Influence of Manufacturing Processes on Magnetic Properties of Stator Cores

L. Mierczak, P. Klimczyk, D. Hennies, P. Denke and S. Siebert

Abstract – **Differences between the prior and post-production magnetic properties of stator laminations are considered as one of the main sources of discrepancy between the expected and actual electric motor performances. In this work Brockhaus Measurement testing methodologies were used to evaluate the influences of two common stator production processes, i.e. stamping and welding, on magnetic characteristics of laminated cores. The experimental data from bulk and local measurements clearly indicated the negative impact of residual stresses of mechanical and thermal origins on power loss and permeability of investigated stators.**

Index Terms—**magnetic properties, stator, residual stress, manufacturing, magnetic measurements.**

I. Introduction

ACCURATE design and prediction of electric motor performance is not a trivial task. Motor design engineers make use of advanced numerical and analytical methods for electromagnetic and thermal analysis, and still find considerable differences in efficiency of modelled and manufactured machines. One of the primary sources for this mismatch is the inaccuracy in stator lamination magnetic properties, such as BH curve and power loss, which are used as input data for calculating flux linkages of the coils and heat dissipation, and consequently determining the main motor parameters including torque and operating temperature. Typically, the magnetic properties implemented in motor modelling are provided by the material supplier based on the Epstein frame measurements, according to the International Standard IEC 60404-2 [1]. The effects of processing of the magnetic materials during motor manufacturing are neglected which gives rise to uncertainty in prediction of motor performance [2,3,4]. In this study two different Brockhaus measurement technologies were used to quantitively evaluate the influence of stamping and welding on magnetic properties of stator laminations.

II. Specifications of Stators

Three manufacturing procedures were used by industrial partner Tempel Steel to produce stator cores for studying the effects of mechanical and thermal processing on magnetic properties of stator cores made of B27AHV1400 non-oriented steel laminations with nominal thickness of 0.27mm. The first stator was manufactured using the standard processes of laminations' stamping and TIG welding. For the second stator the stamped laminations were annealed to remove the residual stress from cutting, and subsequently welded. In case of the third stator the stack of stamped and welded laminations underwent the final annealing [5] to relieve the combined residual stresses originating from both manufacturing processes. The annealing cycle time was 5,5h with heating phase of 150mins at rate of approximately 5°C/min and target temperature of 790°C, followed by cooling phase of 185mins at rate of approximately 4°C/min. The annealing atmosphere composition was a mix of H_2 and N_2. Detailed specifications of prepared stators, which are typically used in traction motor applications, are given in Table 1.

Electrical steel grade	B27AHV1400	-
Lamination thickness	0.27	mm
Density	7600	kg/m^3
Inner diameter	137.8	mm
Outer diameter	200	mm
No of slots	54	-
Stack height	100	mm
Number of weld notches	9	-
Number of weld lines	7	-

Table 1. Specifications of stators manufactured by Tempel Steel.

III. Characterization of Bulk Magnetic Properties

A. Methodology

The bulk magnetic properties of the stators were characterized using the Brockhaus MPG200 measurement system. MPG200 hardware comprised generation, amplification and acquisition units with peak magnetization current of 52A, magnetization frequency up to 20kHz, as well as output and input voltage ranges up of 100V. The primary (excitation) and secondary (sensing) coils were wound on the back irons of stators, as shown in Fig. 1.

Fig. 1. Stator core with wound primary and secondary coils.

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Two magnetization frequencies, i.e. 50Hz and 400Hz, were used in the measurements to verify the effect of residual stress on dynamic power loss components. Due to high volume of magnetized material the utilization of available current and voltages was optimized with variable number of primary and secondary turns at different measurement frequencies, i.e. 54 primary and 54 secondary turns at 50Hz, and 12 primary and 12 secondary turns at 400Hz. This allowed for reaching peak flux densities B of 1.6T at 50Hz and 1.3T at 400Hz. The magnetization conditions during the measurements were controlled with digital negative feedback ensuring accurate regulation of peak amplitude and sinusoidal shape of secondary voltage and flux density waveforms. The measurements and power loss calculations were carried out according to the International Standard IEC 60404-6[6].

