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Effects of Manufacturing Processes on Core Losses of Electrical Machines

Ravi Sundaria, *Member, IEEE,* Antti Lehikoinen, Antero Arkkio and Anouar Belahcen, *Senior Member, IEEE*

***Abstract*—Manufacturing processes such as cutting, welding and shrink fitting are known to degrade the magnetic properties of the electrical sheet during the manufacturing of electrical machines. These effects are often neglected at the design stage and lead to large errors in the simulated and measured core losses of the electrical machine. This paper studies the comparative impact of different manufacturing processes on the stator core losses of a typical industrial motor. Both simulations and measurements indicate a significant impact of manufacturing processes on the stator core losses. A dummy blocked rotor test setup is used to measure the stator core losses. As a result of different manufacturing processes, the stator core losses increased by 23% in the studied machine at the rated condition. The effect on the stator core losses was higher at lower flux levels. Finally, it was shown that the inclusion of the effect of manufacturing processes significantly improved the simulation accuracy of the core losses. A quantification and segregation of the effect of cutting, welding and shrink fitting is also presented for the studied machine.**

***Index Terms*—core loss, cutting, electrical machine, manufacturing effect, modeling, shrink fitting, stress effects, welding.**

I. Introduction

THERE is an increasing focus on the energy efficiency of traditional electrical machines as well as for newer applications such as electrical vehicles, wind energy etc. To improve the efficiency of electrical machines, researchers are focusing on better understanding and accurate estimation of the associated losses. Core losses are one of the major components of the total losses which are infamous for the associated difficulties in the accurate estimation at the design stage. Traditionally, core losses are calculated based on the core loss coefficient provided by the electrical steel manufacturers. The loss coefficients are often derived from the magnetic measurements by Epstein frame or single sheet testers on the electrical steel samples. During the manufacturing of an electrical machine, electrical steel is subjected to different physical processes such as cutting, interconnecting (welding, interlocking, glueing), and shrink fitting or calmping with screws, etc. Each of the manufacturing steps is known to deteriorate the magnetic properties of the electrical steel [1], [2].

Electrical steel sheets are cut to appropriated shapes during the manufacturing of electrical machines. Different cutting techniques such as punching, laser cutting, water jet cutting and wire electric discharge machining (EDM) are popular. Punching is often used in the series production of electrical machines and exerts mechanical stresses in the electrical steel sheets. On the other hand, laser cutting is popular in the small scale production of electrical machines and exerts residual thermal stresses. Both techniques result in changes of the material microstructure near the cut edge too. Depending on the cutting technique and setup of the cutting tool, different magnitudes of degradation are observed. Further, modeling efforts are made to model the cutting effect in the finite element (FE) simulation of electrical machines. Analytical formula based local permeability and core loss density expressions are often used in modeling of the cutting effect. Different analytical expressions based on exponential [3], [4] and polynomial functions [5] are proposed. Based on the modeling and measurements, researchers have found up to 10-28% increase in core losses due to cutting in the studied machines [5], [6].

After the cutting process, the electrical steel sheets are stacked by welding, glueing or interlocking. Glueing results in lowest degrading effect on the magnetic properties of electrical steel, however, the relative effect of welding and interlocking depends on the material type and the number of welding and interlocking joints [7]. Welding is one of the most often used techniques for stacking the stator laminations for industrial production of electrical machines. Tungsten inert gas (TIG) welding and laser welding are often used in the industry. The welding seam short circuit the laminations at the stator outer surface. This may generate the local eddy currents. The heat produced during the welding process generates the thermal stresses which will reduce the magnetic permeability and increase the core loss density [8], [7]. Moreover, if there are lamination shortcircuits generated from burrs during the cutting process, the welding seam will provide the path for the global eddy currents. The global eddy currents will significantly increase the core losses. Depending on the welding speed the increase in the core losses can be in the range of 5 % to 20 % due to the welding effects [9].

The outer frame of the electrical machine is shrink fitted to the welded stator stack. The inner diameter of the frame is marginally smaller (0.1 mm smaller for the machine studied in this paper) than the outer diameter of the stator. As a result, the compressive stresses will be generated on the stator. Compressive stresses degrade the magnetic permeability and increase the iron loss density of the electrical steel [10], [11]. References [12], [13] show the modeling and measurements of stress effects on the electrical machines and an increase as high as 10% in the iron loss was found.

To study the effect of manufacturing processes on the final

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built machine, it is important to understand the comparative effect of different manufacturing processes. As listed above many research efforts are made in modeling the individual manufacturing processes; however a combined comparative study on a single machine/prototype is lacking. References [14], [15] study the effect of manufacturing processes on the stator core losses. However, the test setup is arranged to produce a homogeneous flux in the stator yoke and the magnetic flux is passing through two stator teeth during the measurement. This condition is not equivalent to the real operation of the electrical machine where non-homogeneous flux exists in the stator core and passes through multiple teeth at any given time. Clearly, there is a need to study the effect of manufacturing effects on the electrical machine at the realistic operating conditions as well as segregation of the total effect of manufacturing-related processes into individual components for a better understanding. Such an approach is followed in this paper.

Moreover, [6] proposed building factors to included the effect of manufacturing for a permanent magnet synchronous machine. The proposed building factor varies between 1.1 to 1.32 for the studied machine, however no segregation into individual manufacturing processes was provided. Although [16] obtained building factors 1.22, 1.30 and 1.34 for punched, clamped and welded cores for a 120 W synchronous reluctance machine, the measurements were effectively performed in the yoke region of stators as toroids. Hence the cutting effect of the teeth region was not included. In contrast, this paper presents segregation of manufacturing process on the stator core losses at realistic operating conditions. Further, the proposed approach takes into account the magnetic saturation with different manufacturing processes instead of the constant building factor approaches listed above. Hence, the proposed method will be closer to the physical nature of the manufacturing effects and is considered a major novelty of the presented research work.

