welds are produced at surface focus with a pulse time of 0.1 seconds at a beam power of 200 W. The line welds are produced at an over-focus of 1 mm above the surface with a welding speed of 1 m/min at a beam power of 320 W, which is equal to an energy per unit length of 19 J/mm..

Due to the high number of spot welds the production time was about three times higher than for the line welds. Concerning this it must be taken into account, that the production time was not a relevant parameter for this study and therefore there is a high potential of reduction.

In Fig. 4, the necessary torque required to separate the laminations is depicted. It is observed, that the ultimate torque of the line welded sample is about 26 Nm above those of the spot welded sample, whereby both samples broke at a similar torsional angle of about 2.5°. in [15] a comparable line weld reached the half ultimate torque of about 40 Nm at an energy per unit length of 20 J/mm and also broke at a similar torsional angle.

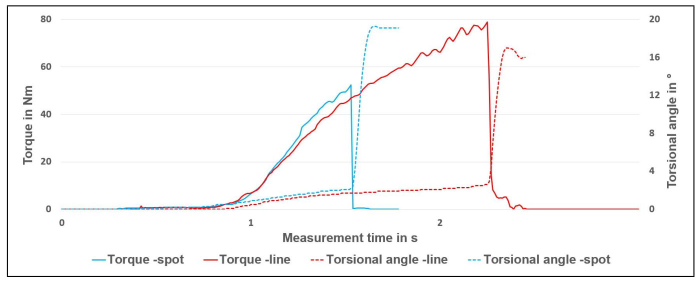

Figure 4: Torsional strength

B. Measurement method

In the measurement setup, the current on the primary winding induces a voltage response on the secondary winding. The specific iron loss and magnetic field strength is then derived from the induced voltage on the secondary winding and the ring core geometry. The ring cores are winded with 80 turns on the primary and secondary sides.

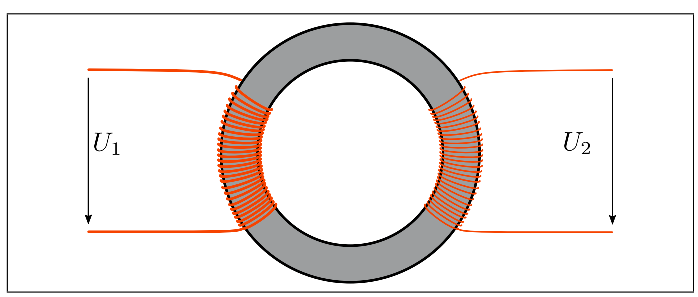

Figure 5: Measurement setup

III. MEASUREMENT RESULTS

For the purpose of a complete comparative analysis of the results, two comparative groups are created namely: group A with reference sample, spot welding sample and the spot welded sample with a quarter less points, group B with reference sample, line welded sample and the spot welded sample. The measured results for the specific iron loss and

