Digitalized Production Planning for Induction Hardening (DigPIn)

Public report

Project within	FFI, Strategic Vehicle Research and Innovation
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Content

Summary

Induction hardening is a fast and energy-efficient process for surface hardening steel components. Only the volume of material to be hardened is inductively heated and then rapidly cooled with a shower quench. The purpose of the project was to introduce a more digitized production planning for induction hardening, which enables rapid implementation of robust processes for new products and new materials. Today, industrial production planning of the induction hardening process is done exclusively through experience-based trial-and-error. The project was divided in three work packages, two of which deal with sub-challenges; WP1: to introduce engineering use of finite element analysis (FEA) and WP2: to quantify incoming material and use data for FEA (AP1) and machine learning. In addition to the implementation plan, AP3 also included pilot cases to link digitized production data (materials, process and performance). Throughout the course of the project three pilot cases were carried out. The project has verified that predictive simulations are possible given a well-defined pilot case with known input data regarding current and material. Moreover, that collecting and analysing production over longer time-periods has the potential to increase quality and capability of this hardening process. The project partners were RISE, LEAX Quality, AB Volvo, VCE, Scania CV, EFD Induction, SKF, Sandvik Mining, Schlumpf Scandinavia, Teknoheat and Swerim.

Sammanfattning på svenska

Projektet har behandlat induktionshärdning, vilket är en energieffektiv metod for ythärdning som används på stålkomponenter inom fletalet industrier. Inom AP1 har projektet utvecklat ett beräkningsfall som kan hanteras i 1-3 dimensioner, vilket är designat för att minimera osäkerheter i den experimentella verifieringen av elektromagnetiska data. En stor utmaning som uppdagades under det senaste året är problematiken med antagandet att strömmen i induktorn har sinusform, vilket krävs för rimliga beräkningar (i fråga om tidsåtgång) i frekvensdomänen. Projektparten EFD har lagt betydande resurser på att arbeta med problematiken (och därmed kraftigt ökad sin budgeterade in-kind) vilket även resulterade i att uppdaterar benchmark av de fyra olika programvaror för FEM-simuleringar av vårt pilotfall. Vilket utförs av projektparterna RISE, EFD, LEAX och SKF. Inom AP2 har huvudparten av arbetet inriktats på att experimentellt kvantifiera alla materialegenskaper som påverkar induktionsvärmningen. Det här var en omfattning som inte stod klart då projektet startade då bedömningen var att litteraturkällor skulle vara mer pålitliga. Inom AP3 kunde till slut tre olika pilotfall med produktionsdata genomföras med parterna LEAX, Sandvik och AB Volvo. Det här var en större omfattning än vad som var projektets ursprungliga ambition. Projektets resultat har sammanfattats och riktlinjer för produktionsberedning planeras att spridas vid ett seminarium under kvartal två 2023.

Background

Induction hardening is a surface hardening technique for steel that is distinguished by short process time, limited distortions, insignificant decarburization, and excellent fatigue performance. It is a thermal hardening process in which the material is austenitized through inductive heating followed by rapid quenching, which causes the austenitized volume to transform to martensite. A typical application of induction hardening is hardening of torsion loaded drive shafts in vehicles. However, there are some drawbacks of the induction hardening process. These are first and foremost: (a) high plant investment cost, (b) geometrical limitations, (c) sensitivity to material variations, (d) each component entails an initial cost for design and validation of coil and quench spray head, and (e) efficient hardening requires strong know-how to establish new processing conditions. For instance, to establish a hardening scheme for a new product, it is highly preferred to apply an integrated view on product design where part geometry and steel properties are designed to match the practical aspects of the induction hardening. That is, the part design should facilitate the required temperature sequence (heating and quenching) and the steel grade should have an alloying content that provides the desired surface hardness and hardenability (Swerea IVF 2012).

Production planning for induction hardening requires strong know-how. Even so it is done by trial and error and can take days or weeks to solve by running experiments. Hence, by including computer-aided engineering (CAE) tools both lead-time and cost should be greatly reduced. Nonetheless, CAE tools, such as finite-element- and boundary-element methods (FEM/BEM), have not been much included in production planning. The reason is the complex physics and requirement of material properties. For instance, to predict residual stresses after induction heating one needs to solve an electro-magnetic-thermal-metallurgical-mechanical simulation problem. This is not easily done. Moreover, most properties involved are interdependent, with strong- or weak couplings as illustrated in Figure 1. If only the induction heating step is concerned, the material properties with the most pronounced effect are electrical resistivity and relative magnetic permeability. Both these properties are nonlinear dependent on temperature. In fact, apart from temperature relative magnetic permeability has been reported to depend on chemical composition, grain size, microstructure, magnetic field intensity and frequency (Rudnev 2011).