The core losses of the stator prototypes are measured at each manufacturing step with the magnetic flux equivalent at the operating condition. To attain the required stator flux without having the rotor related losses in the system, a dummy blocked rotor setup is designed. For studying the laser cutting and welding effects, the magnetic measurements are carried out on the steel laminations and ring cores assembled from stator sheets respectively. Further, the core loss measurements are carried out with and without frame to study the effect of shrink fitting with the dummy blocked rotor test setup. Finally, analytical equations are derived for modeling the laser cutting, welding and shrink fitting effects and the comparative effect on the stator core losses is discussed in detail. The combined effect of manufacturing effects is observed about 23 % on the stator core losses at the rated condition.

This paper is divided into six sections. The background of the effects of cutting, welding and shrink fitting processes in the context of electrical machines and novelty of this research work is provided in the current section. The following section includes the details of different measurement setups used in this study. Based on the measurements, Section III includes the analytical loss models for the cutting, welding and shrink fitting. The identified parameters for the respective loss models are listed in Section IV. Also, a segregation of total manufacturing related losses into individual components is provided at the realistic operating condition. The effect of the manufacturing effects on simulation accuracy is further analyzed. Finally, a discussion and conclusion of the research work are listed in the last two sections.

II. Measurement setups

Different measurement test setups used in this paper are described in this section. The tests are performed to derive the loss models for the cutting, welding and shrink fitting effects as well as to measure the stator core losses of the studied machine.

A. Epstein Frame test on steel strips

The effect of cutting on the electrical steel sheets is usually analyzed by magnetic measurements on steel strips of different widths. The effect of cutting is observed on the measured permeability and core loss density. The presented measurements and respective cutting loss model are based on [3] and briefly summarized here. Five different types of samples were prepared with laser cutting of electrical steel grade M400-50A. The details of the samples are listed in Table I. Half of the samples are cut along rolling direction while the other half are in the transverse direction. Hence, the cumulative effect is measured in the Epstein frame test. Laser cutting is performed with the help of 400 W solid state fiber laser, Trumpf Trulaser Cell 3010 at a cutting speed of 11 m/min. Magnetic measurements are performed following standard IEC: 604004-2 with Epstein frame test setup “MPG 100 D” by Brockhaus Measurements. The excitation frequency is in the range of 20 Hz to 400 Hz.

TABLE I: Test samples

Sample	Detail	Total width (mm)
A	One sample of 30 mm	$1 \times 30 = 30$
B	Two 15 mm samples joined together	$2 \times 15 = 30$
C	Three 10 mm samples joined together	$3 \times 10 = 30$
D	Six 5 mm samples joined together	$6 \times 5 = 30$
E	Ten 3 mm samples joined together	$10 \times 3 = 30$

B. Ring cores

Two sets of ring cores are assembled from the stator laminations to study the effect of welding. One with loose sheets stacked together, called *unwelded* and another one joined by laser welding and called *welded* in this paper. Fig. 1 presents the ring core under measurement and Table II shows the respective stator dimensions. Each ring core consists of 10 stator sheets having 13 welding passes uniformly distributed along the outer surface. Trumpf Trulaser Cell 3000 is used to perform laser welding [17]. The primary and secondary winding each consists of 144 turns. The secondary voltage is controlled such that it maintains a sinusoidal flux in the core during the measurements. The peak value of magnetic flux

TABLE II: Parameters of dummy blocked rotor test setup

Rated voltage	400 V
Frequency	50 Hz
Connection	Star
Parallel path	2
Pole pairs	2
Conductors in a slot	12
Stator outer diameter	310 mm
Stator inner diameter	200 mm
Air gap	0.8 mm
Number of stator slots	48
Width of teeth	7 mm
Axial length	250 mm

density and field strength is noted to obtain the single value BH curves for the ring cores. The comparative analysis of the obtained BH curves reflects the effect of welding on the magnetic permeability. Further, in a similar fashion, the core losses are also measured by calculating the area of generated BH loops and the effect of welding is analyzed.

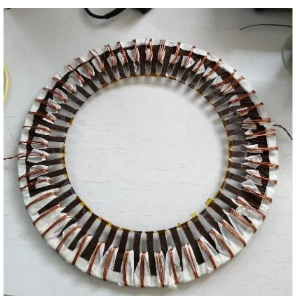
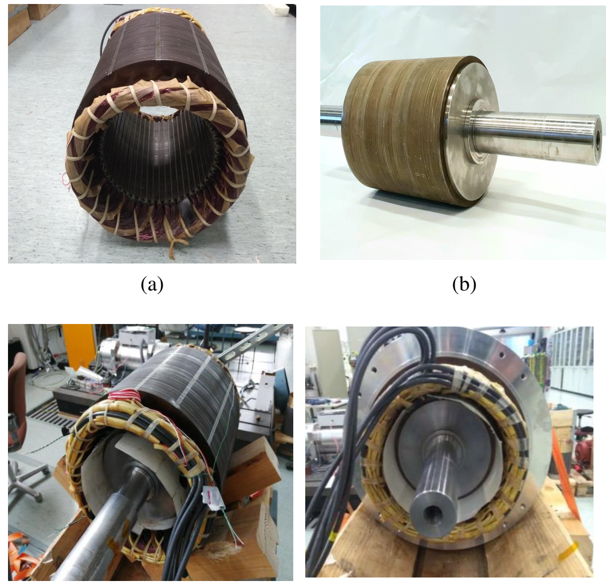


Fig. 1: Ring core assembled from the stator laminations.

