Evolution of Magnetic Properties During Tempering

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Abstract Quality control in heat treatment of steel is often conducted after the treatment. Failure to confine within the specified range of mechanical properties may lead to wasted energy and production resources. Performing quality control in-line in the heat treatment process allows for early detection and possibility to react to changes in the process. The prospects of utilizing the change in the electromagnetic (EM) properties of steel, as means for quality control, is investigated in this paper. The focus is on the tempering process of hardened SS2244 (42CrMoS4) steel. The tempering takes the hardness of the steel from approximately 600 HV down to around 400 HV. The EM signature of the steel is recorded during the tempering process. This is later compared to results from more traditional means of material characterization, such as Laser Scanning Microscopy, X-ray Diffractometry and Vickers microhardness measurement. This initial study shows clear indications of precise detection of the hardness through EM properties during tempering process of selected material.

Keywords In-line Measurement · Quality Control · Electromagnetic Properties · Tempering

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1 Introduction

Tempering is a heat treatment technique in which the goal is to reduce the hardness of hardened steel and thereby increase its toughness. The tempering process is dependent on both process temperature and time as well as material composition. Empirical relations, such as Holloman-Jaffe [1], between hardness and tempering time and temperature are usually used to determine the appropriate process parameters. These give good guidelines, but perhaps not the sufficiently correct value for any given steel if the data available is insufficient [2].

To ensure the performance of the steel or product is as specified, the quality control is traditionally performed after the tempering process. If the performance is substandard, the process parameters can be adjusted. This procedure is fine while tuning the process but will become a problem if something unexpected occurs. In best case, the steel can be put through the hardening process again and then re-tempered. In worst case this leads to scrapping of substandard products. Performing quality control early in the process could potentially catch mistakes before it is too late. Ideally quality control would occur in-line within the heat treatment process, with a non-destructive method. Traditional methods for mechanical testing of steels are hard to incorporate in-line, since they are designed to work in controlled environments. Measurement of any quantitative or qualitative value of, for example, hardness must be performed indirectly, as to not affect the finished product.

Inductive sensors have been used to measure properties indirectly within a variety of different areas. For instance, inductive sensors have been used to measure temperature in domestic induction cooktops [3] as well as in harsh environments [4, 5].

Inductive methods have also been used in quality con-

trol. Detection of cracks and voids in for example welded joints are made possible by inducing eddy currents in the target area and then either measuring the leakage flux [6, 7] or detecting local deviations in the thermal response [8, 9, 10]. Eddy current sensors have also been used in other applications, such as detecting defects buried inside parts made with additive manufacturing [11] and as a method for automated measurement of the thickness of metallic plates [12]. For grinding processes, Barkhausen noise has been used to monitor the process and detect thermal damage [13].

It has also been shown that the depth of decarburization can also be measured by utilizing the difference in the electromagnetic (EM) response at different depths [14].

In this paper, the aim is to investigate the correlation between the variation of microstructure of low alloyed steel and its EM properties during the tempering process. Since the steel hardness is one of the most sensitive properties to the changes in materials' microstructure, the obtained data allow estimation of the applicability (sensitivity and reliability) of the proposed technique for in-line measurements of hardness indirectly through EM properties and/or its monitoring during heat treatment. This paper focuses on tempering, although other heat treatment processes of steels could also be suitable to utilize with this technique. The concept could be realized as a stand-alone sensor, as means for feedback control from the process, or being a part of the system, if induction heaters are used. The analysis of main factors influencing on the magnetic properties and EM measurements of steels are introduced below.

2 Electromagnetic-Mechanical Coupling

There are numerous factors which contribute to the magnetic properties of steels, including chemical composition, impurities, strain, temperature, crystal structure and crystal orientation. Sections 2.1 and 2.2 will provide a more in-depth review on how the magnetic properties are affected by these factors individually. The magnetic properties can be categorized into two groups: structure-insensitive and structure-sensitive [15], summarized in Table 1. In addition, the remanence (B_r) is also considered to be structure-sensitive [16]. In a broad sense this gives an indication to what underlying process may affect a certain magnetic property. As tempering alters the target materials microstructure, it is reasonable to assume that the magnetic properties listed in the structure-sensitive column will change during the process.