Induction hardening is a single-piece flow, where the component (workpiece) makes up a resonant circuit with the power generator and induction coil. Hence, by collecting and analysing production data, such as power, frequency, a process planning tool might be developed. This is already done today, to some extent, although most often as a go/no-go decision for the workpiece at hand and determined by arbitrary set process limits for the individual process parameters. Accordingly, there should be a potential to analysis all data in combination with material- and performance data to assurance product quality.

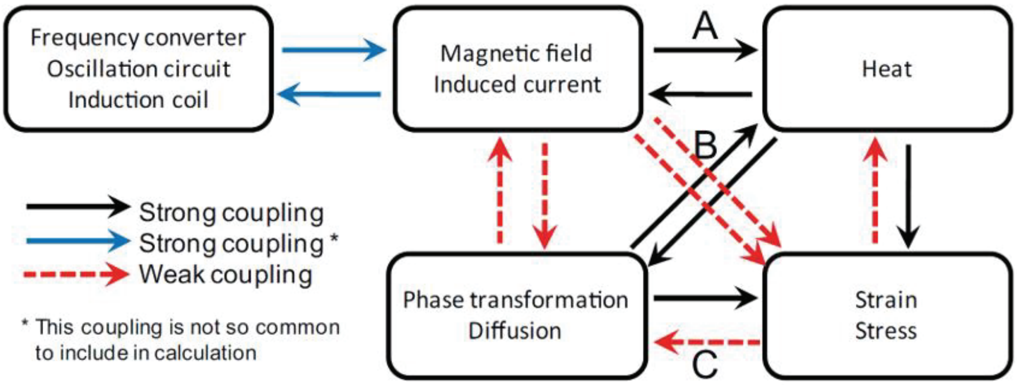

Figure 1 *Couplings between the different events in a simulation of an induction hardening process (Swerea IVF 2012).*

Purpose, research questions and method

The projects' ***purpose*** is defined by its impact goal:

- To enable rapid and robust implementation of induction hardening for new products and new materials by introducing a more digitalized method for production planning.

The projects ***research questions*** were summarized as:

- How to establish a database with material data as input for finite-element calculations of induction heating for commercial steel in both ferritic-pearlitic and quenched-and-tempered state? Today there are no available data collection with electrical-, magnetic-, thermal-, metallurgical- and mechanical properties that satisfy the needed accuracy for production planning simulations.
- What is and what should be measured and characterized on incoming material on batch and component level? The project should identify parameters and develop methods for systematic quantification of material data on batch level, which in-turn would allow for material-process-performance analysis of cause and effect.
- How can a viable method (best-practice) for finite-element calculations of induction heating be established as an engineering- and process-planning tool?
- Can machine learning be used to analyze the large sets of production data from single piece flow induction hardening and thereby couple material-process-performance?

The projects ***research method*** divided by work-package can be summarized as follows:

- WP1 has developed a pilot case for induction heating for simulation and experimental work. Simulation was done with several commercial finite-element solvers.
- WP2 has quantified materials properties of two different delivery conditions (A and QT, as shown in Figure 3) of the steel grade SS 2244 (42CrMo4). Each property has been quantified at elevated temperatures, either through experiments or thermodynamic calculations.
- WP3 was an attempt to apply machine learning on production data from several industrial project members. However, it was realized that the available data was not fit to train an artificial neural network. Instead, a more classical data analysis was performed, which included: data parsing, data mining, visualization, feature selection, linear discriminant analysis (LDA), principal component analysis (PCA), and orthogonal partial least-squares discriminant analysis (OPLS-DA).

Objective

The project objectives are summarized in the following bullets and have not changed:

- To establish material data as input for finite-element calculations of induction heating for steel in both ferritic-pearlitic and quenched-and-tempered state. Especially, magnetic permeability data and how it depends on alloying content and microstructure.
- To identify parameters and develop methods for systematic quantification of material data on batch level, which in-turn would allow for material-process-performance analysis of cause and effect.
- To research and describe a viable method (best-practice) for finite-element calculations of induction heating as engineering- and process-planning tool.
- To demonstrate how machine learning can be used to analyze production data and thereby couple material-process-performance in component production.

