Łódź, 28-10-2024 r.

Prof. Sławomir Wiak, DSc., Ph.D., MEng., ***mutli dr h.c.***

Institute of Mechatronics and Information Systems
Faculty of Electrical Engineering, Electronic, Computer
and Control Engineering, Lodz University of Technology

Review of Doctoral Disserataion
entitled: **"Analysis of Thermal Stresses in Steel Workpiece Heated by Induction"**

Author: ***Debela Geneti Desisa,*** *Master of Science in Engineering.*

made under the guidance of Promoters:
Assoc. Prof. Albert Smalcerz, Ph.D., DSc.
Department of Industrial Informatics, Silesian University of Technology, Poland
Assoc. Prof. Václav Kotlan, Ph.D.
Department of Electrical and Computer Engineering, University of West Bohemia, Czech Republic

1. Basis and purpose of the opinion

As is clearly stated in the Ph.D report: „A Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy (Joint PhD) in the Faculty of Materials Engineering, Department of Industrial Informatics, and the Faculty of Electrical Engineering, Department of Electrical and Computer Engineering".

I have eleborated this opinion based on the letter of Profesor dr hab. inż. Monika Kwoka, Przewodnicząca Rady Dyscypliny Automatyka, Elektronika, Elektroechnika i Technologie Kosmiczne, Politechnika Śląska. August 30.08, 2024 r.

The basis of the opinion is the assessment of the scientific achievements of the Candidate contained in the prepared Doctoral Thesis. This opinion concerns the application to award the academic degree of Dr. Eng. to Mr. MSc. Eng. *Debela Geneti Desisa* in the field of engineering - Technical Sciences, discipline: Automation, Electronics, Electrical Engineering and Space Technologies.

2. Evaluation of the selection of the dissertation topic

PhD thesis entitled **"Analysis of Thermal Stresses in Steel Workpiece Heated by Induction"** concerns the current and developed in recent years field of computer-aided electromechanical systems design incorporating the material sciences.

The great interest in this subject is a direct result of the huge demand in the technical field, as well as the unsatisfactory condition of the currently offered solutions and the need to intensify the work brings new challenges from the research and implementation side, in the field of induction hardening model for gear wheels is calibrated to ensure high precision.

The successful solution of the tasks, undertaken in the reviewed doctoral thesis, contributed to the development of a unique and comprehensive methodology for the Computer Aided Advanced design of the electromagnetic field, the thermal field (heat transfer), and solid mechanics factors (stress/strain) gives the chance to control induction heating process.

An insight into contemporary research directions, including computer technologies in the field of applications of electromagnetism and the so-called "computational electromagnetism" supported by modern information systems, leads to the following conclusions:

- in most electrotechnical structures, the electromagnetic field plays a fundamental role,
- advanced computer systems can already answer the question of what is the result of the system's operation, in this case the distribution of electromagnetic fields and temperature, for different structures of the analyzed objects, under different limit conditions and,
- currently available Computer Aided Design systems allow for advanced electromagnetic and thermal calculations for complex systems and devices.

This opinion is confirmed by a large number of publications describing new designs of electromechanical systems.

I confirm the subject of the dissertation to be fully up-to-date and modern. A wide range of problems that have arisen during the tests, in particular: computer modeling of gear wheels structures ~~(~~axisymmetric structures~~)~~, supported by laboratory tests for real models, as well as the timeliness of this subject from the technical point of view guarantee, that research and implementation of the proposed structures will be continued in the future.

3. Aim and thesis of the work (Thesis outline - p. xvii)

„The present thesis concentrates on the analysis of thermal residual stress in steel metal induced by induction heating. The document is structured as follows: Chapters 1 and 2 - introduce induction hardening, covering aspects of heating and cooling. Chapters 3 to 6 - delve into technical numerical modelling of induction heating, calibration, and optimisation of power control, mathematical modelling of thermal residual stresses, and modelling of thermal strain modelling, including TRIP strain. Finally, Chapter 7 - discusses the conclusions and perspectives".

The work objectives are defined correctly, but the **thesis of the work** should be redfined. I propose to compose (redfine) this thesis basing on the subchapter 7.1 content.

It is clearly stated that (page 112): *„The analysis of thermal stress resulting from induction heating and cooling includes various aspects, including heat transfer, metallurgical changes, and mechanical effects. To achieve the desired mechanical properties, a comprehensive analysis of the entire process is essential".*

The other statement (conclusion) is also so important and valid for the future correct analysis (page 112): *"Although model analysis does not fully represent experimental work, it is crucial for optimisation approaches and reduces the time needed for trial calibration"*. The key findings and contributions of this dissertation to the field are summarised as follows.

Thesis outline (p. xvii):

"The present thesis concentrates on the analysis of thermal residual stress in steel metal induced by induction heating".

My remarks:

The paragraph defined above is not a thesis; is information on the directions of research.