C. Dummy blocked rotor test setup

A dummy blocked rotor test setup is analyzed in this paper for a reliable measurement of the stator core losses. The stator used in the measurement setup belongs to a 4 pole 37 kW cage induction machine. The dummy rotor is modified for testing purposes and does not have any slots or bars. This is done to avoid the inclusion of friction and rotor bars related losses in the measurements; hence increases the measurement accuracy. The measurements are performed with a sinusoidal supply of different voltages between 50 V to 450 V supplied by a synchronous generator. Fluke Norma 4000 power analyzer recorded the supply voltages, current and power. The measured power consists of copper losses of the stator winding and core losses associated with the stator and the dummy rotor. The stator copper losses are calculated based on Ohm's law from the measured stator current and phase resistance. As the same dummy rotor is used in all the experiments, the rotor core losses are considered the same for a given power supply. Then the stator core losses are calculated by subtracting the measured copper losses and simulated rotor core losses from the total measured power losses. The stator and rotor dimensions are presented in Table II and the dummy blocked rotor test setup is shown in Fig 2.



(a) (b) (c) (d)

Fig. 2: Dummy blocked rotor setup. (a) wounded stator (b) laminated rotor without rotor slots and conductors (c) stator without frame (d) stator with frame.

The stator core measurements are performed at three different cases to analyze the effect of different manufacturing processes. The details of the cases are listed below. Only one dummy rotor is manufactured and used in all three cases.

- Case 1: EDM cut welded stator without the frame. As EDM cutting is known to exert low stresses hence cutting related losses can be ignored in the measurements. Only the welding process is considered to affect the measured core losses.
- Case 2: Laser cut welded stator without the frame. Cutting and welding related losses are considered to affect the measured core losses.
- Case 3: Laser cut welded stator with the frame. Laser cutting, welding and shrink fitting related losses are considered to affect the measured core losses.

III. Method

This section is divided into four subsections. The first three subsections describe modeling approaches used in this paper for the cutting, welding and shrink fitting effects respectively. Finally, the details of FEM modeling of the manufacturing effects are described.

A. Loss model for cutting effects

Traditionally, core losses are calculated with standard Epstein frame measurement test setup i.e. measurements on sample A (widest sample). These losses are denoted as P_1 in this paper and no cutting or any other manufacturing effects are accounted in P_1. For the core loss computation, three component core loss formula (1) is applied. K_{h0}, K_e, K_{ex0}

are hysteresis, eddy current and excess loss coefficient of non degraded material.

$$P_1 = \sum_{n=1}^{n=N} K_{h0} B^{\alpha(B)} f_n + K_e B^2 f_n^2 + K_{ex0} B^{1.5} f_n^{1.5} \quad (1)$$

The cutting loss model used in this paper is based on [3] and briefly summarized here. Three component core loss formula is applied and core losses with the cutting effect are denoted by P_2 (2). The effect of generated thermal and mechanical stresses due to laser cutting is included in the analytical expression of local permeability and core losses. The expression of local magnetic permeability ($\mu(H,x)$) is presented in (3). Here μ_{nd} is magnetic permeability of non-degraded material; $\Delta\mu(H)$ and a are fitting parameters.

$$P_2 = \sum_{n=1}^{n=N} K_h(B,x) B^{\alpha(B)} f_n + K_e B^2 f_n^2 + K_{ex}(B,x) B^{1.5} f_n^{1.5} \quad (2)$$

$$\mu(H,x) = \mu_{\text{nd}}(H) - \Delta\mu(H) e^{-ax} \quad (3)$$

The effect of laser cutting is included in the hysteresis ($K_h(B,x)$) and excess loss coefficients ($K_{ex}(B,x)$). Further, similar analytical expressions are applied to derive the respective local core loss coefficients (4), (5) i.e. polynomial functions depending on magnetic flux density ($\Delta K_h(B), \Delta K_{ex}(B)$) and exponential function of distance from the cut-edge (x). $\Delta K_h(B), \Delta K_{ex}(B), b$, and c are fitting parameters. The fitting parameters are the result of the least square curve fitting of the measurement data obtained from samples B-E (Table I). Further, the effect of laser cutting is also analyzed in the measured stator core losses of laser cut and EDM cut stators. Both the stators are identical in terms of winding, geometry and electrical steel grade except the cutting method.

$$K_h(B,x) = K_{h0} + \Delta K_h(B) e^{-bx} \quad (4)$$

$$K_{ex}(B,x) = K_{ex0} + \Delta K_{ex}(B) e^{-cx} \quad (5)$$

B. Loss model for welding effects

The effect of welding on the stator core losses is included by the coefficient $K_{weld}(B)$. K_{weld} represents the relative increase in the measured core losses of *welded* ring core with respect to *unwelded* ring core at 50 Hz. Therefore, it represents the combined effect of local eddy currents in welding passes as well as generated thermal and mechanical stresses due to the welding process. The ring core measurement setup described in Section II-B is used in deriving the coefficient K_{weld}. As presented in Section IV-B, a second-order polynomial of magnetic flux density is applied in driving the coefficient K_{weld}. The stator core losses with cutting effect is denoted as P_2 (2) whereas P_3 included the effects of cutting and welding as presented in (6).

$$P_3 = (1 + K_{weld}(B)) P_2 \quad (6)$$

Further, an engineering approach is followed by the authors to include the effect of welding in the FE analysis of the electrical machine. The type of welding (laser welding) and the number of weld spots are the same in both the studied *welded* ring cores and the manufactured stator to produce a partially similar welding effect. As the ring core magnetic measurements are effectively performed in yoke material, the whole yoke material is considered welding affected area.