Table 1 Magnetic properties divided into structure-sensitive and structure-insensitive groups [15].

Structure-insensitive	Structure-sensitive
Saturation magnetization	Permeability
Curie point	Coercive force
Magnetostriction at saturation	Hysteresis loss
Crystal anisotropy constant	

2.1 Mechanisms leading to change of magnetic properties in steels

There is generally no single cause that determines the magnetic properties of a material. The main contributors to magnetic properties are the composition, crystal structure and crystal orientation. Depending on composition, different heat treatment techniques may be used to alter the crystal structure and hence the mechanical properties such as hardness, yield strength etc. A mechanically hard steel is generally also magnetically hard. This means that processes aimed at making steels mechanically softer, more ductile, would also restore magnetic softness to the same steel. Magnetically hard materials are often characterized with larger coercivity (H_c), which requiring higher magnetic field strength (H) to affect the state of magnetization, e.g. reverse the direction of magnetization or to demagnetize.

Some elements commonly used in steels are more inclined to provide good magnetic properties, while other elements do not show any significant impact on the overall magnetic properties. More on this in section 2.2. Impurities and other imperfections, such as inclusions, dislocations, and voids in the crystal structure, hinder the domain wall motion of nearby domains. Domain walls are generally situated in a local energy minimum, i.e. small applied field strength would cause minor movement of the domain wall around its minimum and as the field is removed the domain wall would fall back to its original resting position. Imperfections are in this case larger energy maximums, which require large field strengths to push the domain walls past it. In fact, the domain walls prefer to bend around the site of imperfection, given the field strength is not large enough to push it completely over the site. Whenever a large enough field strength is applied to warrant a domain wall motion beyond an imperfection, the domain wall would find a new local energy minimum at the other side of the imperfection when the applied field is removed. The effect of the imperfections on the bulk material manifests as decreased initial relative permeability (μ_r) and increased H_c [17].

Steel sample under applied mechanical stress will show different magnetic properties compared to a relaxed

sample. This effect is also different, depending on whether the magnetic properties are measured along the stress axis or orthogonal to it. Applied tensile stress on a sample with positive magnetostriction will favor the magnetic domains oriented in the same direction as the stress, i.e. parallel or anti-parallel to the stress axis. This will make the favored domains grow in size, at the expense of the unfavored, and hence become more easily magnetizable in the direction of the tensile stress [18].

The relative permeability of a ferromagnetic material changes with temperature, becoming paramagnetic as the Curie temperature (T_c) is reached. The behavior is different depending on the field strength applied to the specimen. For high fields strengths, μ_r decreases slightly with increasing temperature at low temperatures. The decrease becomes larger as the temperature increases until the material becomes paramagnetic. For low field strength this behavior is quite different. The change in μ_r is subtle at low temperature, remaining mostly constant. The relative permeability starts to increase rapidly when the temperature approaches T_c . μ_r reaches its maximum value just below T_c , after which it rapidly descends to unity for higher temperatures. This characteristic behavior is associated with the low magnetic anisotropy energy at temperature close to T_c [15].

Crystal orientation of ferromagnetic material are rarely oriented randomly in space, instead they have a preferred orientation, called crystallographic texture. The texture depends on the shape and process used to form the bulk product. The preferred orientation is close to parallel to, for example, the rolling direction for sheet metal. Grain-oriented electrical steel uses the preferred orientation from rolling to its advantage to produce a better magnetic flux conductor commonly used in electrical machines and power transformers [18].

2.2 Sensitivity of alloying elements on magnetic properties

Finding openly published magnetic properties for a steel of a specific chemical composition is hard, if not impossible. Bozorth [15] has compiled the work of numerous researchers, where the most common binary and ternary ferromagnetic alloys are considered. His work is mostly aimed at applications related to permanent magnets or flux conductors, which is to say that the presented compositions are more related to magnetic components rather than structural components. However, there are some overlapping in the composition ranges,

making it possible to correlate some of the effect of composition in a qualitative manner. Below is a summary of how common elements of steels affect the magnetic properties. The information is extracted from [15] if not otherwise stated.

