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Revision of doctoral thesis
M. Sc. Debela Geneti Desisa
entitled: „Analysis of Thermal Stresses in Steel Workpiece Heated by Induction"
under supervision of prof. Albert Smalcerz and prof. Vaclav Kotlan

1. **Basis for the review preparation**

The review was prepared on the basis of a letter dated August 30, 2024, concerning my preparation of a review of the doctoral dissertation of M. Sc. Debela Geneti Desis, in accordance with the resolution of the Scientific Discipline Council No. 64/2021 of August 20, 2024.

2. The topic of the dissertation and the tools used

The reviewed dissertation covers some aspects related to the broad analysis and optimization of the hardening process, with particular emphasis on thermal stresses. The Author focused on the numerical modeling of the induction heating process and the subsequent cooling (hardening). The topic of the th esis, as well as the scientific goal and scope formulated by M.Sc. Debela Geneti Desisa, leave no doubts regarding both the practical application of the results and the scientific nature of the dissertation.

The Author correctly adopted a methods for achieving the stated goals using numerical calculations. He undertook the challenging task of developing models and conducting coupled analyses of the induction heating process, cooling, and stress field analyses. In relation to the heating process, the Author analyzed various power control methods to ensure a proper temperature distribution within the heated charge. As a practical solution, the issue of hardening gears was presented, which requires the use of an advanced mathematical model. The Author rightly noted that due to the limited reliability of material data, the model should be appropriately calibrated. Author proposed such a method. It is also worth mention that the Author correctly used simplified models, which is important for optimizing computation time. Currently, such an approach is similar to 'digital twins,' and in terms of the procedures used, it is highly relevant.

Using COMSOL software for analysis of thermal stresses resulting from temperature gradients and phase transformations occurring during the process was also conducted. The Author correctly determined the distribution of strains and stresses arising during the hardening process. The issues

related to the analysis of plastic deformation caused by transformation are extremely valuable. Utilizing an axisymmetric model in FEM software, it was demonstrated how strains associated with phase transformation lead to the development of stresses.
The simulation and optimization processes were carried out using methods that leave no doubt about their correctness.

3. Characteristics of the Structure of the Reviewed Dissertation

The presented dissertation consists of 116 A4 pages and has been prepared in a double-sided print format. The thesis is divided into seven chapters. The list of references is placed at the end of the manuscript as an unnumbered chapter. Similarly, the author has included a list of their own publications and three appendices containing the results of calculations and MATLAB code for generating graphs. Before Chapter 1, the author has included acknowledgments, as well as summaries and abstracts in English, Czech, and Polish. The main part of the work contains a total of 61 figures, including diagrams, field images, and graphs presenting the conducted research. A total of 213 sources, including books, monographs, scientific papers, and internet sources, are cited.
Such a structure of the manuscript raises no objections and is in line with the classic format for this type of study.

In the Chapter 1, the author introduces the reader to the issues that form the basis of the dissertation: the fundamentals of induction heating are presented concisely, and the main topics addressed in the dissertation are outlined. The analysis is supported by extensive references to current literature. In the final part of the chapter, the author presents the scientific goal and the scope of the work. I consider the information provided in Chapter 1 to be valuable and indicative of the author's good understanding of the topics discussed in the dissertation.

In Chapter 2, named as a literature review, the author presents the mathematical description for the analysis of coupled fields in the calculations of the induction hardening process. The equations related to electromagnetic energy and heat transfer are clearly presented. Additionally, extensive information on the causes of thermal stresses is provided, along with equations for calculating deformations and stresses. The author also includes details on temperature measurements and a general overview of the FEM (Finite Element Method). The chapter concludes with sample computational results. In my opinion the information in Chapter 2 are valuable and necessary. The author has clearly explainded the choice of methods and tools used.