C. Loss model for shrink fitting

A laser cut stator is welded and shrink fitted with an aluminium frame. The core loss measurements are performed before and after fitting the frame on the stator. The difference in the measured parameters reflects the effect of shrink fitting. The dummy blocked rotor test setup with and without the frame is used and presented in Fig. 2 in Section II-C. The measurements are performed at 50 Hz and different supply voltages in the range of 50 V to 450 V; hence, the flux ($\propto V/f$) is varied during the test. The effect of shrink fitting on the stator core losses is accounted through the coefficient $K_{frame}(B)$. K_{frame} represents the relative increase in the measured core losses of the yoke region of stators with and without shrink fitting at 50 Hz. As presented in the result Section IV-C, a second-order polynomial of magnetic flux density is applied in deriving the coefficient K_{frame}. The stator core loss with laser cutting, welding and shrink fitting effect is denoted as P_4 as presented in (7).

$$P_4 = (1 + K_{frame}) P_3 \quad (7)$$

D. Inclusion of manufacturing effects in FEM tool

The FEM analysis is carried out by a FEM solver written in MATLAB environment. The solver is based on well known magnetic vector potential based AV formulation as described in [18], [19]. The cutting loss model is applied such that the distance from the nearest cutting edge was calculated for each finite element of the iron region. Then, the respective local core losses are calculated based on (2). The coefficient of welding (K_{weld}) and shrink fitting(K_{frame}) are applicable effectively for the yoke region. While calculating the core losses as part of post processing, magnetic flux is calculated in each finite element of yoke region. The magnetic flux dependent coefficients (K_{weld} and K_{frame}) are then applied in the yoke region and the rest of the iron regions are considered unaffected by the welding and shrink fitting processes.

IV. Results

This section is divided into five subsections. The first subsection includes the measurement results of the steel strips and derived fitting parameters to analyze the cutting effect. The second subsection includes the magnetic measurement of *unwelded* and *welded* ring cores and derivation of the parameter K_{weld}. The third subsection includes analysis of the measured stator core losses with and without frame to study the shrink fitting effect and derivation of parameter K_{frame}. Finally, the last two subsections include the comparative

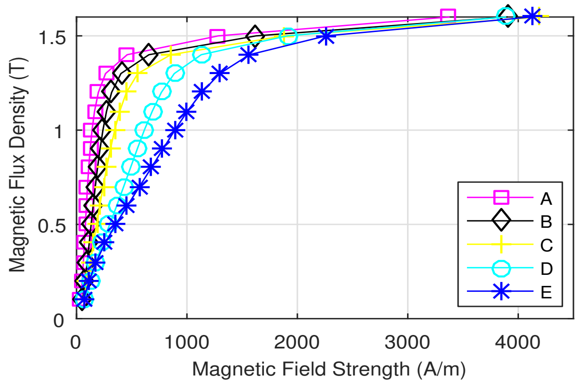


Fig. 3: Measured magnetization curves at 50 Hz for different sample widths. The detail of samples are provided in Table I.

analysis of the manufacturing effects and the importance of inclusion of the manufacturing effects in the calculation of the stator core losses respectively.

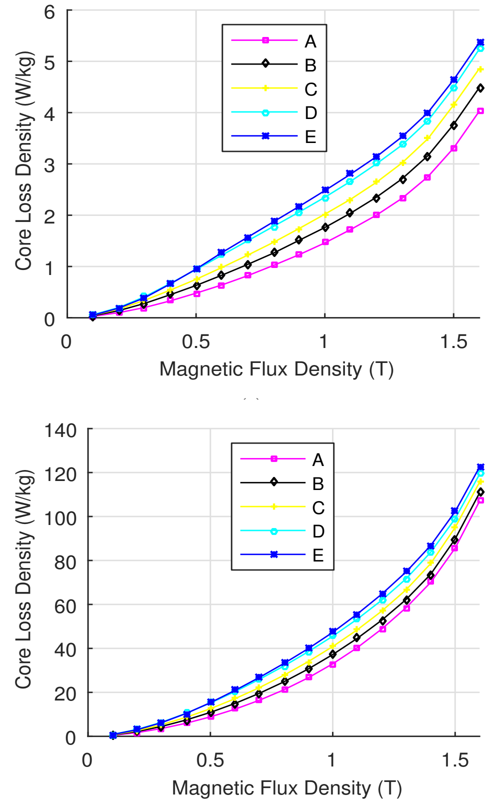
A. Parameters for cutting loss model

As described in Section III-A, magnetic measurements are performed on the strips of different widths with the help of Epstein frame. The measured single value BH curves in terms of the peak value of magnetic flux density and magnetic field strength of different samples (A-E) are presented in Fig. 3. The degradation of magnetic permeability is observed successively from sample A (lowest cutting length sample) to sample E (highest cutting length sample). Similarly, the core loss density is increased due to the cutting effect. Fig. 4a and 4b present the measured core loss density of different samples at 50 Hz and 400 Hz respectively.