Results and deliverables

Work package 1 – Induction heating simulations

This work package developed a pilot case, which was designed to minimize measurement uncertainty during experimental validation and thus reduce error sources in the simulation work. The workpiece measured 150 mm in height and with an outer- and inner diameter of 72 and 52 mm, respectively. The workpiece was made from tubes in two different steel grades, namely 316L stainless steel and 42CrMo4 quench and tempering steel. The main reason for using the austenitic 316L stainless steel was verify the heating model without involving the complexity of ferromagnetism. Induction heating was done at EFD Skien (Norway) workshop using a fully enclosing coil, 70 mm in height with 82 mm inner diameter and 3 mm wall thickness. The coil was equipped with three cooling channels, 10x5mm rectangular cross-section. This setup is seen from Figure 2. The equipment used was a commercially available EFD Sinac 200/320 SM 1U1F. Temperature measurements were done using a Yokogawa SMARTDAC+ GX2 recorder. Four thermocouples of K-type were welded onto the workpieces at half-height on outer- and inner surface. There were two on each position with 180° separation. Several experiments were done using the two different steel grades here we report on experiments named “499”, “500” and “501”.

The experimental uncertainty is minimized by the relative long coil design, which shall generate a stable magnetic field and to a larger extent avoid edge effects. Apart from the temperature recordings, it is vital to accurately measure the coil current since this is a key input quantity for the electro-magnetic simulations. These measurements were done by EFD and reported to the project members together with other frequency and heat time. Material data was collected from work package 2, that is electrical resistivity [Ω·m], thermal conductivity [W/m·K], magnetization (BH-curve), curie temperature [K], specific heat capacity [J/kg·K], Specific mass [kg/m3] and emissivity.

Induction heating simulations were performed using four different software: (1) Altair Flux, (2) COMSOL Multiphysics, (3) DEFORM and (4) NSG ELTA. The simulation results were compared to the experimental temperature measurements. For example, Figure 2 shows the simulation results from NSG-ELTA for the three experiments as solid lines and the corresponding experimental points as dotted lines. As can be seen the simulations agree well to the measured values. A project goal was to benchmark the performance of these software and to research if they present a similar solution given similar input parameters. As can be seen from Table 1, this is not the case as predicted peak temperature can differ a lot between the software. The reasons for this have not been fully explained and moreover all software is not transparent for the user to easy resolve these questions. For instance, an error in one of the commercial software was found by the developer because of discussion and tests regarding our project results. Bottom line is that predicting induction heating results can be very accurate, given reliable material and processing input data. On the other hand, it is difficult to judge if a given prediction is correct, more work is needed to assure broad applicability and reliability.

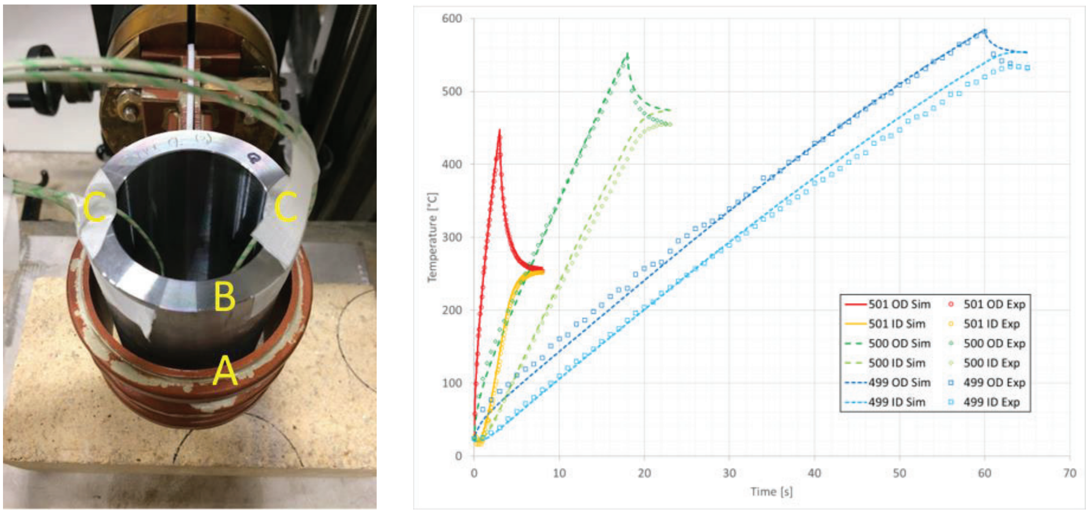

Figure 2 (left-hand side) Induction heating experimental setup with inductor (A), workpiece (B) and thermocouple (C). Temperature measurements were done at half-height on the inner- and outer surface. (right-hand side) Temperature profiles from three experiments and corresponding simulations with NSG ELTA.