Chapter 3 deals with numerical simulations of induction heating. In addition to an extended analysis of theoretical foundations, the author proposed a computational model that ensures high-quality results. I find the analysis results particularly interesting, especially those involving temperature control algorithms through explicit or implicit definition of the hardening process and control via a feedback loop.

Valuable information is also provided in the chapter concerning the hardening of gears. This issue is not simple and usually requires the use of dual-frequency systems to achieve uniform heating of the teeth and roots. Another approach is tooth-by-tooth hardening, which was analyzed by the author of the dissertation. The proposed models are characterized by well-considered simplifications, allowing for rapid calculations. These models yield high-quality results due to the introduced calibration procedure.

Chapter 6 is extensive and includes detailed information and results from complex analyses of stresses and deformations occurring during the induction hardening process. The influence of various factors on stress was analyzed. A significant challenge was to select a TRIP deformation from other plastic deformations resulting from thermal and mechanical stresses during the cooling process. The results of the work are essential for accurately predicting the mechanisms of stress development and the distribution of residual stresses, which affects the production of materials with improved mechanical properties.

The final chapter is a typical summary and compilation of the conclusions drawn from the completed work.

In summary, I evaluate the structure of the work as correct and well-considered. The subsequent chapters are arranged properly and form a cohesive whole. The presentation of information—ranging from theoretical considerations, through simulations, to the formulation of general conclusions—creates the appropriate dynamics and is rated very highly by me.

4. Assessment of the Formal and Linguistic Aspects

From a linguistic point of view, the manuscript has been prepared correctly and can be characterized as a high standard. The author formulates sentences properly and uses technical language. However, there are several typical "typos," colloquial expressions, and incorrectly used definitions:

4.1. The quality of the Summary (page vi) and Conclusion (page xi) in Polish leaves much to be desired. This is a text that has been automatically translated, which results in phrases such as "thermal stresses are intended to ensure the reliability of the structure and reduce inaccuracies…" etc.

4.2. - page 4 – term „… feed velocity …" - is it the workload?;

4.3. - page 5 – term „… current intensity …" - what is it?;

4.4. - page 8 – what is the metallurgical field?

4.5. - page 12 what is the excitation frequency (ω in equation 2.1)?

4.6 – page 15 – table 2.1 – were the inductor made of wire?

4.7. - page 42 - eqn. (3.5) and earlier description - D is a vector quantity

4.8 – page 43 – ω is a angular velocity? Really?

The remarks provided above are not numerous and do not significantly affect the positive assessment of the thesis in terms of language.

From a formal standpoint, I assess that the work has been prepared correctly, but not very meticulously. There are a few errors in the applied notations and references to incorrect formulas. It should be noted that the author often describes the content of a given figure right below it, which creates some inconvenience. However, these shortcomings are minor and difficult to eliminate entirely. I must negatively assess the readability of some graphs and the quality of their descriptions. Often, the figures contain results for a single analysis case, while the captions suggest that they represent general results. Detailed comments regarding the formal assessment are listed below:

4.11. - page 24 „The TTT diagrams measure …" - it will be better to show diagrams.

4.12. - page 15 – table 2.1 – were the inductor made of wire?

4.13. - page 30 – eqns. 2.28 to 2.3 – in the nomenclature we can find the information that symbol gamma γ denotes the conductivity. Here we have strains;

4.14. - page 39 – figure 3.1 shows the magnetic field intensity NOT the current density (description under the figure)

4.15. - page 39 – name of the chapter „physical model" is wrong.

4.16. - page 40 – fig. 3.2 caption „relative permeability …" it is NOT general characteristic. Add name of material.

4.17. - page 45 under the table. There schould be Figure 3.5 not 3.6

4.18. - page 46 – figure 3.5 – there is a group of coils or is it a single coil ?

4.19. - page 47, Figure 3.6 – this is not isothermal contour

4.20. - page 51, before fig. 3.10 Autor present that frequency were changed from 4 to 7 kHz. Under there is 3.5 and 7.5 kHz.