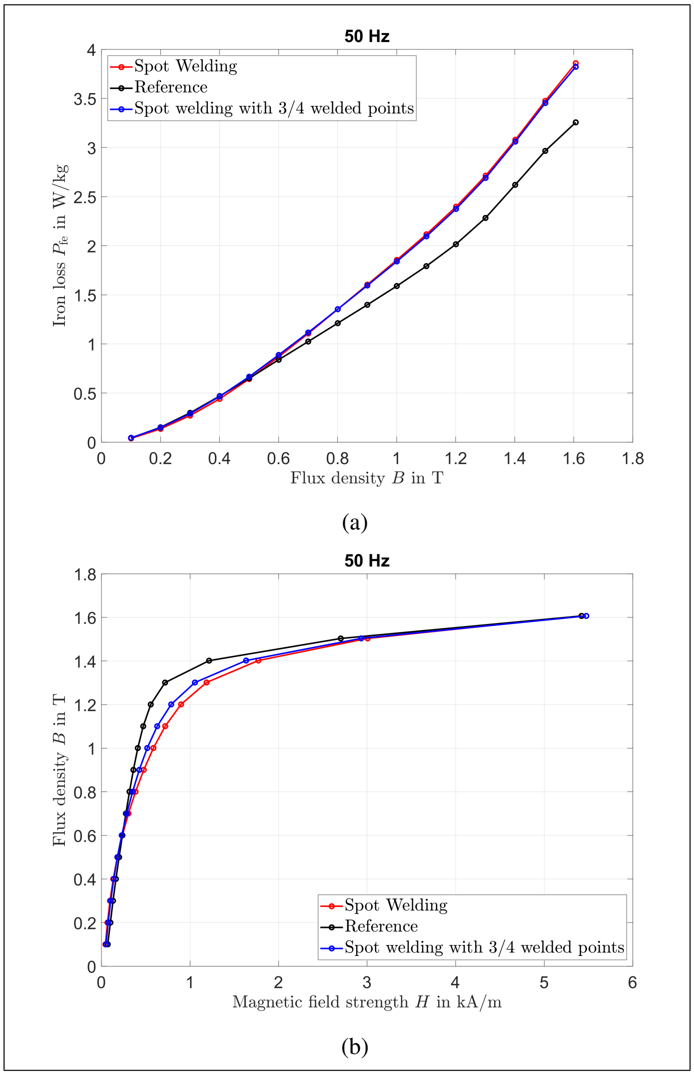

Figure 6: (a) specific iron loss and (b) magnetization curve

magnetization curves of group A at 50 Hz are depicted in Fig. 6. It can be observed, that at lower frequencies the generated specific iron loss is not dependent on the number of welded points. At high frequencies Fig. 7 shows a significant deterioration of the material magnetic properties.

This effect can be explained, because the addition of more welded points consequently increases the eddy-current paths inside the ring cores, thereby increasing the eddy-current loss component of the specific iron loss. This leads to a significant change in the magnetic behavior of the electrical steel sheet at higher frequencies. Other effects are an apparent increase in the residual stress and average damaged area associated with the welding process.

Furthermore, there was a less significant change of the magnetization curves at different frequencies Fig. 6b and 7b observed. Therefore, the amount of welded points has little or no effects on the magnetization of the ring core.

For the use of spot welded ring cores an optimized number

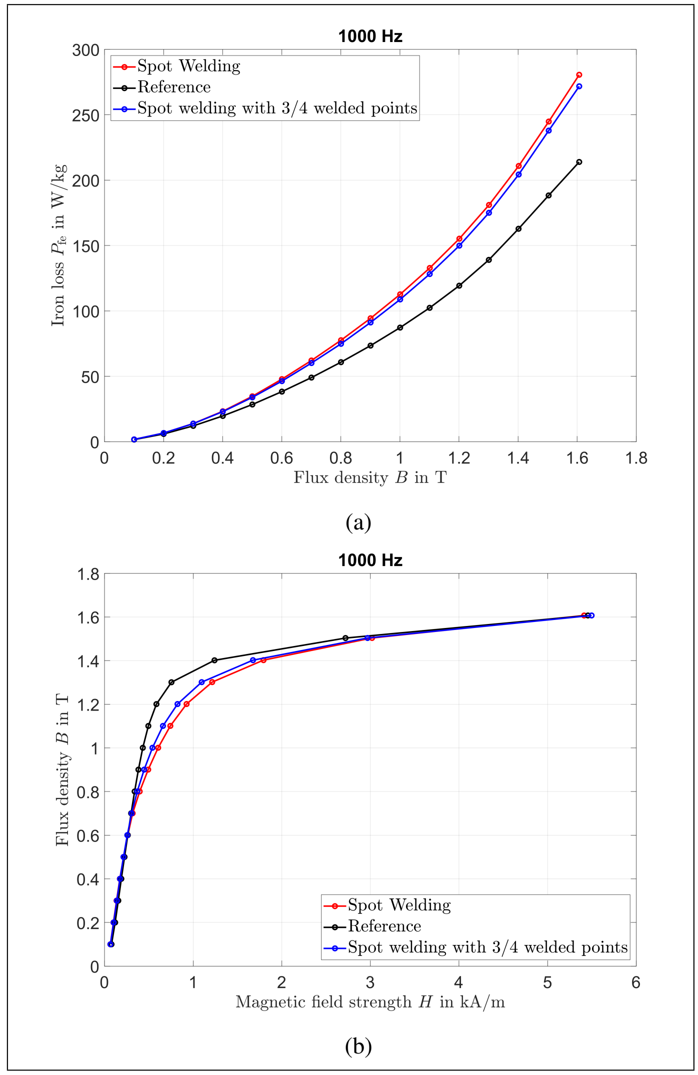

Figure 7: (a) specific iron loss and (b) magnetization curve

of points, which also ensures the mechanical stability of the core, could be determined in further in investigations

The generated specific iron losses and magnetization curve of group B are depicted in Fig. 8 - 11 respectively. These figures show, that at lower frequencies the deviation of the iron loss of both samples from the reference ring core begins at a higher flux density than that of higher frequencies. It confirms, that the eddy-current loss component, which is dominant at higher frequencies contributes immensely to the deterioration of the magnetic properties of the electrical steel sheets. The total iron loss is defined as the sum of the hysteresis loss, classic eddy-current loss and local eddy-current loss component (excess) [4].