Table 1 Summarized simulation results for 42CrMo4 steel grade. Column T[°C] shows experimental peak temperature reading for outer- (OD) and inner (ID) diameter. The corresponding simulated value have been color-coded in accordance with: Green =< ±10°C, Orange =< ±25°C, Red > ±25°C

Exp.	T [°C]	ELTA	DEFORM	COMSOL	FLUX
499 OD	582	585 (+3)	582 (!)	489 (-93)	461 (-121)
500 OD	546	552 (+6)	579 (+33)	529 (-17)	437 (-109)
501 OD	437	448 (+11)	462 (+25)	468 (+31)	340 (-97)
499 ID	520	539 (+19)	520 (!)	450 (-70)	423 (-97)
500 ID	407	429 (+22)	435 (+28)	410 (+3)	343 (-64)
501 ID	130	142 (+12)	147 (+17)	144 (+14)	117 (-13)

Work package 2 – Material data for induction hardening

In this work package, the objective was to quantify material properties (data) in order to
1) be used as direct input in numerical modelling of induction heating (WP1), and
2) identify which material data can is different delivery conditions of a steel grade (see Figure 3) – i.e. needs regular follow-up or quantification. From here, conventional industrial methods would be recommended to follow up these properties.

Magnetic properties were the most challenging to quantify since no standard method can provide both high temperature and field strength simultaneously, as shown in Table 2. In conclusion, more development is needed to measure magnetic properties at high field strengths combined with high temperature. The other material properties – resistivity, thermal conductivity, enthalpy, specific heat capacity –can accurately be described with current laboratory methods and databases such as JMatPro and ThermoCalc.

Table 2: Methods for quantifying magnetic properties (permeability and saturation limit)

	H < 1 KA/M	**H > 50 kA/m**	**H > 500 kA/m**
T < 200°C	- Ring method - IEC 40404-4	- IEC 40404-4	- VSM (only permeability)
T > 200°C	- Ring method	*No method*	*No method*

It was found that microstructural variations of a steel grade mainly influenced the metallurgical properties. As shown in Figure 4, a soft annealed / spherodized (A) microstructure had a higher austenitization transformation start- (A_C1) and finish (A_C3) temperatures compared to the tempered martensitic state (QT). In other words, different delivery conditions of a steel grade will produce different austenitization conditions. Heating rate was also found to increase the transformation temperatures.

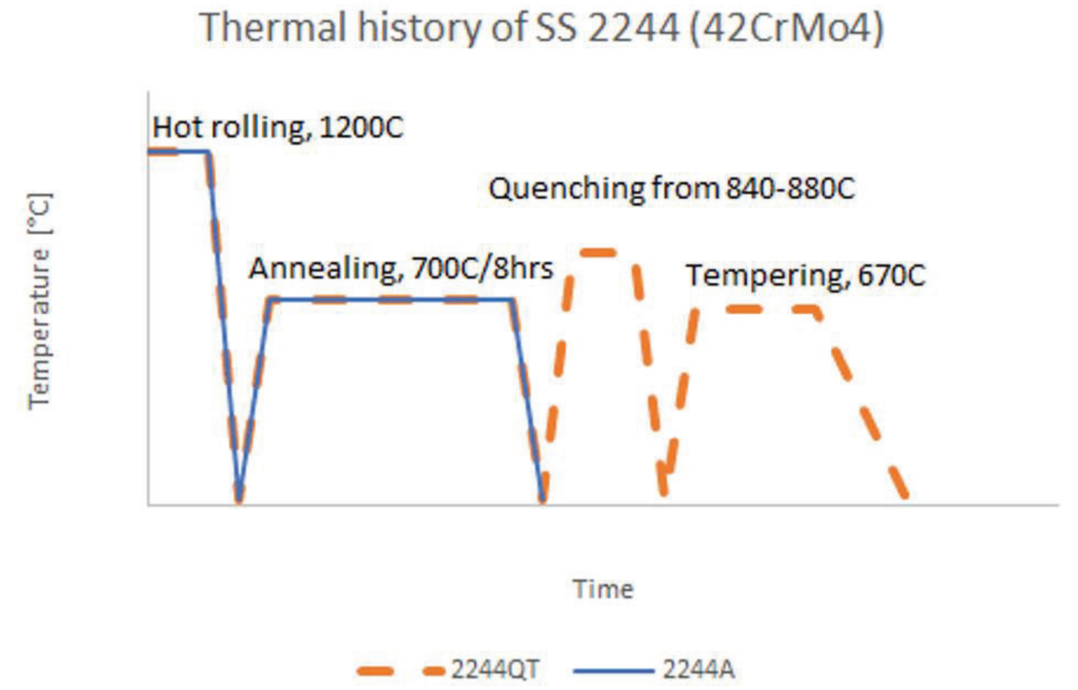

Figure 3: Thermal history of investigated material SS 2244 – representing two delivery conditions "Annealed" and "Quenched and tempered" respectively