The local BH and core losses presented in Section III-A (3), (4) and (5) are derived from these measurements. As a result of the fitting process, the maximum effect of laser cutting in terms of the difference in magnetic permeability ($\Delta\mu(H)$), hysteresis loss coefficient (ΔK_h) and excess loss coefficient (ΔK_{ex}) are presented in Fig 5. It can be observed that the cutting effect depends on the magnetic flux density and tends to diminish at the magnetic saturation. The values of all the fitting parameters and subsequent validation are described in detail in [3]. The effect of cutting on core losses is also studied in the machine prototypes manufactured from laser cutting and EDM cutting (considered partially unaffected from cutting). The measured stator core losses in laser cut stator were 9 % higher as compared to EDM cut stator at the rated supply (400V, 50 Hz). Both the stators are welded with the same laser welding machine and have the same number of weld spots. Therefore, the respective difference in the measured stator core losses is considered only due to the laser cutting.

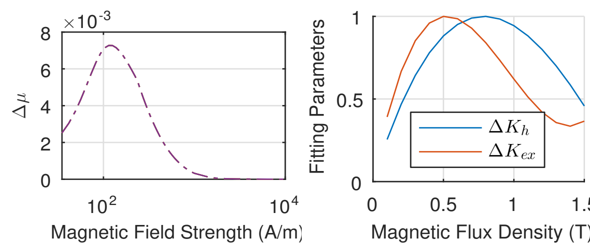
B. Parameter for welding loss model

To analyze the effect of welding, magnetic measurements are performed on *unwelded* and *welded* ring core stacks assembled from the stator laminations. Magnetic flux is controlled to be sinusoidal during the measurements. Figs 6a and 6b



(b)

Fig. 4: Measured core loss curves of different width samples at (a) 50 Hz (b) 400 Hz.



(a) (b)

Fig. 5: Parameters (a) $\Delta\mu$ (b) ΔK_h and ΔK_{ex} in per units. The maximum values of ΔK_h and ΔK_{ex} are 0.023 and 0.0022 respectively. In general effect of cutting diminishes at saturation.

presents the welding effect on the magnetic permeability and core loss density at 50 Hz supply frequency. The welding effect resulted in a decrease in the magnetic permeability and an increase in the core loss density. Fig. 7 presents the relative difference in the measured core loss density (ΔP_w) of *unwelded* and *welded* ring cores at 50 Hz supply. The increase due to welding is observed in the range of 15-30 %. A second-order polynomial is fitted to derive coefficient K_{weld} which is a function of the measured magnetic flux density.

The increased core losses show the cumulative effect of generated residual thermal stresses and local eddy currents in welding passes. A non-monotonic behaviour is observed which

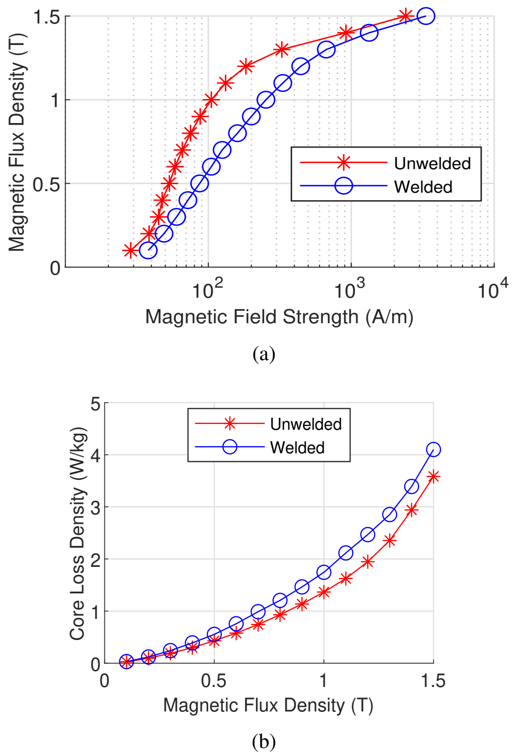


Fig. 6: Magnetic measurements of unwelded and welded ring core samples at 50 Hz(a) magnetization curve (b) core loss measurements.

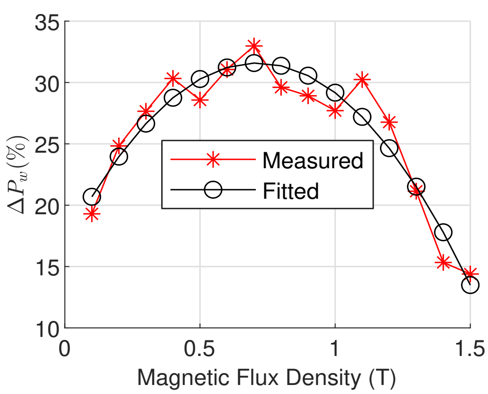


Fig. 7: % Difference in the core loss density due to the welding effect at 50 Hz. Fitting is done with a polynomial of second order.

may be due to increased local eddy currents with increasing magnetic flux. Also, the local eddy currents may push flux in middle of the yoke. However, the effect seems to diminish towards the magnetic saturation. Similar results are observed when the effect of welding was studied on rectangular steel strips with Epstein frame test setup [20].