B. Results and discussion

The BH loops measured for all three stators at peak flux densities of 1.6T and 1.3T, and measurement frequencies of 50Hz and 400Hz are shown in Figs. 2a and 2b, respectively.

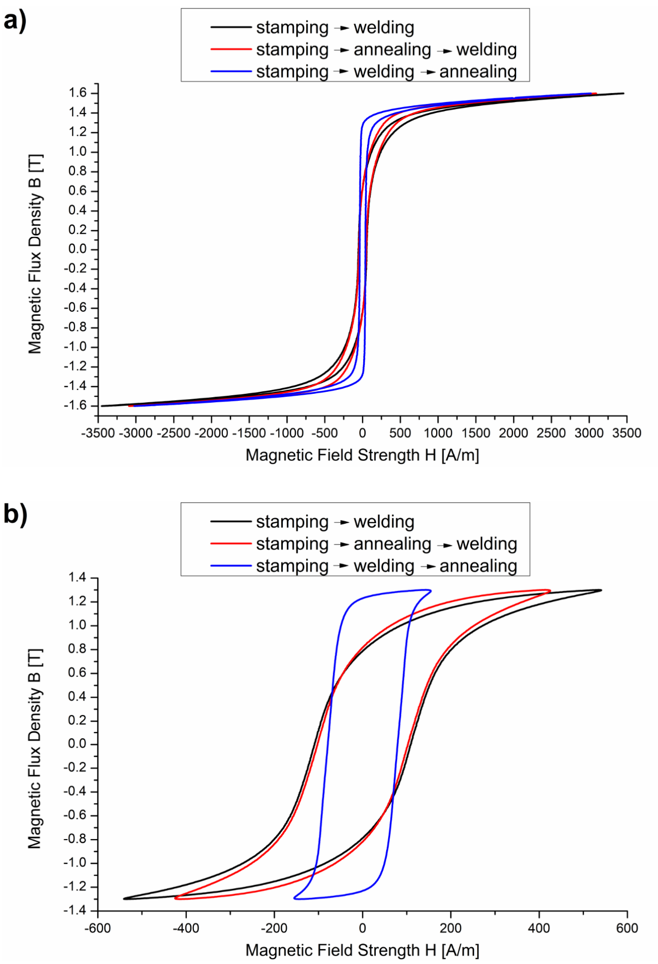

Fig. 2. BH loops of investigated stators obtained at measurement frequencies: a) 50Hz and b) 400Hz.

It can be seen that slopes of the BH loops corresponding to permeability, as well as their areas corresponding to power loss were affected by the manufacturing processes. The impact on permeability of stators at different magnetization levels was even more pronounced when comparing the BH curves obtained from the B_{peak} and H_{peak} values from BH loops measured within range of B from 0.1T to 1.6T at 50Hz, and 0.1T to 1.3T at 400Hz, as presented in Figs. 3a and 3b.