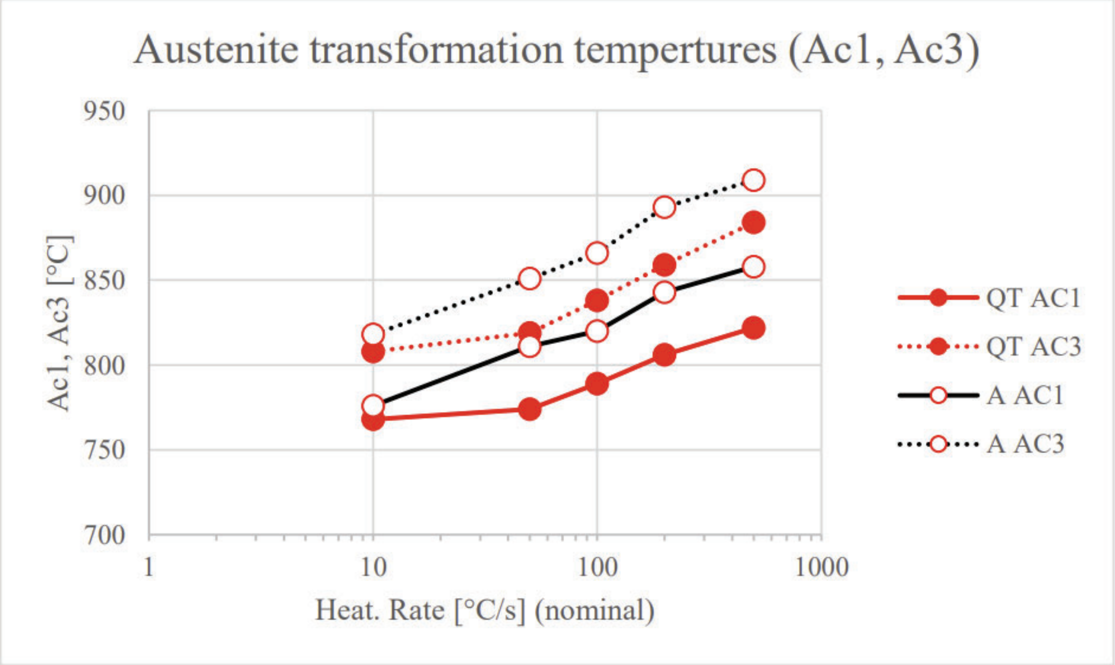

Figure 4: showing how different states of microstructure (A and QT respectively) of a steel charge and inductive heating rate influence the austenitization kinetics through Ac1 and Ac3.

The two delivery conditions of the steel produced identical electric- and thermal properties. For magnetic properties, the picture is still incomplete; It was not possible to measure magnetic data at high field strengths (>50 kA/m) and high temperature (> 200°), which is the space most relevant to inductive heating. It was shown that magnetic data at low field strengths (< 1 kA/m) and low temperatures (> 200°), displayed different behaviour between annealed and martensitic condition, as seen in Figure 5. However, at increasing field strengths (3 – 8 kA/m) the difference in permeability between the two conditions became more diminished. Finally, no difference in saturation magnetization was not observed in room temperature, while at high temperatures the data was incomparable since measurements were carried out at different temperatures. Therefore, no conclusion can be made regarding differences in saturation behaviour between the two delivery conditions. In conclusion, more data is needed to verify how different delivery conditions of a steel grade can influence magnetic properties, but the current data on field strengths < 10 kA/m indicates that increasingly identical magnetic properties is shown with increasing field strength.