Phosphorus (P) and sulfur (S) are considered impurities. Impurities in general increases the H_c while also decreasing μ_r .

Manganese (Mn) is often used to increase the workability of steels. From a magnetic properties point of view, small amounts ($\leq 1\%$) have little to no effect.

In iron-silicon (Fe-Si) alloys, increased Si content increases the maximum μ_r while also reducing the H_c . However, the effect of Si on magnetic properties is small for contents up to 3 %. The resistivity on the other hand do increase about five times.

For iron-carbon (Fe-C), the general behavior is that the resistivity and H_c increases with increasing carbon content, while saturation magnetization, initial μ_r , maximum μ_r , and B_r decreases with increasing carbon content. This behavior is more muted in an annealed state, i.e. the change is less pronounced for an annealed sample if compared to a quenched. For carbon contents over 0.4 %, the change with increasing content is less pronounced, i.e. most of the dynamics is at low carbon content.

When adding chromium (Cr) to steel (Fe-C-Cr alloys) the effect is mostly visible in the B_r , while C shows in the H_c . For low C content ($\leq 0.5\%$) the addition of Cr mainly reduces the B_r , but also slightly increases the H_c . For higher C contents the B_r increases for Cr content above 1 %, after which the B_r starts to decrease again. The effect on H_c at higher carbon content is also more subtle, where it remains approximately constant to about 4% Cr and starts decreasing at higher Cr contents.

For molybdenum (Mo) steels, the presented results are for alloys containing 1-1.3 % C and more than 0.5 % Mo, which is not great for comparison with structural steels. Mo content is usually maintained fairly low, usually within a few tenths of percent for structural steel [19]. With a constant C content, the Mo content mainly affects the H_c , reaching a maximum at about 3 % Mo. In the range 0.5-3 % Mo the H_c increases about 75 %, with a near linear rate of change at the lower part of the range.

Nickel (Ni) in Fe influences the magnetic properties quite a bit, but only at quantities in the order of several tens of percent. At low quantities of Ni ($< 1\%$), the effect is minimal on the magnetic properties but could be visible in the increase of resistivity.

Table 2 Standard chemical composition for SS2244 (42Cr-MoS4).

Element	Weight [%]
C	0.38-0.45
Si	0.1-0.4
Mn	0.6-0.9
P	0.35 (max)
S	0.02-0.035
Cr	0.9-1.2
Mo	0.15-0.30
Fe	Rest

Table 3 Comparison of mechanical properties between tempered and quenched sample of 42CrMoS4 according to material specification.

Properties	Tempered	Quenched
UTS [MPa]	1200	1900
0.2 % YS [MPa]	1100	1550
Elongation [%]	12	3
Impact strength [J/cm ²]	65	30

3 Experimental work

3.1 Procedure

The steel SS2244 (42CrMoS4) is chosen as the target material for the measurement as a conventional construction material that usually undergoes heat treatment (both quenching and tempering) before use. The standard chemical composition is shown in Table 2. The steel had been hardened by oil quench at 840 °C to approximately 600 HV prior to tempering.

The tempering temperature was selected to 560 °C, providing relatively large change in the mechanical properties of the steel as compared to quenched material, see Table 3.

The experimental work is divided into two parts: one is related to characterization of the samples' microstructure and microhardness and one for the EM properties of steel samples with different tempering time. As the result of tempering is dependent on both time and temperature (for certain sample material), the ovens were preheated to 560 °C to provide a consistent starting point for the samples for both the mechanical properties and the EM properties.

For the estimation of variation of steel's microstructure and microhardness, cube shaped samples with a side length of 8 mm were used. The samples were extracted one by one after specific times ($t = 1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 25$ min) in the oven and left to cool down in room temperature. This allows for analyzing the effect of the tempering at a later point and to correlate these properties to the EM measurement.