My proposal - New thesis of PhD work could be as follows:

To achieve the desired mechanical properties, a comprehensive analysis of the entire process is essential. For such multiphysics experiments, numerical modelling makes invaluable contributions by providing visualisation and a deep understanding of the process.

My comment: *Author of this PhD report precisely conclude the above paragraph in chapter 7.1, p.112.*

4. Mathematical - Numerical Modelling – Integrated System

As is clearly stated in subchapter 7.1.1 (page 112 citation): *„Therefore, controlling input power through a feedback control loop linked to the power generator is crucial to obtain the desired temperature and subsequent mechanical properties. Three distinct algorithms were developed to assess the temperature distribution from the surface to the core: explicit and implicit event control algorithms, along with discrete frequency control synchronised with the coil current."*

"This approach addresses the common problem of electro,magnetic heating "skin effect" and improves the efficiency of heat energy" (p. 112).

Author of PhD degree report *(subchapter 7.1.1 - Numerical modelling for the automation of induction power control)*, **defines the core of the research work correctly** *as follows:*

1. explicit and implicit event control algorithms, along with discrete frequency control synchronised with the coil current,
2. In an implicitly controlled event, it is typically necessary to specify a fixed maximum absolute value for the temperature variation,
3. Controlling input power through a feedback control loop linked to the power generator is crucial to obtain the desired temperature and subsequent mechanical properties,
4. Controlling input power based on the temperature feedback loop does not affect heat transfer across the radial direction.

Author of the PhD degree report *clearly states as folllows; defining the strategic research areas and technical implementation (selected statements* *Abstract, pp. iv-v):*

1. Thermal stress analysis involves examining the thermomechanical system, which is subjected to heat transfer and heat generation within the material (i.e., induction heating). Therefore, types of multiphysics analysis achieved through numerical methods are the appropriate approach.
2. The study consists of two phases: controlling the heating parameters and subsequent cooling (quenching). Each phase has its own design strategy and controlling mechanism, and failure of one affects the desired mechanical properties,
3. A precise numerical model that describes the events on the surface of a workpie during induction heating (IH) as well as the temperature changes within the workpiece is challenging to develop,
4. To address this challenge, the model employs three different algorithms to analyse the temperature distribution from the surface to the core: explicit and implicit event controlling algorithms and a discrete frequency control approach aligned with the coil current,
5, The induction hardening model for gear wheels is calibrated to ensure high precision, based on a reliable mathematical model and the correct selection of input parameters,
6. The calibration strategy integrates key parameters to achieve the most effective combination for the specified application, control heat flow, and ensure optimal energy efficiency,
7. Therefore, the model must be appropriately calibrated to achieve an acceptable agreement between the calculated results and the experimental data. The detailed calibration strategy is described and illustrated with a typical example,
8. A general model of induction surface hardening was analysed on the basis of coupled electromagnetic, thermal, mechanical, and metallurgical phenomena. The distribution of mechanical strains and stresses is determined in the surface layers of steel materials subjected to induction hardening,
9. The distribution of mechanical strains and stresses is determined in the surface layers of steel materials subjected to induction hardening. This distribution is influenced not only by thermoelastic processes but also by plastic deformations of the exposed layers and the transformation of specific levels of steel,
10. Extracting the TRansformation-Induced Plasticity (TRIP) strain from the total strain by experimental analysis of quenching poses significant challenges,
11. The combined effect of thermal and TRIP strains on mechanical properties is demonstrated through an illustrative example using a cylindrical workpiece with a length of 100 mm and a radius of 20 mm. The model also illustrates how phase transformation strains produce stresses and deformations by coupling temperature-dependent phase transformations with an elastoplastic analysis.

5. Background of the PhD Project - *Conclusions and Perspectives*

Let me quote a very important paragraph from the PhD report relating to induction heating and cooling. Author of this doctoral dissertation states that:

"The analysis of thermal stress resulting from induction heating and cooling includes various aspects, including heat transfer, metallurgical changes, and mechanical effects. To achieve the desired mechanical properties, a comprehensive analysis of the entire process is essential. For such multiphysics experiments, numerical modelling makes invaluable contributions by providing visualisation and a deep understanding of the process. Although model analysis does not fully represent experimental work, it is crucial for optimisation approaches and reduces the time needed for trial calibration" (chapter 7.1 – Conclusions, page 112-115*).*

The key findings and contributions of this dissertation to the technical sciences are **perfectly** summarised by the author, which are as follows" *(chapter 7.1 –* Conclusions, pages 112-115, chapter 7.2 – Perspective, pages 116-117).