C. Parameter for shrink fitting loss model

A laser welded stator with and without an outer frame with the dummy blocked rotor test setup is measured to study the effect of shrink fitting. The test is performed at 50 Hz and supply voltages in the range of 50 V to 450 V. The measured

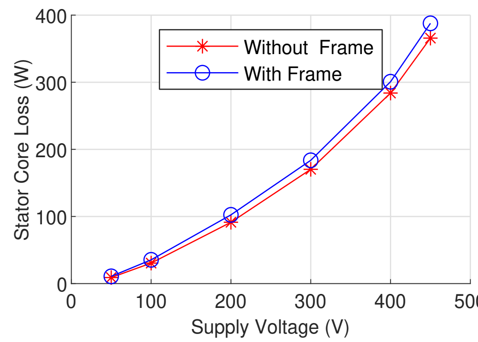


Fig. 8: Measured stator core losses with and without shrink fit at 50 Hz and different supply voltages.

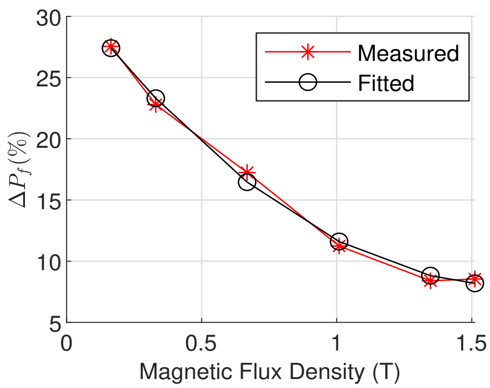
stator core losses are presented in Fig. 8. It is observed that the stator core losses have increased due to the generated compressive stress during the shrink fitting process. Although it is well known that magnetic permeability of electrical steel decreases due to mechanical stresses [21], [22], the measured current showed negligible effect due to mechanical stresses generated due to shrink fitting process in the studied machine. This is expected as air-gap of the machine contributes majority of the reluctance of the magnetic circuit.

FE simulation of the test setup is performed to calculate average flux density in the yoke region at each measured data point. The weighted average of magnetic flux density with respect to area of the mesh elements of the yoke region was calculated. Further, the core losses are calculated by FE post-processing and it was observed that most of the stator core losses are contributed by the yoke region (about 70 %). As shrink fitting generated stresses mainly affect the yoke region [12], the difference in the measured stator core losses is due to the increased core losses in the yoke region. Fig. 9a presents the relative increase in the core losses in the yoke region (ΔP_f) with respect to the average magnetic flux density at 50 Hz. The increase due to shrink fitting is observed in the range of 6-28 %. A second-order polynomial is fitted to derive the coefficient K_{frame}. Effect of shrink fitting start to diminish towards magnetic saturation. Similar observation are also reported in literature [12], [21].

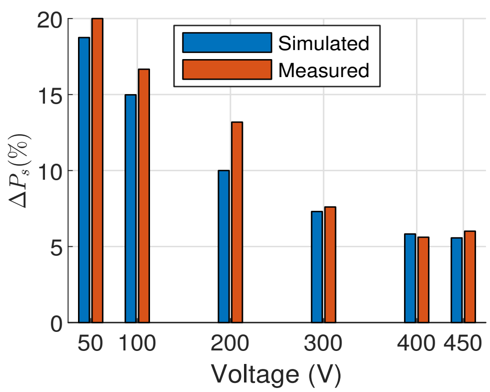
FE analysis of the dummy rotor test setup is performed and coefficient K_{frame} was considered at the post-processing stage to include the effect of shrink fitting in the iron losses. Fig. 9b shows the simulated and measured increase in the stator core losses. The simulated increase in the stator core losses follows the respective measured values closely. This proves the suitability of K_{frame} in calculating the effect of shrink fitting on the core losses of the studied machine.

D. Segregation of effects of manufacturing processes

The effect of manufacturing processes i.e. laser cutting, welding and shrink fitting of the frame is included in the time-stepping FE analysis of the dummy blocked rotor test setup described in Section II-C. A voltage source FE analysis is performed which is based on well known AV formulation. The flux density distribution at rated supply (400 V, 50 Hz) is presented in Fig. 10.



(a)



(b)

Fig. 9: (a)% Difference in the yoke region core losses (ΔP_f) due to the shrink fitting at 50 Hz. Fitting is done with a polynomial of second order to calculate K_{frame} . (b) % Increase in measured and simulated stator core losses due to shrink fitting. Coefficient K_{frame} was considered to include to the shrink fitting effect in FE simulations.

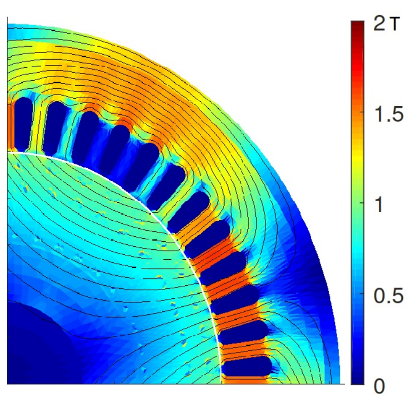


Fig. 10: Flux density distribution at 400V and 50 Hz supply. The color discontinuities are only artifacts due to the plotting routines.

The FE simulations are performed at different supply voltages in the range of 50 V to 450 V at 50 Hz sinusoidal supply frequency. The contribution of individual manufacturing processes (laser cutting, welding, shrink fitting) is calculated as per following.

- The stator core loss P_1 is based on the Epstein frame test on sample A (widest sample). Hence does not include any manufacturing effects.
- The core loss increase due to laser cutting is calculated as $P_2 - P_1$.
- The core loss increase due to welding is calculated as $P_3 - P_2$.
- The core loss increase due to shrink fitting of frame is calculated as $P_4 - P_3$.