As for the EM measurement, the procedure is somewhat different. The same sample is subjected to the entire tempering cycle, because the interest in this study lies in finding the correlation of the in-line measured EM signature of the sample to the finished tempered sample. The EM properties were measured at specific times, trying to match the ones from the other measurement part as well as take supplementary measurements in between where possible.

3.2 Hardness and microstructure

Assessment of the mechanical properties was performed through the measurements of Vickers microhardness with loading of 1 kg and duration of 10 seconds (THV-30MDX). The microhardness was measured 8-10 times in different places on the polished sample surface and mean values were taken into account.

For the microstructural study, the samples were first mounted and then polished mechanically to mirror finish using 1 μ m colloidal silica suspension. The samples were then etched with 2 % Nital etchant for revealing the microstructure, and investigation was done with laser scanning microscope (LSM) (Keyence VX-200).

The changes of the samples' microstructure due to the heat treatment was also studied with X-ray diffractometry (XRD) in CuK α radiation (STOE STADI MP). The relative concentration of carbon in martensite phase at different tempering times (from 1 to 25 min) was estimated by calculation of the interplanar spacing of martensite lattice in (110) direction by the equation

$$d^2 = \frac{a^2}{h^2 + k^2 + \frac{l^2 a^2}{c^2}} \quad (1)$$

where $c/a = 1 + 0.467p$ – lattice tetragonality, p – carbon content in the martensite [20].

3.3 Electromagnetic properties

Depending on what the aim is with measurement of EM properties, the frequency at which these are measured may be selected differently. A low frequency is generally a good choice if the fundamental EM properties of a material is of interest. Here, the measured magnetic hysteresis loss (W_h) can be correlated to microstructural hardness of the sample. For higher frequencies, in the order of several kHz, other factors tend to drive the losses. The bulk of the induced currents are located closer to the exterior (closest to the excitation winding) of the sample due to the skin effect, increasing the eddy current losses significantly, when the frequency is increased. The hysteresis losses are still present in the

Figure 1 Illustration of the measurement setup, highlighting the main components. The windings are colored to differentiate between excitation current I_{ex} (red) and induced voltage U (blue).

sample but now obscured by eddy current losses and separation between the losses is all but simple to establish. Of course, parameters such as sample size should be considered when selecting the frequency. For very thin samples, a higher frequency is more relevant to get appropriate readings. Higher frequencies could also be useful when trying to mimic a real process, e.g. induction heating. In this case one would also have to revise the sample and coil geometry to something analogous to the process. The result would then also be more related to inductance with some effective μ_r parameter, rather than the fundamental B-H relationship.

The EM properties are measured on a toroid (see Figure 1) sample with the size 80 mm outer diameter, 64 mm inner diameter and 8 mm height. The toroid is wound, like a transformer, with a primary and a secondary winding. The turns ratio is 30:30, i.e. there is the same amount of turns on the primary as the secondary winding. The insulation of the wire used in the winding is rated to withstand 1000 °C, allowing measurements to be made at elevated temperatures, without running the risk of short-circuiting the windings. To measure the EM properties, the primary side is excited with low frequency high amplitude current, which induces a voltage across the secondary winding. The primary current corresponds to the magnetic field strength (H), giving according to *Ampere's circuital law*

$$H = \frac{N_p I_{ex}}{l_e} \quad (2)$$

where N_p is the number of turns on the primary, I_{ex} is the excitation current and l_e is the effective magnetic path length. According to *Faraday's law of induction*, the time integral of the induced voltage on the secondary side corresponds to magnetic flux density (B) with

$$B = \frac{1}{N_s A_e} \int_0^T U dt \quad (3)$$

Figure 2 Illustration of a (a) generic B - H curve, (b) initial magnetization and (c) the corresponding relative permeability, where μ_{r0} is the initial relative permeability and $\mu_{r,max}$ the maximum relative permeability.

where N_s is the number of turns on the secondary side, A_e is the effective magnetic cross-sectional area and U is the induced voltage drop. A_e and l_e is used to compensate for the toroid geometries which have a large difference between the inner and outer diameter. These formulas recalculate the geometry to match the mean path perceived by the magnetic field. In this case these could be approximated with the average circumference and the cross-sectional area, and still be below one percent error in the approximation.