The key conclusions and contributions this dissertation to the science have been perfectly summarised by the author, which are as follows:

→ Low-frequency induction heating is suitable for heating large areas of a workpiece without significantly affecting the surface, but it requires long heating durations, leading to inefficient energy usage. In contrast, high-frequency induction heating offers good energy efficiency due to a high-power supply but is limited to heating only the surface,

→ Three distinct algorithms were developed to assess the temperature distribution from the surface to the core: explicit and implicit event control algorithms, along with discrete frequency control synchronised with the coil current. This approach addresses the common problem of electromagnetic heating "skin effect" and improves the efficiency of heat energy,

→ Controlling input power based on the temperature feedback loop does not affect heat transfer across the radial direction. As the core temperature is low, the high temperature on the surface continues to flow toward the lower temperature, significantly influencing the surface temperature and preventing overheating,

→ For an accurate computation of thermal stress and strain, it is crucial to track the entire sequence of phase transformations in parallel with the temperature evolution. The process involves solving Maxwell's equations for the electromagnetic field, the heat conduction equation for temperature evolution, and the Koistinen-Marburger equation for the martensitic phase transformation. It is highly coupled and requires consideration of temperature-dependent material properties and well-defined boundary conditions,

→ The distribution of strains and stresses within hardened layers is crucial to assessing the risk of cracks and other damage, particularly in critical components used in machinery, automotive, or aerospace industries. Surface hardening aims to improve the mechanical properties of the workpiece surface for machine components subjected to surface loads (e.g., gears, sprockets, shafts). The distribution of strains and stresses within hardened layers is crucial to assessing the risk of cracks and other damage, particularly in critical components used in machinery, automotive, or aerospace industries,

→ The cooling rate is a critical factor in martensite formation, significantly influencing the final microstructure and mechanical properties of the material. The faster the cooling rate, the more likely it is to form martensite. From the CCT curve, one can determine the optimal cooling rate and temperature range can be determined to achieve the desired microstructure and mechanical properties in the final product.

6. General overview of PhD *content of the report and evaluation*

The PhD report of the doctoral dissertation includes chapters and subchapters, list of references and appendices. It is clearly stated as follows: "The content of each chapter, selected and cited by me as referee, is the core of this PhD project.

As author states *(chapter 1 - selected key topics of this chapter; PhD candiddates' knowledge, acheivements, and report):*

> Chapter 1 – Introduction (pp. 1-11), *citation of selected acapits*:

"Induction heating (IH) is a technology that employs an alternating current (AC) magnetic field to generate power in an electrically conductive material. Numerical modelling can be applied in induction heating to simulate and understand heat transfer processes, optimise system design, and evaluate the performance of different heating configurations and parameters.

The simultaneous dual frequency (SDF) heating method uses two different currents, medium frequency (MF) and high frequency (HF), to uniformly harden the surface layer of the workpiece (i.e., shafts, sprockets, and gear) with consistent contour thickness.

This allows the regulation of output power to control the hardening depth at both the root and the tip of the gear. Induction hardening involves multiple design parameters, including electromagnetic, thermal, metallurgical, and mechanical fields. Each of these fields comprises design parameters contributing to the quality of the output. Single-objective optimisations have limited scope in this context.

Controlling the hardness thickness in induction hardening is highly complex due to the numerous parameters that influence it. The objective of induction hardening is to achieve a hardened martensitic layer on the surface of a component while preserving the unchanged core microstructure. The depth of the heated layer is influenced by process parameters such as frequency, current intensity, and time, as well as material properties. The development of FE analysis has progressed in both electromagnetic and thermal stress modelling, incorporating phase transformations in induction hardening.

In the context of thermomechanical processes, it is emphasised that models integrating both thermal and mechanical effects can offer a more precise estimation of phase contents and transformation temperatures."

The above selected research topics and aplications are so important contribution to this research project, as the part of PhD degree procedure.

> Chapter 2 - Literature review (pp. 12 – 37), *citation of selected acapits*:

"Induction heating is a technique to increase the temperature of an electrically conductive material by exposing it to an alternating electromagnetic field. When a conductor is exposed to a varying magnetic field, the magnetic flux passing through it changes over time. Consequently, electromagnetic induction occurs, leading to the induction of an electromotive force (EMF) in the conductor, which gives rise to eddy currents. These eddy currents circulate within the conductor in closed loops, creating localised magnetic fields that oppose the change in the original magnetic field.

Thermal stress refers to stress induced by variations in temperature. When a material is rapidly heated or cooled, a temperature disparity arises between its surface and interior. If a material is heated or cooled uniformly, there are no temperature gradients, ensuring the workpiece remains free of stress. Without constraints there would be no stresses.

The primary factor driving stress and strain accumulation during heating is the non-uniform thermal expansion (resistance to this expansion) caused by induced temperature gradients. Throughout the heating process, phase transitions and variations in specific volumes occur across different phases and structural morphologies.

The condition of thermal stresses during and after the quenching process can result in one or more of the subsequent issues, depending upon the quenchant type and material composition: Formation of quench cracks, Distortion of the component, Change in service properties, Distortion during machining.