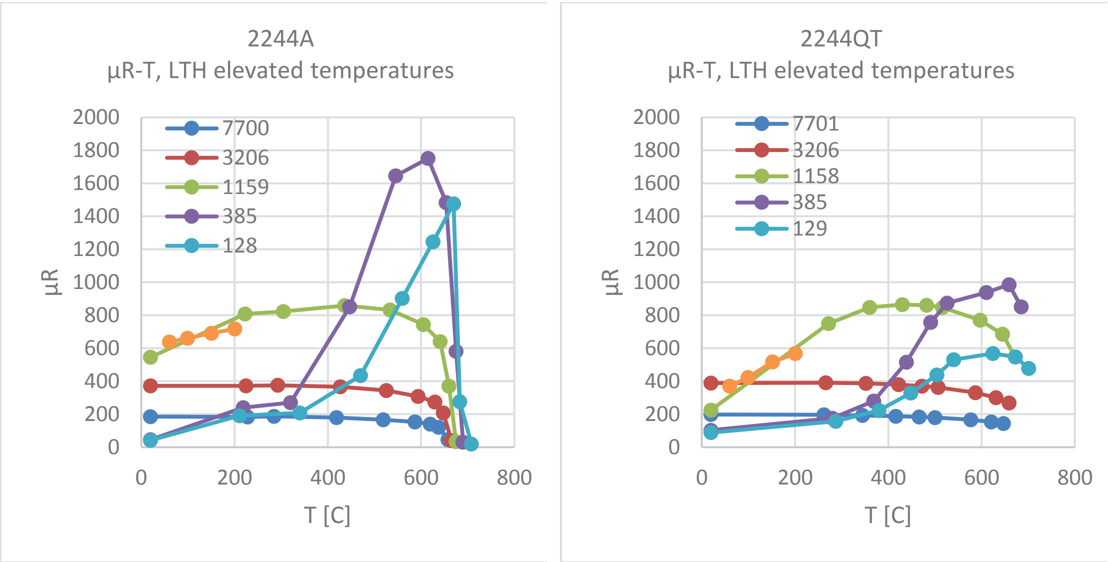

Figure 5: Relative permeability mapped to temperature, for various field strengths H (A/m). Data from measured at different site (MPH) is also displayed.

Because of the similarity observed in thermal-, electric- and magnetic properties, the recommended industrial guideline of how to digitalize the incoming material is to focus on quantifying the metallurgical properties – such as A_C1 and A_C3. Hardness measurement can be used to indirectly map the metallurgical state prior to induction hardening, such as degree of martensitic transformation, which influence A_C1 and A_C3. Investigation of additional industrial methods is recommended to efficiently quantify metallurgical properties. Further studies with Barkhausen noise or ultrasonic methods could be of interest. In addition to A_C1 and A_C3, it would also be relevant to map other metallurgical variables to the austenitization kinetics in inductive heating, such as variance in incoming grain size.

Work package 3 – Production data analysis

After an initial survey among project members, three pilot cases were selected for more in depth analysis. These are summarized here in separate paragraphs in the present section.

LEAX: Induction hardening machine logs were collected for a production component. In total more than 100 000 process logs were parsed, which contained information on power, frequency, time and quenchant flow. These components were manufactured from more than 10 different material batches. The material certificates could be matched to the processing data using time stamps. In addition, surface hardness and case depth (performance) are systematically controlled, and more than 500 samples could be matched to the material- and process data. The collected data was merged and preprocessed to remove inconsistencies and missing data. Data analysis was done by process variability (parameter distribution), correlation matrix, PCA, LDA and OPLS-DA. Even though limitations, such as imbalanced data sets, small sample sizes, merging issues, were acknowledged a concluding statement could be made – process variability exists and it can, to a large extent, be linked to material batch. In other words, there should be an opportunity to increase process capability by researching and act on the variance due to material batch.

Volvo Lastvagnar: Times series data was extracted from an induction hardening production line, including millions of data points. The time-period was several years and included information such as, energy usage, heating time, quenching volume, and performance parameter run-out. In addition, there was also manually recorded information on coil in production. After initial data parsing a correlation matrix approach was applied to research if any information or parameter could be coupled to *total run-out* (combined change in concentricity and orientation of a part). This showed no non-trivial strong correlations. It was then decided to remove all outliers and data that deviated more than 10 % and thus research “normal” production. Still no non-trivial strong correlations were observed. From the data analysis two conclusions were made: (1) Production process variance does not seem to increase over time, hence coil production time and refurbishment seems appropriate. (2) No process feature was correlated with run-out, hence it depends weakly on the induction process. A hypothesis was presented, that run-out and production deviations more strongly depend on material variations – this data was not available in the present pilot case.

Sandvik Rock Tools: The task here was to correlate material- and processing data with hardness and case depth after induction hardening. Two workflows were presented: 1) Historical data analysis to investigate the influence from induction-hardening process parameters and steel charge (alloying content). The historical data ended up quite small since data from material certificate, processing and hardening outcome needed to be coupled manually. It was too small to use machine learning, so a qualitative approach was used. 2) Experimental campaign to investigate the influence of the quench and tempering process prior to induction hardening. Results showed that

- 1) Case depth in some areas of the part saw a reduction as the use of given coil increased. The hypothesis is that natural damage of field multiplier over time drives worse inductive output. No influence of materials data on hardening outcome was observed in the historical data.
- 2a) Using multiple steel charges (for a given steel grade) will increase the variation of needed energy for performing a standard induction hardening. Conversely, having one steel charge significantly reduce the variance of needed energy.
- 2b) Variation quenching and tempering showed no influence on hardening outcome or energy consumption.