The analytical expressions of P_1, P_2, P_3 and P_4 are described in Section III. At the rated supply (400 V, 50 Hz), the contribution of manufacturing processes was observed about to be 23 % of the total stator core losses as presented in Fig. 11. The remaining losses are a result of standard Epstein frame measurement i.e. P_1. The contribution of laser cutting, welding and shrink fitting was about 10 %, 7 % and 6 % respectively. The effect of manufacturing processes increases towards lower supply voltages i.e. lower flux conditions in the machine. This observation is in line with the presented dependency of the coefficients of hysteresis loss $K_h(B,x)$, excess loss $K_{ex}(B,x)$, welding $K_{weld}(B)$ and shrink fitting $K_{frame}(B)$. The contribution of laser cutting, welding, and shrink fitting is increased to 12%, 12 % and 16 % respectively at 50 V supply. While comparing the 200 V and 50 V results, the contribution of shrink fitting has increased while welding is reduced. This observation is due to increased value of coefficient K_{frame} (Fig. 9a) at lower flux levels while opposite effect is observed for the coefficient K_{weld} (Fig. 7). In summary, a significant effect of the manufacturing processes can be seen in the studied stator.

E. Effect of manufacturing effects on the simulation accuracy of core losses

The effect of including manufacturing effects on accurate estimation of the core losses of the electrical machine can be analyzed by comparing simulation and measurement results. Simulation results are compared with the respective measured values of Cases 1-3 of dummy blocked rotor test setup which include the effect of different manufacturing processes. The details of the cases are listed in Section II-C.

Fig. 12 presents the relative error in the simulated stator core losses with and without considering all manufacturing effects. If manufacturing effects are not included in the simulations the error in the computation of the stator core losses is as high as 46 % at low flux levels which decreases to about 13 % for the measured values at the rated flux (supply voltage). The errors are calculated with respect to the measured values and indicates that the measured losses are higher than the respective simulated values when manufacturing effects are ignored. Significant improvement in the computation of stator core losses is observed as the respective error is within $\pm 12\%$ across the different data points. Figs 13 and 14 represent the errors in measurement of Case 1 and Case 2 respectively. Relatively high errors are observed at 400 and 450 V even when manufacturing effects are considered. This may be partly due to the higher magnetic flux in the yoke region at these operating points since presented welding and shrink fitting

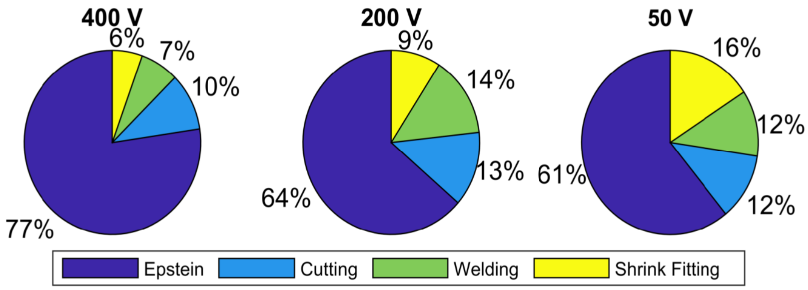


Fig. 11: Impact of manufacturing processes on stator core losses at 50 Hz supply frequency. Core losses from standard Epstein frame test is calculated as P1. Laser cutting, welding and shrink fitting effects are calculated by differences P2-P1, P3-P2 and P4-P3 respectively.

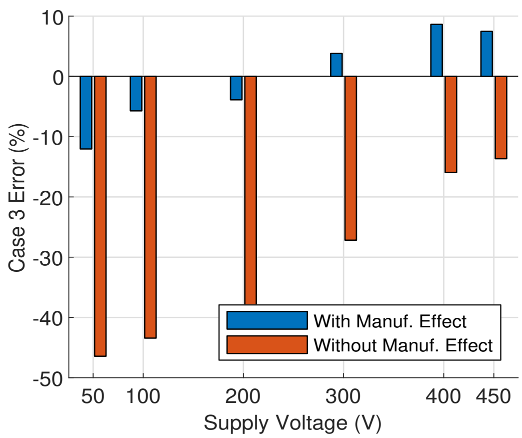


Fig. 12: Error in the stator core losses with and without considering the manufacturing effects in Case 3 (laser cutting, welding and shrink fitting) at 50 Hz and different supply voltages. Laser cut welded stator is measured with frame.

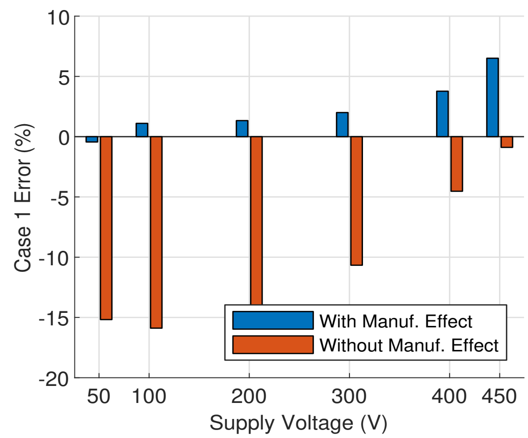


Fig. 13: Error in the stator core losses with and without considering the manufacturing effects in Case 1 (only welding effects) at 50 Hz and different supply voltages. EDM cut welded stator is measured without frame.

loss models are limited to 1.5 T. All the studied cases show improvements in the simulated core losses with respect to the measurements when the effect of manufacturing processes is included in the core loss computation. Hence, indicates the necessity to model the manufacturing effects at the design stage for the accurate estimation of core losses.