In numerous studies, it has been acknowledged that the formation of thermal stress and strain during and after the quenching process of steels is influenced by the following factors: Geometry of the component, Temperature gradients, Thermal contraction due to cooling, Expansion resulting from the transformation of austenite into other phases, Viscous phenomena, Transformation-induced plasticity. The evaluation of thermal stress and strain generation during quenching relies on an understanding of the following key factors: Temperature distribution within the quenched material, Phase transformation history of the material, Temperature-dependent thermal and mechanical properties of the material.

*There are two main types of transformation diagram used to determine the optimal steel and processing route to achieve desired properties: Time-Temperature Transformation (TTT) and **C**ontinuous **C**ooling **T**ransformation (CCT) diagram. The CCT curves offer information on the temperatures associated with each phase transformation, the amount of transformation product achieved for a specific cooling rate over time, and the cooling rate required to produce martensite. The critical cooling rate is determined by the time needed to prevent pearlite formation in the quenched steel.*

Recently, simulations of quenching and other heat treatment processes have increasingly relied on numerical methods such as the Finite Difference Method (FDM), the Finite Volume Method (FVM), and especially the FEM.

The above selected research topics and aplications are so important contribution to this research project, as the part of PhD degree procedure.

> Chapter 3 - Numerical model for induction heating (pp. 38 – 54),
***citation of selected acapits*:**

As author states *(chapter 3 - selected key topics of this chapter; PhD candiddates' knowledge, acheivements, and report):*

Case study and applications: The electrical and thermal fields of induction heating must be effectively coupled to achieve the desired hardness profile (Barglik et al., 2021b). This process involves three key step of analysis. First, a COMSOL Multiphysics 2D/3D model was created, considering both the material properties and the machine parameters (p. 46). Second, a comprehensive examination of the temperature distribution, surface characteristics, and depth of the case was conducted by varying the machine parameters to achieve the target temperature. During this phase, the current density of the coil, which is responsible for supplying power and facilitating heat transfer to the workpiece, was also determined. Finally, a sensitivity study was conducted using various statistical tools to assess the hardness profile under different settings of machine parameters.

1. *The finite element method (FEM) was used to simulate the model. In COMSOL Multiphysics, from the mathematics branch, ODE and DAE interfaces, as well as events for process control involved in the setting. This branch of physics offers a distinct foundation for study and aids in algorithm development. The start of the process, the event duration, and the reinitialisation condition were all discreetly configured.*
2. *"Three distinct algorithms were developed to assess the temperature distribution from the surface to the core: explicit and implicit event control algorithms, along with discrete frequency control synchronised with the coil current. These methods are significantly advantageous for achieving the target temperature of conductor materials, including irregular shapes (Fig. 3.6, p. 47). Adjusting the power of the coil provides another effective method of controlling the heat source. This adjustment can be easily accomplished by appropriately varying the coil voltage. It is known that the coil power is directly proportional to the square of the voltage. Consequently, the power density of electromagnetic heat sources can be regarded as a convenient time-dependent control function commonly used in the induction heating process".*
3. *"There are multiple approaches to estimating an acceptable deviation in the final temperature distribution from the desired one. Typically, it is necessary to specify a fixed maximum absolute value for the temperature variation. This implies ensuring that, at the end of the heating process, the temperature at any point within the workpiece does not exceed the prescribed value ε from the desired temperature $T*$."*
4. *"Optimal selection of power, frequency, and coil length in induction heating involves subjective decisions influenced by factors such as the metal being heated, desired temperature uniformity, and duration of heating. Among these parameters, frequency is of significant importance. When the frequency is too low, it can cause cancelation of the eddy current within the heated material, ultimately reducing the efficiency of the coil."*
5. *"To optimise the design, manufacturers of induction heating systems must prioritise minimising losses in system components and maximising energy transfer to the load. These are key strategies to improve overall efficiency.*

Combining both electrical and thermal efficiency provides a comprehensive measure of the system's effectiveness in converting electrical energy into useful heat for the intended application. Many factors influence the efficiency of induction heating, which requires collective improvements to achieve the desired efficiency of the system."

It is so valid (important) contribution to this field of research, as the part of PhD degree procedure.

My comments:

1. *Referring to the following statement:* "Finally, a sensitivity study was conducted using various statistical tools to assess the hardness profile under different settings of machine parameters". ***I expect a broader analysis*** *(discussion),*
2. *Referring to the following statement:* "Careful consideration must be given to the selection of boundary conditions, as artificial reflections at the boundary of the air domain can alter finite-element computations of electromagnetic fields within the air", ***I expect a broader analysis*** *(discussion).*
3. *Refering to point 5, it istated as follows: " Many factors influence the efficiency of induction heating, which requires collective improvements to achieve the desired efficiency of the system".* ***I expect more precise discussion***.