4.21. - page 65, introoduction to chapter 4.4 – „The field equation for an axisymmetric problem in a cylindrical coordinate system is provided as follows." And here we have eqns. (4.19) and (4.20) in Cartesians system.

4.22. - page 67 and 68 – figures 4.8 and 4.9 – add type of the steel. It is not general.

4.23. - page 64, figure 4.5 caption. On the right there is no time evolution …

4.24. - page 104, eqns. 6.34 and 6.35 – here k and c are named as material constants. Maybe define, what types of constants they are.

Despite a certain number of shortcomings, I assess the level of preparation of the work as satisfactory. Most of the errors outlined in the review do not affect the quality of the presented considerations and likely occurred during the final formatting stage of the text before printing.

5. Substantive Assessment of the disertation

The presented dissertation of Mr Debela Geneti Desisa has a simulation character, and its results can be applied in practice. The primary goal is to enhance the understanding of the fundamental principles governing thermal stress development and to optimize industrial processes. These issues are significant in hardening processes and have been addressed by research teams in various centers in recent years, indicating the relevance of the topic. It is worth mention that the topic has not been completely resolved, and the solutions proposed by the author in the form of analyses of numerical calculation results should demonstrate favorable operational indicators. In the age of seeking Best Available Techniques (BAT), especially in the field of metal processing, solutions utilizing induction heating are highly valued and optimizing the hardening process should yield real economic benefits. Therefore, I assess the subject of the dissertation as current and valuable. However, considering the scientific objective set for optimization work, I found no clearly defined criteria or practically any optimization analyses.

According to the scientific objective of the dissertation and its scope, five main parts can be distinguished:

- literature analysis;
- modeling of the induction heating process;
- modeling of thermal stresses in the hardening process;
- modeling of the hardening process of gears;
- analysis of thermoelastic-plastic properties.

In the initial chapters of the dissertation, the author conducted a literature review connected to induction heating, hardening, and stress analysis. In most cases, the provided data is correct. Nevertheless, several doubts arise:

5.1. – Why does the author reference multi-inductors systems (such as ZCIH) in the literature review, while analyses of this type are not present in the thesis?

5.2. Since Chapter 2 is a typical "literature review," why does it provide only basic information, which is often repeated in subsequent chapters? Additionally, in the case of temperature sensors, only minimal information is provided. However, the author mentioned that this is an important issue for proper process control. Therefore, an expanded analysis of the dynamics of sensors and measurement errors would be advisable.

In Chapter 3, the author proposes a computational model that takes into account electromagnetic, temperature fields and solid mechanics. Analyses of the heating process are conducted for a duration of up to 200 seconds. This duration seems rather long for surface hardening, which, of course, leads to excessive heating of the core of the workpiece. I assess the calculations of the influence of the power control method on the state of the temperature field inside the workpiece as an original contribution. However, several comments arise:

5.3. In the description, boundary conditions are provided only for the temperature field. The boundary conditions for the electromagnetic field are also of interest.

5.4. During heating, when the outer layers of the charge have a temperature higher than the Curie point, there is, of course, a change in magnetic permeability. May I request the variation of the magnetic field intensity H or current density as a function of the radius within the charge in this state? I am interested in how the contact between materials with different permeabilities was analyzed.

5.5. The author has treated radiative heat transfer in an extremely simplified manner. The lack of analysis of multiple reflections in a system where there is no thermal insulation between the charge and the inductor may lead to significant errors.

5.6. As the excitation, the author applied current density. Has the skin effect and proximity effect in the inductor been neglected? Has it been analyzed what kind of errors such a simplification leads to?

5.7. In this chapter, the author also mentioned of the factors affecting the efficiency of induction heating. These analyses apply to volumetric heating and do not have a direct correlation to the hardening process. Nevertheless, without analyzing electrical parameters, it is difficult to speak of a complete analysis of efficiency, particularly due to the inability to select a resonant capacitor, etc. Were such analyses (of electrical parameters) conducted?