V. Analysis and Discussion

It is worth to note that the presented paper followed a local approach while modeling the effect of laser cutting; however, a global approach is applied in case of welding and shrink fitting modeling. The effects of laser cutting, welding, and shrink fitting are analyzed in the machine by superposition. In practice the superposition of interdependent effects will lead to an overestimation of the core losses, however, the respective error was found to be minor as compared to neglecting the effect of manufacturing processes altogether. It is important to note that the steel strips, ring cores, EDM and laser cut stators are manufactured from the same mother coil (MC) hence the variation in magnetic properties of MCs can be neglected. According to [23] the variation in magnetic properties between MCs can be as large as 7 %. The combined effect of manufacturing processes both in simulations and measurements exceeds the variation due to MCs.

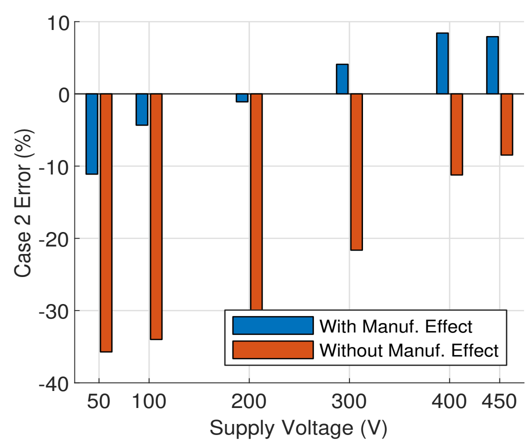


Fig. 14: Error in the stator core losses with and without considering the manufacturing effects in Case 2 (only laser cutting and welding) at 50 Hz and different supply voltages. Laser cut welded stator is measured without frame.

Admittedly, while calculating the core losses (P_1-P_4), the magnetic field was considered purely alternating and effect of rotational core losses were ignored. [24] compared the effect of rotational core losses on the computation of stator core losses and found the respective error within 6% when rotational core losses are ignored. The effect of manufacturing presented in the paper far exceeds the effect of rotational core losses. Further, as comparative measurements with dummy blocked rotor test set up at different manufacturing processes (laser and EDM cut stators, and stators with and without shrink fitted frame) are presented, rotational core losses are believed to have a nearly identical effect on the measured quantities. Hence, it does not affect the quantification o f d ifferent manufacturing processes in the studied machine.

Stator core loss measurements are performed with sinusoidal frequencies of 25 Hz, 33.33 Hz as well with presented dummy blocked rotor test setup. The supply voltage/frequency ratio is kept the same across the frequencies. The obtained results are shown in Fig. 15 with and without the frame to analyze the shrink fitting effect. A minor increase in the stator core losses can be seen with increasing frequency. Magnetic experiments on steel samples in the frequency range of 50-500 Hz shows all loss components i.e. hysteresis, eddy current and excess losses are affected by applied stresses [25].

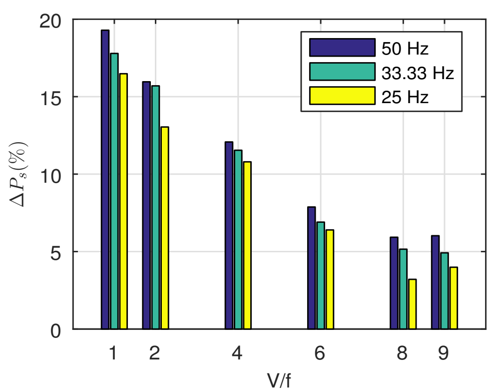


Fig. 15: Effect of shrink fitting on the measured stator core losses at different supply voltages and frequencies. V/f ratio is kept same across different frequencies.

Moreover, the local eddy current losses due to welding are affected by supply frequency as shown in [26], [27]. This may increase the contribution of welding effects at higher frequencies as compared to respective cutting and shrink fitting effects. Indeed, the presented segregation of the effect of manufacturing processes on core losses is limited to 50 Hz (rated) supply frequency which is intended for the studied industrial motor. As the sinusoidal supply is provided by a generator and limited to a maximum value of 50 Hz, the results thus can not be extended to higher frequencies. However, considering the limited frequency range in this study future research in this challenging area is encouraged.

A 0.7 mm thick glass fibre sheet is used to maintain approximately uniform airgap with the presented dummy blocked rotor test setup. Therefore a static eccentricity of about 12.5 % is present during the measurements. FE simulations of the test setup are performed with the static eccentricity in the range of 10-40%. A relatively minor (below 0.2 %) increase in the stator core losses is found. These observations are in line with literature ([28], [29]), where reported increase in the iron losses are below 1% for about 30 % static eccentricity. Further, an identical eccentricity is present in all the measured test cases, hence the effect of eccentricity can be ignored in the presented analysis.

VI. Conclusion

The effect of manufacturing processes such as laser cutting, welding, and shrink fitting is studied on the stator core losses of a typical industrial motor. The modeling parameters representing the effect of manufacturing processes are derived with the help of analytical equations obtained from magnetic measurements. The combined effect of manufacturing processes is observed about 23 % on the stator core losses at the rated condition which increases towards lower flux levels. Further, segregation of the effects of laser cutting, welding and shrink fitting on the stator core losses of the studied machine are also presented. The proposed modeling approach follows the respective measured values closely.

The energy efficiency of electrical machines are getting more attention not only due to sustainability requirements but also emerging applications such as electrical vehicles, electrical aircraft, etc. The inclusion of manufacturing effects in the core loss computation will improve the accuracy of simulations and thus will help the machine designers to design energy-efficient machines in the future.

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