> Chapter 4 - Mathematical modelling of thermal stresses in induction surface hardening (pp. 55 – 72), *citation of selected acapits*:

As author states: Surface hardening involves a wide variety of techniques designed to improve the wear resistance of components without affecting their softer and tough interior. These techniques are categorised into three: thermochemical diffusion methods, applied energy (thermal methods), and surface coating (modification) techniques (Davis, 2002). The distribution of hardness in the hardened material can be determined from the CCT diagram provided that the austenitisation temperature and the cooling rate are known with a sufficient accuracy (Geng et al., 2020).

My comments: *It is the key statement for surface hardening process – defined by the autor of this report. The above short summary is well composed.*

As author states (chapter 4 - selected key topics of this chapter; PhD candidates knowledge, acheivements, and report). Case study and applications:

1. There are numerous applications associated with induction surface hardening, which is required to enhance strength and wear resistance. For example, crankshafts, axle shafts, modern transmission shafts, and gears are among the components that require surface hardening. The induction hardening process for crankshafts, axles, and transmission shafts is increasingly becoming automated,
2. The control system of this line is designed to enable decision making with a programmable controller. Consequently, all aspects of the heat treatment process and mechanical operations are pre-programmed and can be easily adjusted to accommodate various part sizes and heat treatment parameters,
3. Induction hardening is a form of transformation hardening, involves heating the surface layer beyond the critical temperature Ac1 to trigger austenitization, followed by quenching to form hardened martensite. It is based on the fundamental principles of physical metallurgy, which connect processing,properties, and structure,

4. In the domain of induction heating, the development of thermal stress is dictated not only by material properties that; electromagnetic properties also play a significant role. Key electromagnetic properties such as electrical resistivity (or electrical conductivity) and magnetic permeability significantly influence the depth of heating. Consequently, the electrical resistivity and relative magnetic permeability of the workpiece exert a substantial impact on various aspects of an induction heating system, including coil efficiency, selection of primary design, and process parameters,
5. Distortion during induction hardening can occur during austenitizing or during quenching.Austenitizing-induced distortion usually arises from the release of residual stresses accumulatedduring prior processes such as forging or machining, as well as from nonuniform heating,
6. The distortion caused by the quenching process is largely a function of the austenitizing temperature, the uniformity of the quenching process, and the choice of the quenching medium. Higher austenitizing temperatures, which induce higher residual stresses, result in increased nonuniform contraction during cooling,
7. The process of hardening itself consists of two parts: induction heating and subsequent cooling. The time gap between both processes is very short and will not be considered. The induced electromagnetic field in the workpiece is governed by Maxwell's equations,
8. A computer experiment was carried out on a simple case of induction surface hardening of a cylinder, made of steel AISI 4140 (Table 4.1), by use the commercial COMSOL software.

It is so valid (important) contribution to this field of research, as the part of PhD degree procedure.

It is stated by autor of PhD report, as follows (page 62): *"The computations were performed using the commercial software COMSOL Multiphysics 6.0. FE simulations were used to solve this model numerically with 1360 elements and 972 nodes. A free triangular mesh has been used, covering an area of 0.002 m2, and, due to symmetry, only half of the cylindrical geometry is considered. This type of mesh is commonly used to accurately resolve thin boundary layers. The boundary layer mesh is applied to a depth of 4 mm, consisting of 6 layers with a stretching factor of 1.5, as shown in Figure 4.4."*

My comments:

1. *Referring to above I expect a broader analysis of discretization procedure concerning the number of elements of the mesh, making up the network. This is a key problem in terms of the accuracy of mapping the phenomena occurring in the cylinder,*
2. *The key statement is as follows (page 63):* "The aim of the study is to investigate the surface hardness by measuring the depth of the indentations using a conventional hardness scale". *It is well done case study.*
3. *Let me stress that key point of the either 2D or 3D boundary conditions definitions in the technical problems is one of the challenges. In this report the boundary condtion is defined correctly; cited (p. 66): "The boundary condition of the surface*

subjected to induction heating may include a convective heat loss term and an imposed heat flux from the induction coil.

However, during the quenching process, because of the short duration caused by the intense thermal gradient, radiation can be neglected. This concept is further explained in the experimental investigations by (Barglik et al., 2018.; Barglik et al., 2015)."

Chapter 5 - Model calibration of the induction hardening process for gearwheels (pp. 73 – 87), *citation of selected acapits*:

As author states (chapter 5 - selected key topics of this chapter; PhD candiddates knowledge, acheivements, and report):

Case study and applications: The process of hardening gear wheels demands a high degree of precision, relying on the application of an effective mathematical model to adjust input parameters for heating and and subsequent cooling, ensuring the desired outcomes are achieved. The desired output involves achieving a specified distribution of hardness and microstructure within the surface layers of the tooth, often accompanied by the evaluation of the overall efficiency of the system, *which are as follows:*