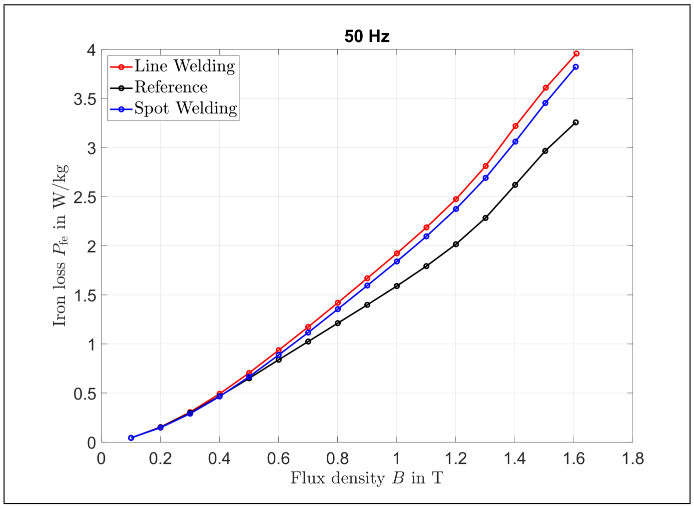

Figure 8: specific iron loss

$$P_{total} = k_{\text{Hyst}} \cdot B^{\alpha} \cdot f + k_{\text{cl}} \cdot B^2 \cdot f^2 + k_{\text{exc}} \cdot B^{1.5} \cdot f^{1.5} \tag{1}$$

Whereby k_{hyst}, k_{cl} and k_{exc} are the hysteresis loss constant, classical eddy-current loss constant and excess loss constant respectively and α is the exponential coefficient of the hysteresis loss [4]. As can be seen in equation 1, the classical eddy-current loss is quadratic proportional to the frequency.

It can be observed in Fig. 8 and 10, that compared to the reference sample an improvement of iron loss of up to 5% is achieved, if the spot welded ring core is utilized instead of the line welded core. The spot welding shows a significant improvement of the magnetization Fig. 9 and 11 compared to line welding procedure.

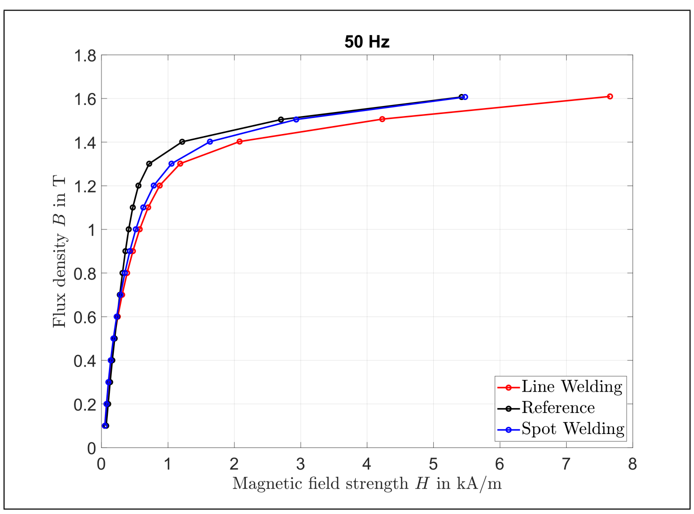

Figure 9: magnetization curve

It is also observed, that the rate of deviation of both welded samples is almost linear for both methods of welding. This confirms that the source of this material degradation is the same for both procedures.