Finally, to summaries the project results considering both the FFI-programme objectives and initial project proposal: It can be confirmed that material properties and -data are a major cause for production variance and simulation uncertainty. On the other hand, it has been shown that many physical quantities are unaffected by alloying content (within steel grade) and microstructure variations. This has often been reported in literature (Rudnev 2011). Accordingly, material data reported from work package 2 can be generally applied for simulation challenges using the common steel grade 42CrMo4. Moreover, the project lays the groundwork for engineering use of FE simulations for the purpose production planning. This by presenting a pilot case with very accurately known input data in regards of coil current and -frequency output together with assembled material data from literature and new experiments. The next step for wider impact on production is to assess material data for other common steel grades as well as strategies for handling more complex coil and workpiece geometries.

Contribution to the goals of the FFI-programme

The following section is written in Swedish to not distort goals and related questions, it will complement the final paragraph on the preceding page.

Projektets bidrag till övergripande FFI-mål samt Hållbar Produktions delmål har sammanfattats i följande tabell:

Mål	**Bidrag från projektet**
Övergripande FFI-mål	
Att öka forsknings- och innovationskapaciteten i Sverige och därmed säkra fordonsindustriell konkurrenskraft och arbetstillfällen	Ja, digitala verktyg för induktionshärdning skapar förutsättningar till att mera effektivt hantera prototyptillverkning och även komponenttillverkning för elektriska drivlinor och optimera befintlig tillverkning. Projektet har både tagit fram material data och simuleringsstrategier för finita element-beräkningar (FEA) av induktionsvärmning. Vidare har projektet analyserat processdata från ett antal företagsfall, vilkets potential ofta diskuteras.
Att utveckla internationellt uppkopplade och konkurrenskraftiga forsknings- och innovationsmiljöer i Sverige	Inte primärt, framför allt riktar sig projektförslaget till att utveckla produktionsberedning för svensk industri. Det norska bolaget EFD Induction AS ingår i projektgruppen. Vidare har projektet nyttjat konsulttjänster från Magnet-Physik, vilka har en framstående position gällande magnetiska mätningar.
Att främja medverkan av små och medelstora företag	Ja, ett antal små och medelstora företag ingår i projektgruppen.
Att främja medverkan av underleverantörer	Ja, Leax och SKF ingår projektgruppen. Leax med en större roll som industriell projektledare.
Att främja branschöverskridande samverkan	Ja, förutom fordon ingår rullningslager (SKF) och bergborr (Sandvik) i projektgruppen.
Att främja samverkan mellan industri och universitet, högskolor och institut	Ja, projektgruppen består av tio företag och två forskningsinstitut.
Att främja samverkan mellan olika OEM	Ja, Scania, AB Volvo, VCE, Sandvik Mining och SKF.

Hållbar Produktions delmål	
SMART produktionsberedning	Projektets huvudfokus, viktiga bidrag: • Digitala verktyg möjliggör att på ett tidigt skede i designprocessen få svar på om komponentkrav kan uppfyllas genom induktionshärdning. • En digitaliserad produktionsberedning ger förutsättningar att mera effektivt hantera små serier och utveckling av prototyper för elektrifiering. • Digitaliserade produktionsdata, som är kopplad via maskininlärning, möjliggör att kunskap bevaras i företaget och inte endast finns tillgänglig som erfarenhet hos personal. • Sammantaget ger FEA och digitaliserad produktionsdata ett större beslutsunderlag och därmed förutsättningar att hitta bättre lösningar på kortare tid. Mätbara delmål: • AP1: Projektet har utfört prediktiva FEA beräkningar för induktionsvärmning. Samtidigt har benchmark genomförts för fyra (4) beräkningsprogramvaror. Projektet har levererat FEA riktlinjer baserade på de resultaten till projektparterna, samt har för avsikt att sprida resultaten bredare under 2023. • AP2: Projektet har karaktäriserat det vanligt förekommande seghärdningsstålet 42CrMo4 gällande alla för induktionsvärmning relevanta fysikaliska egenskaper. Vidare har även inverkan av mikrostruktur undersöks. Resultaten har medfört att rekommendationer för produktionsuppföljning av inkommande material kan framläggas projektparterna. • AP3: Tre (3) fallstudier har genomförts med produktionsdata för induktionshärdning. Via dataanalys har material-process-prestanda data kopplats samman.
Robust och effektiv produktion av nya produkter, funktioner eller egenskaper	Effektmål – projektresultaten kommer att bidra till en mera robust och effektiv produktion. Logiken bygger på att digitalisera produktionsdata och därmed kvantifiera felkällor.
Resurseffektivitet i produktion för minskad miljöpåverkan och ökad konkurrenskraft	Effektmål – projektresultaten kommer att bidra till en mera robust och effektiv produktion. Logiken bygger på att induktionshärdning, som är resurseffektivt, blir mera robust och flexibelt (bl.a. i avseende ingångsmaterial). Vilket i sin tur ökar metodens konkurrenskraft för härdning till nya komponenter. Till exempel vid små serier och elektrifiering av drivlinor.