1. From the mathematical viewpoint, induction hardening represents a coupled task characterised by a strongly nonlinear interaction of magnetic and temperature fields, which is accompanied by metallurgical and chemical changes in the structure of the processed material.
2. The hardening arrangement is mostly 3D and solution of the full forward model is long (many hours or even days), while the solution of the backward model (optimisation) is practically unfeasible.
3. Gear wheels pose a unique challenge because of their irregular shapes, which requires careful management of heat distribution to achieve the desired depth within a reasonable time frame. Induction surface hardening (ISH) offers an innovative solution for gear wheels, allowing for the creation of a thin, hardened layer across their entire working surface. The microstructure within the internal portion of the gear wheel remains practically unaffected (Barglik et al., 2014, Rudnev et al., 2014).
4. For larger gear wheels, achieving the desired temperature distribution during induction surface hardening (ISH) can be easily achieved with the Tooth-by-Tooth Induction Heating (TTIH) method (Barglik et al., 2014; Lupi, 2017). However, for smaller gear wheels, this approach is not feasible, making it difficult to achieve a uniformly thick hardened contour zone across the entire surface of the tooth using TTIH methods.
5. During the induction heating process, the desired temperature distribution can typically be achieved in one or two cycles. In a single-cycle heating process, single frequency induction hardening (SFIH) or, more commonly, simultaneous dual frequency induction hardening (SDFIH) is used, employing both medium-frequency (MF) and high frequency (HF).
6. In this model, SFIH is used, with a focus on enhancing its efficiency through the implementation of innovative ideas, defining the objective function discussed

in Section 5.4. Initially, the process is calibrated to meet the objectives defined in the function using the commercial software COMSOL Multiphysics 6.0. This involves understanding the combination of parameters required to achieve the desired hardness. The second step involves detailed modelling to provide a visual representation of the actual process. Finally, the obtained optimised parameters are implemented in practical applications. The task was to calibrate and optimize the hardening gear wheels manufactured of AISI 4340.

7. CCT diagram is a crucial basis for making an optimal heat treatment process for steels with required microstructure and properties. The diagram provides insight into the hardening behaviour of steels and the process of austenite transformation at different cooling rates. Hence, a rapid and precise prediction of the CCT diagram has significant practical value.
8. The mathematical description of the process comprises two models: the forward model, which characterises the induction hardening itself, and the backward model, tasked with proposing 79 a surrogate model of the process and optimising the input parameters to achieve optimal design outcomes. The use of surrogate models in engineering design and optimisation involves *two key steps: constructing accurate surrogate models and applying them to diverse optimisation problems*. Construction involves data collection, model selection, and accuracy validation. The application involves integrating surrogate models into optimisation algorithms to efficiently explore design spaces and identify optimal solutions.
9. Model simulation helps predict system performance, allowing exploration of the design space and the search for an optimal design. Model calibration involves the precise adjustment and simulation of the induction hardening process applied to gear wheels. Calibration ensures that the parameters of the hardening process, such as power settings, frequency, and duration, are accurately set to achieve the desired hardness and mechanical properties in the gearwheels.

The above nine cited paragraphs are so valid (important) contribution to this field of research, as the part of PhD degree project and procedure.

My comments:

1. *Let me refer to the following conclusion (page 85), which is of course true – "The calculations were performed using the commercial software COMSOL Multiphysics 6.0 and SolidWorks to construct geometry. For the forward problem, the number of DOFs was about 700,000, and evaluation of one variant took about three hours on a top-parameter personal computer. An effective approach to striking a balance between accuracy and efficiency is through the adoption of multifidelity surrogate models. These techniques play a crucial role in supporting engineering design and optimisation."*

2. *I recommend for the future research works to install the software on server systems – not to waste the time. The above gives wide range for the future more advanced 3D models.*

3. *As is stated in PhD report (p. 86): "Optimisation was performed by several techniques; the best results were obtained using the Nelder–Mead and BOBYQA algorithms. To avoid a poor-quality model, it is common practice to construct multiple*

surrogate models based on input and output data from simulations, assess their accuracy, and then select the one with the highest quality."

The above analysis and the well defined conclusions constitute an important substantive contribution in the area of analysis, modeling and optimization of the analyzed knowledge areas - Thermal Stresses in Steel Workpiece Heated by Induction.

Chapter 6 - Analysis of thermoelastic-plastic properties including TRIP strain (pp. 88 – 111), *citation of selected acapits*:

As author states (chapter 6 - selected key topics of this chapter; PhD candiddates knowledge, acheivements, and report):