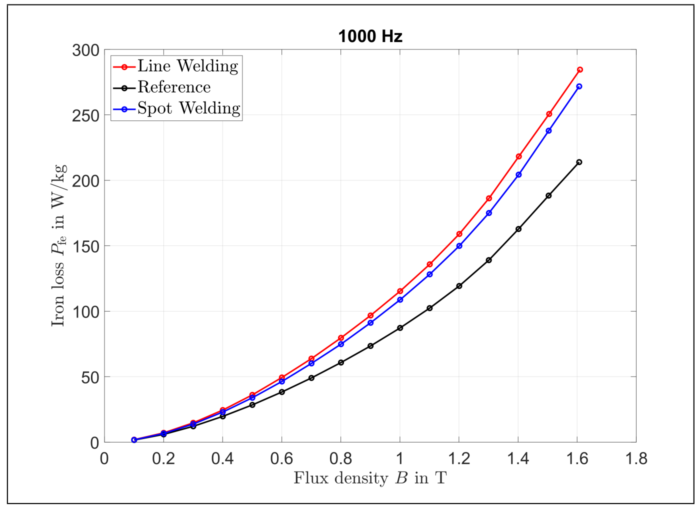

Figure 10: specific iron loss

Whereas the attainment of 1.6 T flux density at a magnetic field strength of around 5500 A/m was achieved by spot welding procedure, for the line welding a magnetic field strength of around 7800 A/m was required. Line welding shows a higher deterioration of the permeability at higher flux density in comparison to the spot welding.

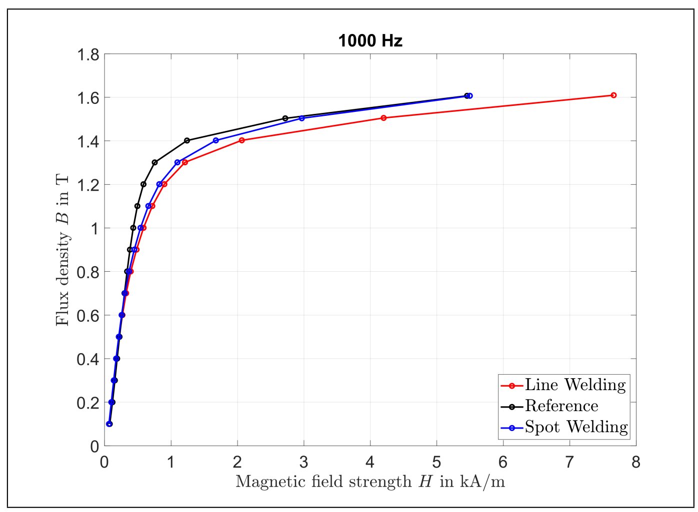

Figure 11: magnetization curve

In Fig. 12, 13 and 14, the iron loss of line welded, spot welded and reference samples at different frequencies and flux density are depicted. It confirms the hypothesis, that the generated iron losses are more dependent on the frequency as on flux density. At high frequencies, a more visible deterioration of the magnetic properties of the ring core is seen. At lower flux density, the deterioration starts at a much higher frequency than that of higher flux density when compared to the reference sample result.

At lower frequencies, the increase in iron loss appear due to residual stress and change in grain structure accompanied with the increase of the thermal energy within the ring cores through welding. This phenomenon effects the hysteresis