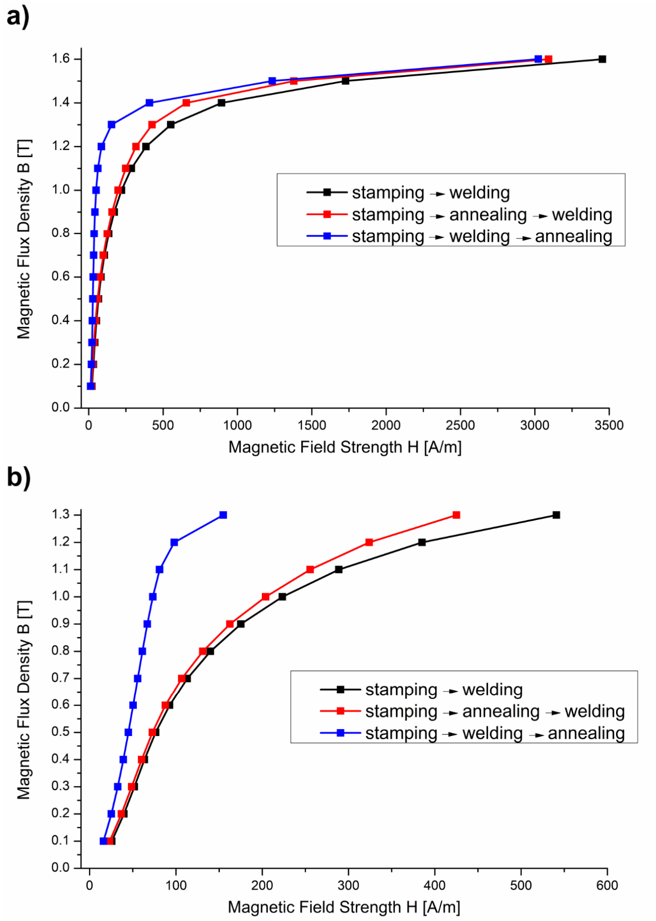

Fig. 3. BH curves of investigated stators obtained at measurement frequencies: a) 50Hz and b) 400Hz.

The BH characteristics obtained for stator with combined residual stresses from stamping and welding (black curves) indicated the lowest permeability, as the magnetic field strengths required to reach the given levels of flux densities were the highest. The BH characteristics measured for the stator made of annealed laminations (red curves) showed gradually improved permeability with higher dB/dH response. A significantly higher permeability was observed for the stator subjected to final stress relief annealing, where slopes of BH characteristics (blue curves) were much steeper, especially in the low magnetic field H regions. These magnetization behaviors can be explained by analyzing the influence of welding and stamping on grain and magnetic domain structures.

In the process of stamping the lamination area near the cut edge undergoes plastic deformation from the mechanical cutting stress. As a result, this affected area has microstructure with finer grains and higher density of grain boundaries [7], which act as pinning sites impeding domain wall motion. Moreover, the plastic deformation generates the residual stress remaining in the region adjacent to cut edge which affects the local magnetization due to the magnetomechanical effect [8].

During welding, material experiences thermal conditions ranging from melting point to room temperature which leads to creation of regions with compressive residual stress in vicinity of weld lines. These regions are referred to as heat affected zone (HAZ) and similarly to areas near cut edges exhibit deteriorated magnetic properties.

The post-annealing can effectively remove the negative effects of mechanical and thermal treatments by recrystallization and residual stress relaxation. This in return improves the permeability of electrical steel laminations, as shown in Figs. 3a and 3b. This beneficial effect of annealing on performance of synchronous reluctance motors was previously described in [9].

The other important magnetic property in motor design is the specific power loss P_s related to heat dissipated in the stator core. The power loss measured for investigated stators at 50Hz and 400Hz are presented in Figs. 4a and 4b, respectively.