1. The impact of thermal input on a stress field within a solid can be viewed as influencing three main aspects: (1) - thermal stress induced by dilatation, (2) – change in material properties, and (3) - change in the yield surface when the solid undergoes loading beyond its elastic limit.
2. Transformation-induced plasticity (TRIP) occurs during phase transformations, typically from austenite to martensite, under certain conditions of mechanical loading and temperature. Extracting TRIP strain involves capturing additional plastic deformation resulting from thermal and mechanical stresses during cooling. Modelling these processes requires addressing inherent complexities such as phase transformations, significant variations in material properties, and diverse boundary conditions (Barglik, 2018). An accurate assessment of the TRIP strain is crucial for predicting the final residual stresses. The TRIP strain significantly influences the distortions and residual stresses of the components.
3. As Author states (p. 90): "*In this work, FEA was utilised to examine the proposed models, accounting for the influence of coupled thermal, metallurgical, and mechanical phenomena during quenching operations. These models were integrated into COMSOL Multiphysics, where numerical simulations were conducted. The results suggest that by assigning suitable behaviours to each stage, particularly by leveraging the elastic-viscoplastic properties during high -temperature phase changes and considering TRIP strain, more accurate predictions of residual strain and stresses in heat treatment processes can be achieved.*
4. As Author states (p. 91): "*The TRIP strain generated during the austenitisation phase has a negligible effect on the final residual stress state. However, the TRIP strain produced during the martensite transformation significantly influences the mechanical properties of the steel. Two key factors are responsible for the irreversible deformation of an iron-based alloy during and after a martensitic phase transformation:*
   1. *The accommodation process, driven by the change in the transformation volume change and the shear stress τ that leads to additional elastic and plastic straining, results in a compatible deformation and strain state;*
   2. *The orientation process is triggered by forming preferred variants that may align themselves in partially self-accommodating groups. This effect is often termed the "Magee" effect."*

5. Thermomechanical analysis serves as a technique in thermal analysis that is used primarily to measure thermal expansion and changes in mechanical properties, such as thermal stress, deformation, and strain. The constitutive equations used to simulate quenching are derived from the additive decomposition of the total strain as elastic and plastic. The general governing equations of coupled thermoelasticity can also be expressed in terms of the stress tensor and temperature.
6. The FE simulation of the quenching process was used to visualise and investigate the distribution of the temperature, phase fraction, and mechanical characteristics of the quenched steel. The model configuration for the interface of study involved solving the physics of heat transfer in solids, solid mechanics, and austenite decomposition. It was accomplished through multiphysics coupling of phase transformation latent heat and phase transformation strain sequentially under a timedependent solver.
7. As Author states (p. 98): *Physics interphases can solve these aspects collectively in a time-dependent multiphysics interface Heat transfer module --> heat transfer in solids (ht); Structural mechanics module --> solid mechanics (solid); Heat transfer module --> metal processing --> austenite decomposition (Audc). The FEM solution of induction hardening is complicated for studying complex industrial cases and needs to compute fully coupled Multiphysics. This model reduces such complexity by categorizing the physics interface in different studies and computing them in a selected step.*

The above cited acapits are is so valid (important) contribution to this field of research, as the part of PhD degree procedure.

***My general comments**: The above wide range summary of the PhD project (cited in this chapter), based on the literature analysis, confirms high rank of the performed research work and literature analysis, by Author of this report.*

Chapter 7 - Conclusions and Perspective (pp. 112 – 117), *citation of selected acapits*:

As author states (chapter 7 - selected key topics of this chapter; PhD candiddates knowledge, acheivements, and report):

It is celary stated by the PhD candidate, as follows: "The analysis of thermal stress resulting from induction heating and cooling includes various aspects, including heat transfer, metallurgical changes, and mechanical effects. To achieve the desired mechanical properties, a comprehensive analysis of the entire process is essential. For such multiphysics experiments, numerical modelling makes invaluable contributions by providing visualisation and a deep understanding of the process. Although model analysis does not fully represent experimental work, it is crucial for optimisation approaches and reduces the time needed for trial calibration. The key findings and contributions of this dissertation to the field are summarised as follows." (*chapter 7.1 – Conclusions, page 112*).

Let me state that scientific contributions by Debela Geneti Desisa, according PhD procedure are so important. The following selected conclusions (statements) from the PhD report, confirming my opinon are as follows:

1. In this work convective cooling was performed by providing a uniform and intense water jet to the surface. The simulation was conducted twice: one involving the transformation with TRIP consideration and the other without considering TRIP.
2. A boundary condition of the quenching process requires a separate definition of thermal and mechanical boundary conditions. Thermal boundaries differ from mechanical boundaries in that they involve an unknown scalar temperature and only two types of boundary: those associated with thermal flow during quenching and symmetry planes where thermal flow is assumed to be zero,
3. At the initial stage of quenching, austenite cools down without phase transformations due to significant thermal gradients. Consequently, the surface contracts faster than the core, resulting in tensile stresses on the surface and compression stress at the core Figure 6.5 (left) to maintain a balanced stress state on the surface. The second stage begins when the martensitic transformation starts on the surface. The third stage begins when phase transformations start at the core leading to a complete transformation and cooling of the surface,
4. Isotropic hardening is the most straightforward hardening model that involves the expansion of the yield surface without any distortion or translation. Kinematic hardening involves a rigid body translation of the loading surface while keeping the remaining geometric properties of the loading surface unchanged. The evolution of the loading surface might follow a combination of isotropic and kinematic hardening rules to capture both loading surface expansion and translation of the loading surface respectively,
5. The general governing equations of coupled thermoelasticity can also be expressed in terms of the stress tensor and temperature. In classical linear thermoelasticity theory, the components of the strain tensor are linearly a function of both the components of the stress tensor and those of the strain tensor resulting from temperature changes,
6. The TRIP strain tensor is a crucial parameter for characterising the mechanical behaviour of materials that undergo plastic transformation. It aids in understanding how materials deform plastically during phase transformations and is essential for designing advanced materials with enhanced mechanical properties. This combined effect is essential to predict and manage the mechanical behaviour of materials throughout quenching processes. It encompasses the sum of thermal and TRIP strains.