Currently, analyses such as those in Chapter 2 do not pose a significant challenge, particularly given that more advanced programs have developed algorithms that allow for convenient coupling

calculations and, for example, the CFD analysis under convection. Of course, the simplifications made do not disqualify the obtained results and conclusions. However, they do have reduced value and may be used in engineering practice rather than in scientific research. Therefore, the part of the t hesis related to the calculations of the induction heating process is assessed as merely acceptable.

In the next chapter, the author presents issues related to modeling thermal stresses. After a theoretical introduction (which is partially repetition), a computational model and the results of the simulations are presented. The performed calculations are advanced, and I assess it highly.

5.8. Certain doubts arise regarding the boundary conditions for the cooling process. A heat transfer coefficient has been applied. Besides the mention of its values ranging from 4 to 20 W/(m^{2}K), no additional information has been found. Moreover, phase transformations, evaporation, etc., also occur on the surface of the cooled charge. How were these phenomena taken into account, if at all?

In Chapter 5, the author presents a very interesting problem of the induction hardening process for gearwheels. After presenting the model, a description of the forward and backward problems is provided. The author's optimization algorithm and the results of the calculations are also presented. I n my opinion this chapter can be characterized as valuable. The author has demonstrated knowledge and ingenuity in developing fast-working models (simplified analyses), which allowed for a comprehensive analysis of the issue.

Chapter 6 is advanced and presents complex issues of phase transformations and thermal stresses and their impact on the hardening process. The analyses were conducted using the finite element method, which is an appropriate approach. The results obtained are characterized by high quality and make a significant contribution to the field, both in coupled calculations and in electromagnetic-thermal transformations. In my opinion, this part of the thesis has been executed at a high level. Both the literature review conducted and the abundance of the author's data demonstrate the doctoral candidate's high level of knowledge.

Summary of detailed comments:

5.9. - page 7 - voltage-source inverter is absolutely not only possibility to control the power in induction heating systems. Can you describe other solutions?

5.10. - page 7 – Fourier's law of thermal conduction is acceptable in steady state in regiong without heat sources. In induction heating you will analyse dynamic processes and heat sources. Can you present more accurate equation?

5.11. - page 12 – formula (2.3) – are you using amplitude or rms value of current density?

5.12. - page 12 – under formula 2.3 there is a λ in the formula

5.13. - page 21 – in chapter 2 you analysed the axisymmetric cylindrical object. Why equationd from 2.9 were presented for Cartesian coordinate system?

5.14. - page 22 – equation 2.18is presented for 1D model. Why?

5.15. - page 26 – You described that e.m.f. of the thermocouple is proportional to temperature gradients. Wrong. It is proportional to temperature difference.

5.16. - page 38 – in my opinion introduction here is not necessary. We have basic information only and the repetition from previous chapters.

5.17. - page 74 – formula for the resistance is acceptable for DC

In summary, despite some reservations, the work is valuable. The assumptions developed by the Author are supported by analytical evidence. This is His contribution to the development of the discipline.

6. Summation

M.Sc. Eng. Debela Geneti Desisa has demonstrated sufficient knowledge in the field of electrical engineering, the creation of original computational models, the execution of computational experiments, and the accurate interpretation of results. The critical remarks mentioned in the review do not negate the value of the Dissertation, and regarding the substantive comments, it is possible and necessary to engage in debate with them. **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).** , Especially:

- it presents an original solution to the scientific problem of improving the energy efficiency of railway switch heating using induction devices;
- it demonstrates the overall theoretical knowledge of the Doctoral candidate in the discipline of Automation, Electronics, Electrical Engineering, and Space Technologies;
- it confirms the Doctoral candidate's ability to conduct independent scientific research.

I recommend to the Council of the Discipline of Automation, Electronics, Electrical Engineering, and Space Technologies at the Silesian University of Technology that it be allowed to proceed to public defense.