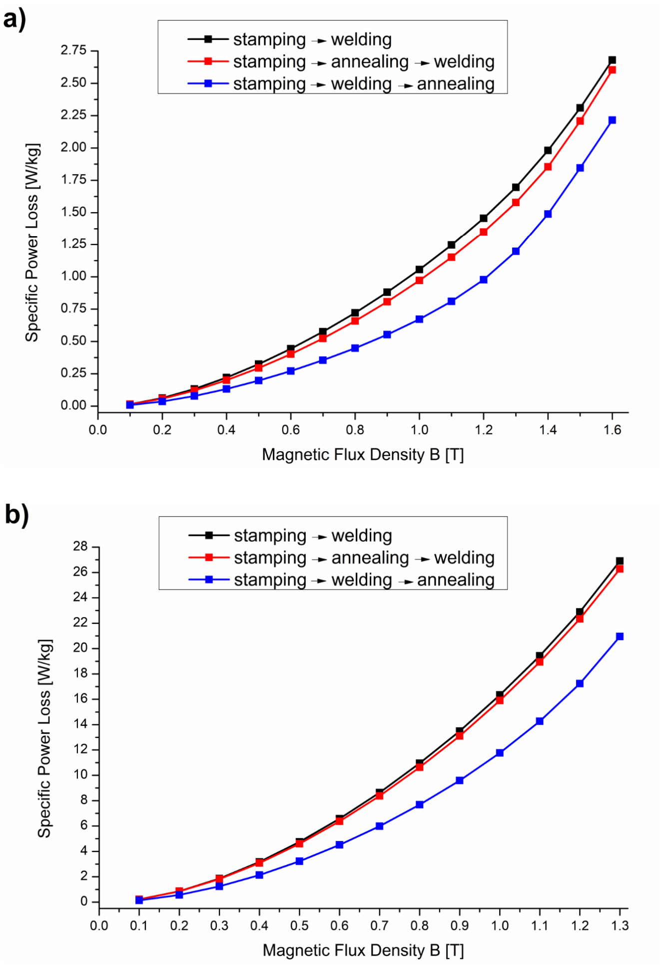

Fig. 4. Specific power loss of investigated stators obtained at measurement frequencies: a) 50Hz and b) 400Hz.

The variations in measured power loss follow the same trend as previously observed for permeability, where the most deteriorated properties, i.e. highest P_s, was measured for unannealed stator, while the stators after intermediate and final annealing showed improved properties, i.e. reduced P_s, within the full magnetization range. However, the extent to which the intermediate and final annealing decreased the power loss was different. This implied that the effect of stamping on magnetic properties of stator laminations was noticeably lower than effect of welding. When assuming that the intermediate annealing eliminated the negative influence of stamping then the differences between red curves and blue curves in Figs. 4a and 4b indicated the increase in power loss from welding. Consequently, the differences between the black curves and red curves in Figs. 4a and 4b reflected the increase in power loss from stamping. The percentage changes in power loss of stators from these individual processes are plotted in Figs. 5a and 5b.