Dissemination and publications

1.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The gained knowledge will currently be transferred into three new activities: (1) Planning of a full-day seminar on induction hardening, where project members can invite colleagues, subcontractors and customers. (2) Ideas for spin-off research projects within the Swedish Heat Treatment Centre, where all project members are participating. (3) An application for a new research project were we aim to research questions listed in future work
Be passed on to other advanced technological development projects	X	Project knowledge will be included in industrial projects members internal development projects.
Be passed on to product development projects	X	Project knowledge will be included in industrial projects members internal development projects.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

1.2 Publications

The project group have discussed and plan to condense the project results into an open-access publication. Apart form publishing, RISE and Swerim also intend to share results on upcoming national meetings and conferences, such as the Swedish Heat Treatments membership meeting and manufacturing R&D cluster conference in Södertälje 2023.

Conclusions and future research

In concluding this project report, induction hardening is one of the toughest finite element simulation challenges that can be attempted. The reason is, as already discussed, that it involves both electromagnetic-thermal and thermo-metallurgical simulation challenges in combination with the more commonly solved mechanical challenge. The solution quality, and thus the applicability to production planning, will rely to a large extent on determining all non-linear material properties and input quantities with high accuracy. Here is a short summary of lessons learned and guidelines for induction heating simulations. The last paragraph contains a few suggestions for future work.

- Relative permeability and saturation magnetization are key properties for induction heating simulation. Unfortunately, both are difficult to measure and model at high temperatures and field strengths, which is vital for the present case.
- This work shows small effects of alloying content and microstructure on physical quantities, such as electric- and thermal conductivity. Therefore, it is reasonable to suggest that these metallurgical aspects mostly affect austenitization, while peak temperature stays constant. More particularly, the relative stability of ferrite and austenite as well as total carbon content in solid solution.
- Changes with material batch cause production variance for induction hardening. It is seen from the process parameters and indicated in hardening performance. Admittedly, other factors may contribute to variance and even interact with material batch properties. For instance, complex geometries and coil degradation. Hence, design know-how and regular maintenance is vital.
- Induction hardening generators are of AC-to-DC-to-AC type. However, the inverter output waveform is not a pure sine wave of constant amplitude. This causes a complex interaction of magnetic field strength and work-piece magnetization.
- Engineering induction heating simulations are practically limited to the frequency domain with an assumed sinusoidal AC power supply. Accordingly, there would be a discrepancy between “assumed” and “real” coil current.
- To improve simulation accuracy, it is advised to review power generation in terms of output waveform of voltage and current for the system under study.

Here are some topics for future research that has been discussed during the project:

Improved input data for increased FE-simulation accuracy, including:

- Development of new methodology and strategy for measurement of magnetic properties at elevated temperatures and large field strengths.
- Strategies and guidelines to review power generation, in terms of output shape of voltage and current, for a given induction hardening equipment configuration.

Adapting processing parameters with respect to variance in incoming material:

- Heating rate has been shown to vary austenitization rate, therefore should be possible to optimize it to compensate for variance caused by incoming material.
- Investigate the influence of other metallurgical factors that can vary between steel batches, such as grain size.
- To enable in-line adaptations of incoming material, it is important to investigate how to best quantify variance in the metallurgical state prior to induction heating.

Increased usage of induction hardening simulations for production planning:

- The next step for wider impact on production is to assess material data for other common steel grades as well as strategies for handling more complex coil and workpiece geometries.

Participating parties and contact persons

The following companies were participating in the DigPIn project. Listed in the table is also main point of contact.

Company	Contact
RISE Research Institutes of Sweden AB	Albin Stormvinter, PL
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AB SKF	Andreas Hultkrantz
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Sandvik Mining and Construction AB	Peter Kolmskog
Scania CV AB	Matti Näslund
Teknoheat AB	Lars Ullmark
Volvo Construction Equipment AB	Lennart Björk
Volvo Lastvagnar AB	Lena Magnusson Åberg