8. General overwiew of PhD content of the report

The PhD report of the doctoral dissertation includes chapters and subchapters, list of references and appendices:

> Chapter 5 - Model calibration of the induction hardening process for gearwheels (pp. 73 – 87)
> Chapter 6 - Analysis of thermoelastic-plastic properties including TRIP strain (pp. 88 – 111)
> Chapter 7 - Conclusions and Perspective (pp. 112 – 117)

> Bibliography - (pp. 118 – 137)

My comments: *List of publications contains a huge number of publications; but following the common standard it shoud be composed by numbering*

> Author list of publications - (pp. 138 – 139)

Additional scientific acheivement, closely correlated with the PhD project of Debela Geneti Desisa is the list of papers, closely correlated with the PhD topics; published in Journals and presnted on International Conferences: Journals: **Surface and Coatings Technology, Research Journal of the Polish Society of Composite, Energies, International Journal of Renewable Energy Development, and sixs** Conferences: 27th IFHTSE Congress & European Conference on Heat Treatment, Wyndham Grand Salzburg, Austria, September 5–8, 2022**, International conference on heating by electromagnetic source (HES-23), Padova, Italy, May 9 – 12, 2023.**

8.1. Appendix A - (pp. 140 – 143)

In Appendix A it is presented as follows:
> Shaft model - From heat transfer field the following equation was solved by the operator in COMSOL multiphysics,
> Martensite and retained austenite phase in 3D model contour - Effective thermal properties and mechanical properties were selected to be computed for the entire process,
> In the gear model, attention was given to temperature control methods. Before conducting optimization, it is recommended to try it at a low computational cost using sweep analysis.

> Appendix A-C - (pp. 140 – 156)

My comments:

Following the above analysis and the results I expect more deep/precsie discussion concerning 3D model (Fig. A.4) of 3D structutre of the gear** (page 143)**.

9. General ovewiew of PhD *research work – General summary*

General Conclusion: ***I would like to declare that PhD report is clearly stated, the written version is formulated correctly.***

I could state that the work is written very carefully, the layout of the work is precise and logical, the graphic side of the work is exemplary. The final conclusions obtained in the report are correct and interesting.

The general and specific remarks presented above do not lower my high assessment of the work.

The results of the considerations contained in the work authorize the statement that the theses of the dissertation have been proven and the assumed objectives of the work have been achieved.

The presented dissertation proves that the PhD student is able to use the latest literature in the chosen field of knowledge, approaches it critically and is also able to creatively develop the achievements of other authors.

I state that the presented dissertation entitled "Analysis of Thermal Stresses in Steel Workpiece Heated by Induction" Debela Geneti Desisa, MSc, is an independent solution of the research task and meets all the requirements for doctoral dissertations by the Act on Academic Title and Degrees.

Law Regulations (statements): „Doctoral dissertation by M.Sc. Eng. Debela Desisa titled "Analysis of Thermal Stresses in Steel Workpiece Heated by Induction" is in accordance with the requirements of the Article 190, paragraph 2 of the Act of July 20, 2018 - Law on Higher Education and Science (consolidated text: Journal of Laws of 2023, item 742, as amended)."

In view of the above, I submit a motion to accept the presented thesis as a doctoral dissertation and to admit its author, Mr. Debela Geneti Desisa, M.Sc. Eng. for the public defence of labour.

professor Slawomir Wiak,DSc, PhD, MEng.,*dr h.c.*

Łódź, 28-10-2024 r.

Review of the doctoral dissertation of Debela Geneti Desisa, MSc

Additional proposal

Taking into account the high substantive level of the work (advanced methods of computer modeling and simulation used), the modernity of the subject matter, very interesting research results, precisely formulated final conclusions and the exemplary graphic side of the work, possible technical (industry) implementation I consider the reviewed work to be outstanding.

I submit an application for the distinction award of a doctoral dissertation, entitled **„Analysis of Thermal Stresses in Steel Workpiece Heated by Induction",** author *Mr. Debela Geneti Desisa, M.Sc. Eng.*

professor Slawomir Wiak,DSc, PhD, MEng.,*dr h.c.*