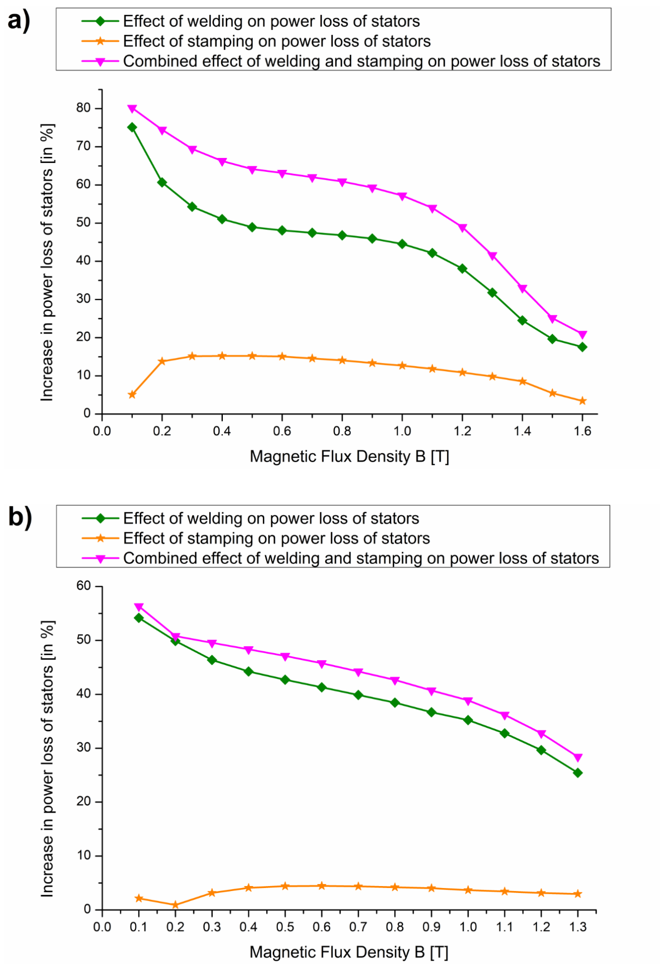

Fig. 5. Percentage increase in specific power loss of investigated stators at measurement frequencies: a) 50Hz and b) 400Hz.

The comparison data presented in the above graphs confirmed the higher impact of welding on power loss at both frequencies. This could be attributed to the greater spatial distortion in magnetic properties, as the typical size of heat affected zone is in the range of few millimeters from the weld line [10], whereas the area affected by stamping is considered to be up to three times the lamination thickness [11], which for the investigated stators would be approximately 0.8mm. Additionally, variations in magnitudes and distributions of residual stresses in both types of affected areas would cause different severity of deterioration in magnetic properties.

Another aspect of this analysis is the frequency dependence of the relative changes in power loss caused by residual stress, as presented in Fig. 6.

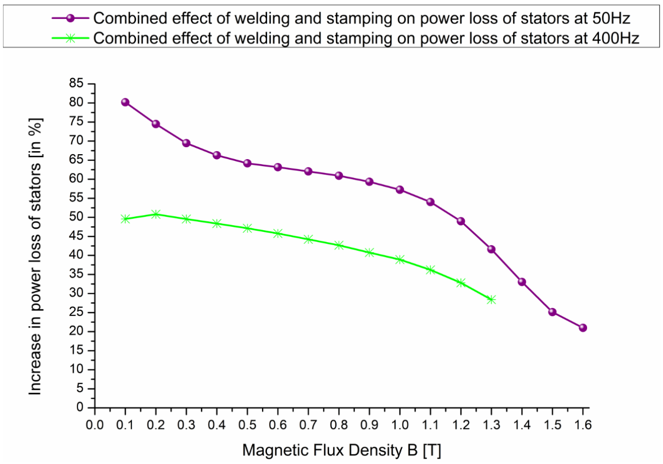

Fig. 6. Effect of frequency on percentage increase in specific power loss of investigated stators.

At all levels of flux density within range from 0.1T to 1.3T the percentage increase in P_s was lower at 400Hz than at 50Hz. This frequency dependence of stress-induced relative increase in P_s can be described by analyzing the hysteresis, classical eddy current and excess loss components of the Bertotti model [12]:

$$P_{tot} = c_{hy} B_p^2 f + c_e B_p^2 f^2 + c_{exc} B_p^{1.5} f^{1.5} \qquad (1)$$

where P_{tot} is the total power loss, B_p is the peak amplitude of flux density, f is the magnetization frequency, c_{hy}, c_e and c_{exc} are the hysteresis loss, classical eddy current loss and excess loss coefficients, respectively.

It was reported by multiple authors that the stress affects only the c_{hy} and c_{exc} coefficients, and consequently hysteresis and excess loss components [13,14,15]. The coefficient c_e and eddy current loss component do not depend on stress within the elastic limit. However, with increasing magnetizing frequency the contribution from eddy current component to total loss becomes more dominant and therefore the relative changes in total power loss from stress-biased hysteresis and excess loss components decrease.