B and H give the *constitutive relation*

$$B = \mu_0 \mu_r H \quad (4)$$

where μ_0 is the vacuum permeability ($4\pi 10^{-7}$ H/m) and μ_r is the relative permeability. This relation is often illustrated with the B - H curve, shown in Figure 2. The figure illustrates other measurable quantities as well, such as the coercivity (H_c), remanence (B_r) and the hysteresis loss (W_h) (enclosed area of the B - H curve).

The Fischer Feritscope FMP30, hereinafter referred to as Feritscope, was used as a complement to the EM measurements. This device is normally used to measure ferrite content in weld beads for parts made of austenitic stainless steels. At its core, the Feritscope induces a magnetic field into the target material and

measures the EM response of the material, likely in the terms of magnetic permeability [21]. As austenitic phases are paramagnetic, the device can detect the degradation of the permeability, i.e., a fully austenitic steel would have a μ_r close to one while a steel which is a mixture ferromagnetic phases (such as martensite) and austenite would have a higher μ_r . The response shown by the Feritscope is, through its internal software and calibration reference, converted to a value corresponding to a ferrite content as indicated by the reference calibration. The ferrite content reading given by the Feritscope can be converted into a martensite content, given that a calibration curve has been established. This type of study has been performed for austenitic steel grades AISI 304 and 301LN [22], where the authors found that a simple linear correction factor could be applied to get the martensite content from the ferrite content reading given by the Feritscope. It cannot be assumed that this correction factor applies directly to other steel grades, such as the one used in this study. No actual effort has been put into finding appropriate correction factor for this specific steel. But it is still interesting as a point of reference of a method closely related to the proposed approach. A subset of the samples from the hardness and microstructure analysis was selected to be measured using the Feritscope ($t = 0, 1, 2, 4, 12, 25$ min). Each of the samples was measured 10 times at arbitrary locations to get an average reading.

4 Results and Discussion

4.1 Hardness and microstructure

Measured microhardness of the samples at different tempering times is illustrated in Figure 3a. LSM images of the microstructure are also shown on the diagram (Figure 3b-e). It is evident that decreasing character of the microhardness curve with increase in tempering time is related to the degradation of martensite during the process as demonstrated by the LSM images (see Figure 3). In order to look in-depth into the martensite transformation during the tempering the XRD analysis was performed. General view of the XRD spectra is shown in Figure 4. Analysis of XRD spectra shows that all significant peaks correspond to the martensite lattice in different direction (Figure 4a). No austenite phase and no doublets or triplets of the peaks were detected at the given test and measurement conditions ($2\theta = 20 - 110^\circ$, $\Delta\theta = 0.05^\circ$, dwell 10 seconds).

More detailed measurements were performed for two samples - a reference sample (not tempered) and a sample tempered for 25 min (Figure 4b). The measurements conditions: diapason $2\theta = 30 - 110^\circ$, $\Delta\theta = 0.02^\circ$, dwell

Figure 3 Correlation between (a) microhardness and microstructure LSM images for different tempering times: (b) 0 min, (c) 4 min, (d) 12 min and (e) 25 min.

15 seconds. The precise measurements confirm the previous conclusions regarding the present phases but allows detecting the shift of the peaks in the plane (110) that apparently is related to the diffusion of carbon atoms from the martensite lattice (see embedded image in Figure 4b).

Further measurements were focused on the peak shift in the diapason of 2θ angles from 42° to 48° for assessment of the change of carbon content in the martensite during heat treatment. The measurement conditions were: $\Delta\theta = 0.01^\circ$, dwell 30 seconds. The results are illustrated in Figure 5. The results show that the peaks' intensity increases while the width decreases with increasing tempering time, a behavior which is related to the diffusion of carbon. Besides that, the peak displacement is quite significant at small tempering times and becomes negligible when tempering time exceeds 10 minutes. That result correlates quite well with microhardness curve (Figure 3a).

The measured peak shifts at different tempering times allows, using the equation (1), estimating the change of relative carbon content in the martensitic phase, presented in Figure 6. From the results in Figure 6, it is evident that it is in good agreement with obtained data for microhardness.