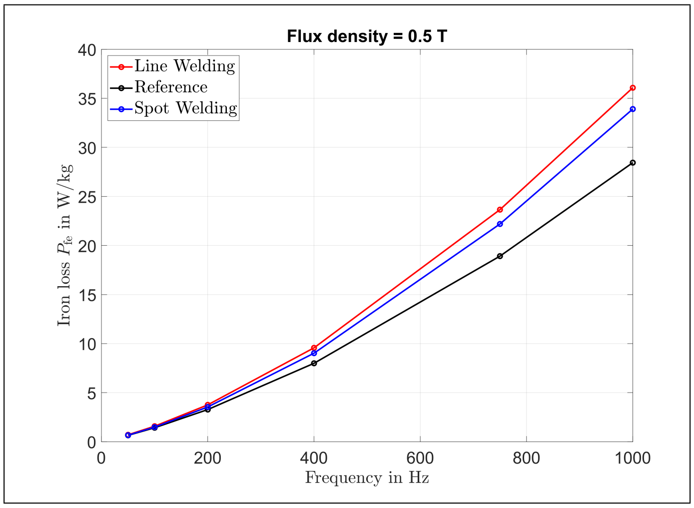

Figure 12: specific iron loss at 0.5 T

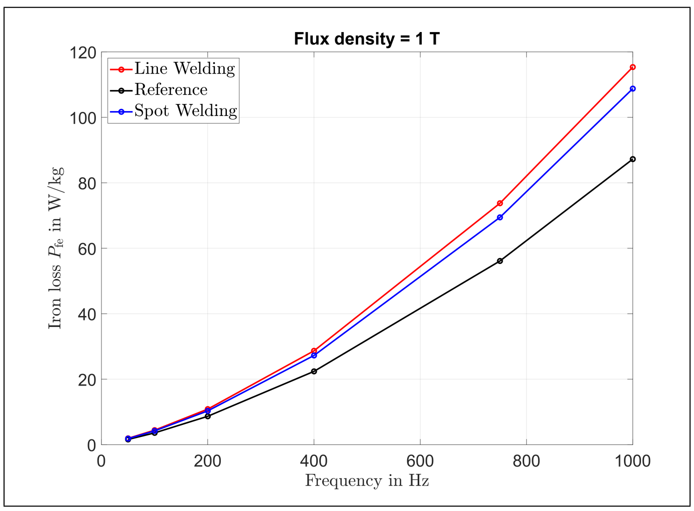

Figure 13: specific iron loss at 1 T

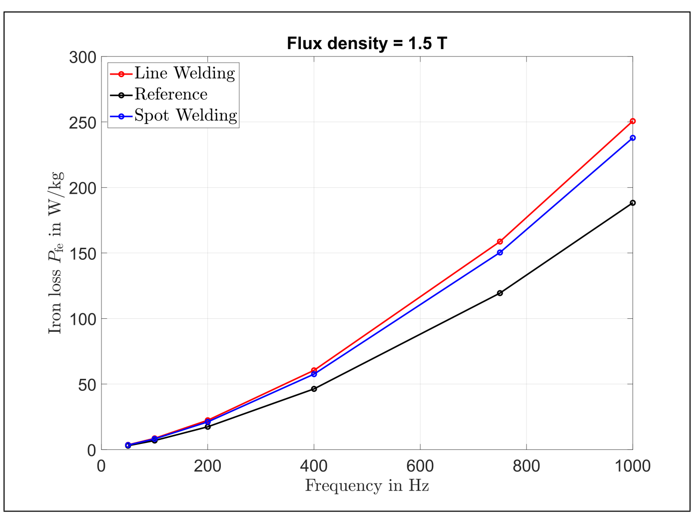

Figure 14: specific iron loss at 1.5 T

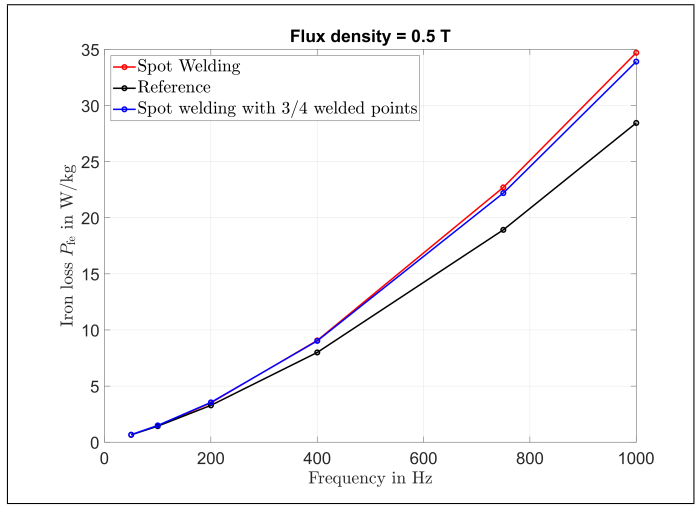

Figure 15: specific iron loss at 0.5 T

component of iron loss.
At higher frequencies, the effect of magnetic short circuit of the electrical sheets increases, thereby making the eddy current loss component more evident. It leads to a significant deviation of the results of the welded samples from the reference sample. In Bertotti iron loss model [4] the excess loss is influenced mainly by the core size. At the welded (damaged) area, there is an apparent change of the grain sizes, which in turn increases the excess loss of the examined ring core. To evaluate accurately how welding affects electrical machine characteristics, an FEM-simulation with these data needs to be carried out. In Future works the resulting torque-speed characteristics will be evaluated with different peculiar driving cycles.

It is observed in Fig. 15 and 16, that at higher flux densities the generated iron loss is lower in samples with fewer welded points irrespective of the frequency.