IV. Characterization of Local Magnetic Properties

A. *Methodology*

In the second phase of this work the manufactured stators were evaluated using the Brockhaus BST-L system integrated with MPG200. The Brockhaus BST-L system included a custom designed sensor head, enclosed within housing installed on a dedicated gripper, and integrated with multi-axis positioning system and rotating table for automated measurements at different angles and heights within tested stators. The main practical advantage of the BST-L set-up is the location of the sensor head, allowing magnetization through the teeth, which is accessible after each stator production stage including winding and housing. The 3D images of the complete BST-L system and sensor head unit are shown in the Figs. 7a and 7b, respectively. The schematic cross-sectional view of the sensor head, comprising U-shaped yoke made of high permeability material with pole faces curvature obtained using EDM, and sets of primary (orange) and secondary (yellow) windings, at reference measurement position against stator teeth is presented in Fig. 8. During the measurement the sensor head legs, of which the outer curvature was matching the inner stator radius, were pressed against the stator teeth to eliminate the influence of the airgap.

a)

b)

Fig. 7. a) Brockhaus BST-L system, b) BST-L sensor head unit.

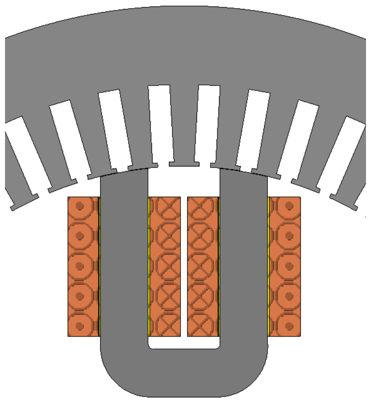

Fig. 8. Schematic cross-sectional view of BST-L sensor head at reference measurement position.

Two stators were selected for measurements with BST-L. First stator had combined residual stresses from stamping and welding, and the second stator was the fully annealed one which was stress relieved. The size of sensor head was designed such that the regions with and without weld lines could be measured separately. That allowed to differentiate the individual effect of stamping. The angular position of sensor head was changed by 20° at three different heights within the stator core, which gave a total number of 54 measurement locations per stator. The amplitude and sinusoidal shape of flux density measured on the yoke was controlled using the MPG200 digital feedback.

B. Results and discussion

The stator characterization using BST-L system relied on indirect measurement of magnetic properties. The total power loss measured within magnetic circuit of BST-L included the loss of yoke and loss within the magnetized segment of the stator. However, by prior power loss characterization of the yoke material it was possible to subtract its contribution from total loss obtained at given flux density. Moreover, using the combination of FEM analysis and CAD model the volume, and consequently mass of the magnetized stator segment was identified. As a result, the specific power loss for each investigated core segment could be calculated. This type of measurement is different from the back-iron test with directly wound coils presented in the previous sections. The divergence of flux within stator sections magnetized with BST-L sensor results in non-uniform flux density distribution. Therefore, direct comparison with results presented in Figs. 3 and 4 would not be meaningful. Nevertheless, the BST-L can be used for comparative study where the obtained data provides indication on variations in magnetic properties within analyzed stator segments. In this work the average power losses were measured at angular steps of 20 degrees at 18 positions in each measured layer. Three layers were measured within both of the two investigated stators which in total accounted for 54 annealed segments, 33 stamped segments, and 21 stamped segments with weld lines. The average P_s evaluated within those segments is plotted for different yoke flux densities B at 50Hz in Fig. 9.

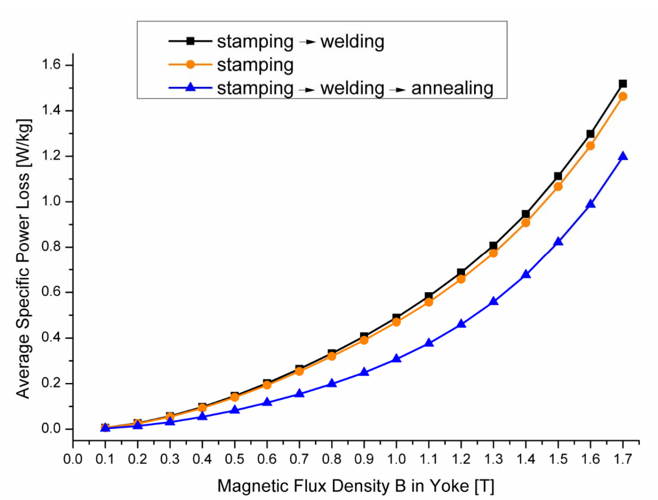

Fig. 9. Power loss Ps as function of yoke flux density B at 50Hz measured for different sections of investigates stators.