Figure 4 (a) General view of the XRD spectra of the samples at different tempering times and (b) more detailed view of the XRD spectra for reference sample and sample tempered for 25 min.

Figure 5 Phase change at different tempering times.

Figure 6 Change of relative concentration of carbon in martensite during tempering.

Figure 7 Collection of B - H curves measured during tempering. The B - H loop is decreasing in size as the tempering time is increasing.

4.2 Electromagnetic properties

The B - H curves measured during the tempering process are shown in Figure 7 where the initial magnetization curves from the demagnetized state are excluded. Here the curves are decreasing in size as the time elapses, with a more rapid pace in the beginning.

Since it is a bit cumbersome to read specific values from the cluster of B - H curves, these are summarized in Figure 8. From here it is easier to identify what happens as the time elapses. Time zero corresponds to the electromagnetic properties in its hardened state, i.e. prior to inserting it into the oven. The first measurement at heated state occurs at 4 minutes, corresponding to the time it took to insert the sample into the oven with the windings attached and connecting it to the measurement system. The remaining measurements were taken approximately 2 minutes apart. The time necessary for one measurement was around 6 seconds, excluding postprocessing and time to write acquired data

Figure 8 Collection of discrete values from the B - H curves, with $H_{peak} = 5.36$ kA/m. The figure includes (a) peak magnetic flux density, (b) relative permeability at H_{peak} and B_{peak} , (c) remanence, (d) coercivity and (e) hysteresis loss. Note that figures (a)-(e) share the same x-axis scale.

to disk for later analysis. The long acquisition time allowed for 3 periods at an excitation frequency of 0.5 Hz. Multiple periods allow for effectively erasing any remaining magnetization from previously applied field during the first period. The excitation current through the primary winding was held constant throughout the measurement series, corresponding to an average peak magnetic field strength of 5.362 kA/m, with a standard deviation of 0.763 A/m.

The most prominent changes can be seen for the H_c and W_h , which are approximately decreased by a factor of two during the first 10 minutes of measurements, followed by a smaller change B_r . The variation μ_r and B_{peak} are not consistent with the change in material properties, rather caused by the variation in the applied magnetic field strength.

The structure-sensitive properties will generally improve

Figure 9 Comparison between HV and H_c .

with larger grains, less dislocations, reduced debris in the grain boundaries and reduced residual stresses. This is observable in the EM measurements, i.e. both the hysteresis loss and coercivity decreases as the tempering time increases (Figure 8). It should be noted that μ_r does not appear to change with any significance during the tempering. This lack of response in the measured relative permeability is likely due to the choice of its representation, i.e. μ_r at peak applied field strength. As the B - H loop of ferromagnetic material is non-linear, there is no single value of μ_r which describes the entire loop. If instead the initial magnetization was analyzed there would probably be noticeable difference in the initial μ_r and/or maximum μ_r . The initial μ_r is inherently hard to acquire due to the accuracy required in both producing and measuring in low magnetic field strengths. As described by *Rayleigh law* the permeability converges to a constant value as the field strength goes toward 0 A/m. The maximum μ_r is on the other hand easier to capture since it would generally appear at field strengths in the vicinity of H_c . To get reliable measurement of the maximum μ_r , one would have to perform a demagnetizing cycle in between each successive measurement. This was, however, not performed to allow for measurements in more rapid succession.

The results from both microstructure characterization and EM measurements show good correlation between microhardness and coercivity. The results from both measurements are alongside each other in Figure 9 for easy comparison. The first 10 minutes show the most prominent response, with the highest gradient, for both cases. Beyond the first 10 minutes the response flattens out, only showing small changes with increasing tempering time. The microstructure analysis suggests that the EM response is linked to the transformation of martensite grains due to the diffusion of carbon atoms and relieving stresses of the martensite lattice (see Figures 3 and 5).