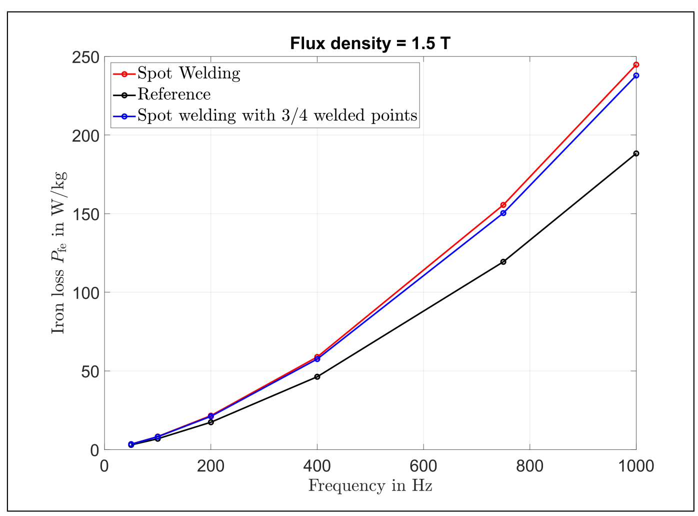

Figure 16: specific iron loss at 1.5 T

It is also observed in Fig. 17 and 18, that an increase in the flux density leads to a proportional increase of the

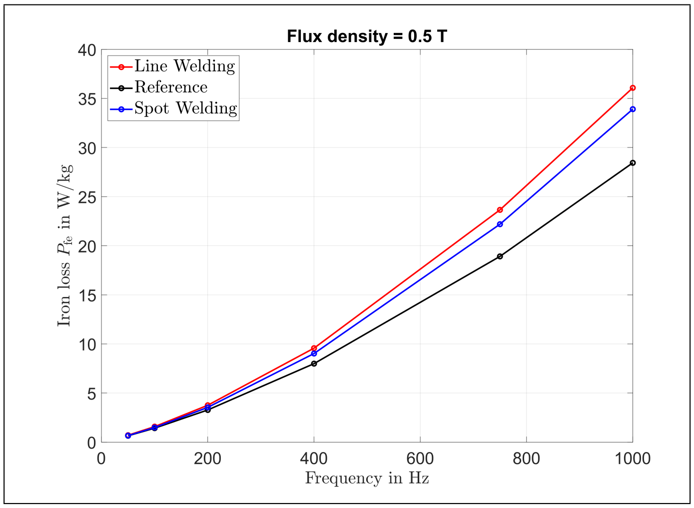

Figure 17: specific iron loss at 0.5 T

generated iron loss of the line welded sample irrespective of the frequency.

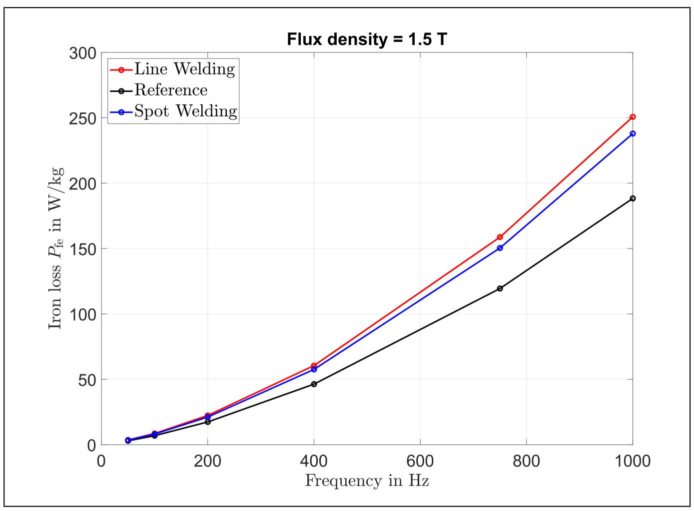

Figure 18: specific iron loss at 1.5 T

IV. Conclusion

To evaluate the influence of different welding procedures on the magnetic properties of electrical steel sheets, ring cores with spot welding and line welding procedure are measured and analyzed. It can be observed, that although both procedures lead to magnetic deterioration of the examined electrical steel sheets, the rate of deterioration of line welding is higher than that of the spot welding.

The amount of welded points during the spot welding procedure affects the generated iron losses. This is due to the increased amount of the average thermally damaged area and possible increase in the eddy-current paths inside the ring cores. The damaged areas leads to increase in losses (hysteresis loss) at lower frequencies, and increased short-circuiting leads to a greater iron loss (eddy-current loss) generation at higher frequencies.

A more accurate evaluation of the effects of welding on electrical machine will be achieved by applying this measured and calculated magnetic properties on the FEM-simulation of electrical machines.

Acknowledgment

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