Analogously to the back-iron analysis the stress relaxation improved the power loss in all measured stator segments. However, the BST-L results indicated a greater influence of stamping on P_s than welding, as presented in Fig. 10.

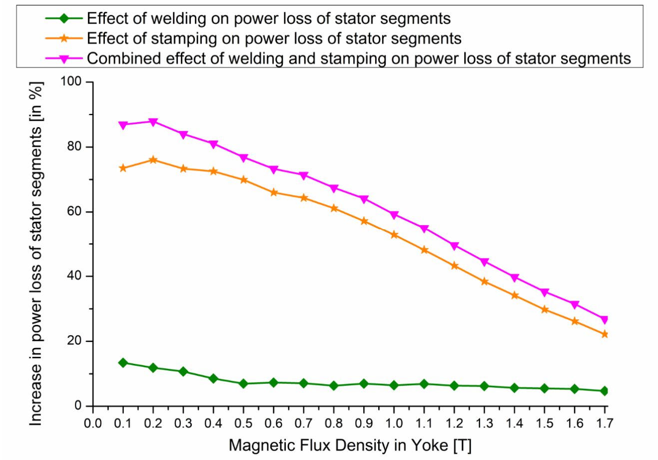

Fig. 10. Percentage increase in specific power loss of investigated stator segments at measurement frequencies of 50Hz.

The higher impact of stamping on power loss of stator segments measured with BST-L could be attributed to two effects. Firstly, the stator segments were magnetized through teeth which were narrower than back iron. Therefore, the cutting affected areas of teeth, that were proportionally greater than in back iron, showed higher relative deterioration from stamping. Secondly, the magnitudes of flux density B in teeth were higher than in the back iron which generated non-uniform distribution of power loss within magnetized stator segment, as shown in Fig. 11. Nevertheless, the significant differences in power loss between stamped and annealed stator segments (22% to 76%) could be primarily assigned to the degradation of magnetic properties in stator teeth.

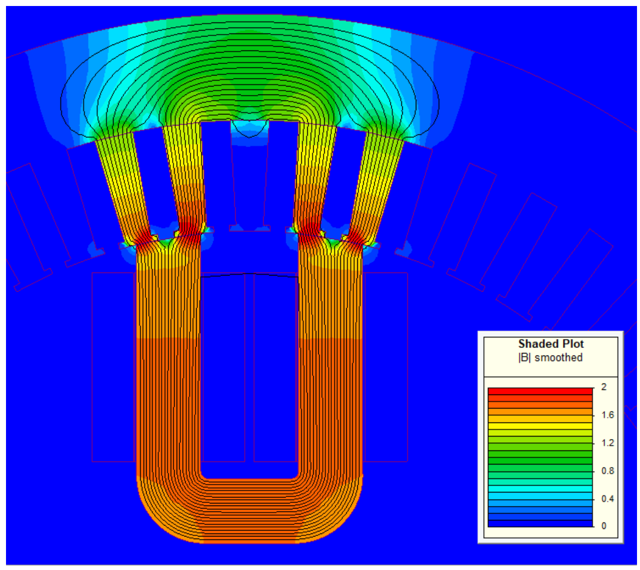

Fig. 11. Simulated distribution of magnetic flux density B in magnetized stator segment at yoke magnetization level of 1.7T. Sensor head was modelled in direct contact with stator teeth (no airgap).

Another informative characteristic that could be obtained from BST-L measurements was the angular variation in power loss of the stator, as presented in Fig. 12.