The Feritscope reading shows a small decrease in ferrite

Figure 10 Ferrite content measured with Feritscope. Squares indicate mean value, and the vertical lines indicate the width of the standard deviation.

content with increasing time, when looking at the mean values of the individual measurement for each sample (see Figure 10). The error bound is however quite high, rendering the results impractical for this purpose. Given the results from microstructure analysis, the lack of response from the Feritscope is understandable since no other phases than martensite appears to exist in the samples.

5 Conclusions

This initial study showed that during the tempering of low alloyed steel 42CrMoS4 the needle-like structure of martensite of quenched steel transforms, by diffusion of carbon atoms, to tempered martensite with rounded needles/grains (formation of sorbite or troostite were not detected by LSM and XRD). Despite small changes in the material's microstructure its microhardness decreases by more than a third during the first ten minutes, making it possible to detect the changes of material's microstructure by measuring its EM properties. The change in coercivity and hysteresis loss shows the most prominent EM response for the tempering process, decreasing by approximately a factor of two from its hardened state. The change in remanence showed similar trend, while the change was not as prominent. This correlation between microhardness and EM properties is quite promising for further applications in quality monitoring and control systems on the industrial level. The method used to measure the EM properties in this paper is feasible for laboratory work but might be problematic when considering the practical implementation in a real industrial process. To make use of this in a real process, the change in EM properties of a bulk material needs to be translated to other quantities which are more easily measurable. For the processes using induction heating, this could potentially be realized using the

heating coil. For other heating types, one would have to use a separate inductive sensing head, much like the Feritscope. The results from the Feritscope measurements shows no significant response to the tempering process. The error bounds are too large in comparison to the overall change to give any clear conclusion with regards to microstructural or microhardness changes. In all fairness, this is likely due to that the device is operated outside of the range of its intended application. As the investigation focused on only one steel grade, the results are not necessarily applicable directly on any other steel grade. However, the general behavior is believed to manifest in similar manner in most ferromagnetic steels. Depending on the chemical composition and microstructure, the magnitude of the response might vary.

According to the analysis presented in Section 2.2, the main sensitivity with regards to the magnetic properties in the composition due to alloying elements for this type of steel is in the C and Cr content. Other steels matching these composition ranges could provide similar results as presented in this paper, which could potentially include several Cr and Cr-Mo steels. For steels containing no, or very small amounts of Cr, the presented results might be out of scope. Similar caution should be shown for steels with higher Ni content, such as Ni-Cr and Ni-Cr-Mo steels.

6 Future work

In the next phase the study will continue with a wider range of different steel grades, to get a broader perspective of applicability of this type of measurement. The sensitivity of this type of measurement with regards to chemical composition is also of interest, e.g. to study how steel grades with similar chemical compositions would affect the EM signature.

Furthermore, a practical realization of this type of measurement should be conducted. This in a semi-industrial scale, preferably together with an induction heating process.

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Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no conflicts of interest.

Availability of data and material

Not applicable.

Code availability

Not applicable.

Authors' contributions

Ville Akujärvi: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft

Tord Cedell: Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Writing – review & editing

Oleksandr Gutnichenko: Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing

Matias Jaskari: Investigation, Validation, Visualization, Writing – review & editing

Mats Andersson: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing

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Figures

Figure 1

Illustration of the measurement setup, highlighting the main components. The windings are colored to differentiate between excitation current I_{ex} (red) and induced voltage U (blue).

Figure 2

please see the manuscript file for the full caption

Figure 3

Correlation between (a) microhardness and microstructure LSM images for different tempering times: (b) 0 min, (c) 4 min, (d) 12 min and (e) 25 min.

Figure 4

(a) General view of the XRD spectra of the samples at different tempering times and (b) more detailed view of the XRD spectra for reference sample and sample tempered for 25 min.

Figure 5

Phase change at different tempering times.

Figure 6

Change of relative concentration of carbon in martensite during tempering.

Figure 7

Collection of B-H curves measured during tempering. The B-H loop is decreasing in size as the tempering time is increasing.

Figure 8

please see the manuscript file for the full caption

Figure 9

Comparison between HV and H_c .

Figure 10

Ferrite content measured with Feritscope. Squares indicate mean value, and the vertical lines indicate the width of the standard deviation.