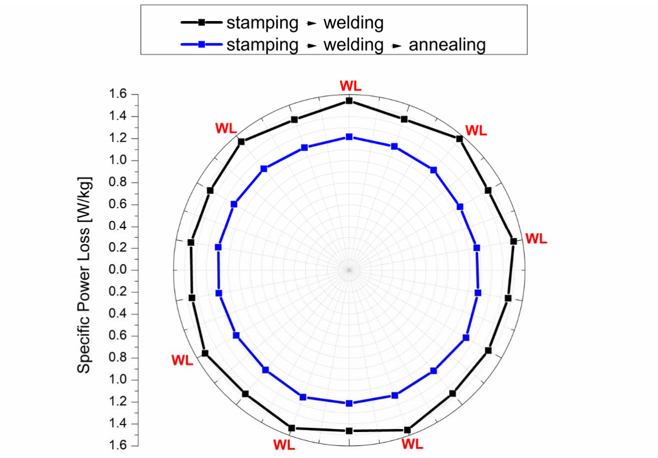

Fig. 12. Angular variation in power loss in the investigated stators measured at yoke magnetization level of 1.7T.

It is apparent that the power loss was higher at each angular position in the stator with post-manufacturing residual stresses. The additional increments in P_s within segments with weld lines (labelled with 'WL') were distinguishable, yet the relative effect of stamping in teeth was dominant. In case of the annealed stator the angular distribution was relatively uniform. Finally, the percentage increase in P_s for all angular positions at yoke magnetization level of 1.7T is shown in Fig. 13.

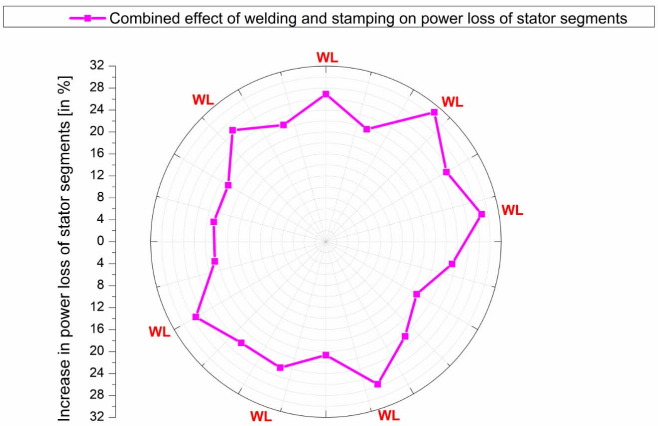

Fig. 13. Percentage difference in power loss between annealed and unannealed stamped and welded regions measured at different angular positions within the investigated stators at yoke magnetization level of 1.7T.

The above graph confirmed the primary negative influence from cutting with relative increase of P_s in stamped only segments within range from 20% to 25%. The further influence of thermal residual stress in segments with weld lines accounted for minor additional increments that brought the total relative increase in power loss to level as high as 31%.

V. Conclusions

In this work the variations in bulk and local magnetic properties of stators were evaluated using Brockhaus MPG200 and BST-L testing systems. The obtained results indicated the detrimental influence of residual stresses from thermal and mechanical treatments on permeability and power loss of investigated laminated cores. It was shown that welding caused relatively higher degradation of magnetic properties in the back iron of stators, whereas stamping affected more significantly the properties of stators teeth. This research confirmed the requirement of magnetic measurements at different stages of stator production to assure expected efficiency and consistency in motor performance.

VI. Acknowledgment

Authors would like to acknowledge Tempel Steel for manufacturing and supplying stator cores for this research.

VII. References

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VIII. Biographies

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S. Siebert, MSc, received his diploma in electrical engineering from South Westphalia University of Applied Sciences. Since 1996, he has been a Managing Director of Brockhaus Measurements. His area of expertise includes methods of measurement of soft and hard magnetic materials. He is a Member and Project Leader of the IEC TC68 group responsible for international measurement standards relating to the magnetic and other physical properties of alloys and steels.