# INDUCTION HEATING OF EXPLOSIVELY CLADDED LAYERED MATERIALS

## Introduction

Induction heating is currently applied in many industrial fields due to its operating characteristics and unique features. The heating process is primarily contactless, and thermal energy is generated directly within the processed workpiece. At the same time, the process achieves high efficiency, while the possibility of precise control of the heating power and the workpiece temperature allows for full control of the heating process. These advantages have led to the application of induction heating in numerous sectors, ranging from the machinery and automotive industries, through power engineering and experimental medicine, to the food industry. The development of semiconductor electronics has enabled a significant reduction in the size of induction heating equipment, as demonstrated by the induction heaters used in this study.

In parallel, the increasing availability of more advanced and accurate simulation environments makes it possible to predict and design the entire process, in this case the induction heating of a workpiece with a selected geometry. In many situations, such an approach can replace the development of costly physical prototypes at an early stage of the design process, where numerous design errors frequently occur. Consequently, this methodology leads directly to significant cost savings.

Despite the numerous advantages of induction heating discussed above, the process also exhibits a certain limitation. When larger areas are heated, the nature of the electromagnetic field may lead to the formation of regions with higher and lower temperatures. One way to address this issue is the use of a multilayer material, which simultaneously enables the application of induction heating (through a ferritic layer), provides high thermal conductivity, and allows direct contact with the processed medium.

The explosive welding technology used for the production of multilayer materials originated in the 1950s and 1960s. The fundamental concept of this technology has remained largely unchanged to the present day. Nevertheless, its characteristics are highly desirable in modern industry, primarily due to the ability to join different metals with dissimilar properties into a single, durable material system. In certain applications, identifying a metallic alloy that simultaneously satisfies multiple, often strongly conflicting requirements is difficult or economically unjustified. An example is the use of expensive materials, such as titanium, to meet only a single requirement, for instance resistance to marine environments. In such cases, a more effective solution is the application of a carbon steel structural base layer clad with a much thinner titanium layer, which allows a significant reduction in production costs.

## Characteristics of the research problem

Based on the conducted literature review, no information was found on the combination of the two aforementioned technologies, namely induction heating and explosive welding. Consequently, it was decided to address this research gap, as preliminary investigations revealed the presence of phenomena that were not observed during the heating of homogeneous workpieces. Furthermore, the literature review concerning induction heating and its numerical modelling identified certain omissions and inconsistencies in the analysed studies. These included, among others:

- verification limited to a narrow temperature range,
- a lack of clear specification regarding the consideration of temperature-dependent material properties,
- the absence of validation of the cooling process.

The proper formulation of a numerical model for induction heating necessitated the consideration of multiple phenomena inherent to this process. In particular, it was essential to obtain reliable material properties, such as electrical and thermal conductivity, specific heat capacity, and the temperature dependence of these parameters. Neglecting these aspects would result in numerical models with insufficient accuracy. The materials analysed in this work, including ferritic materials, are not typically used in electrical engineering, which further hindered the acquisition of magnetic material properties required for the numerical simulations.

The study involved materials with differing electrical properties, which resulted in a non-uniform distribution of induced currents and temperature, depending on the thickness and properties of each individual layer. The analysis of these materials conducted in this work is original on a global scale.

## Aim of the study and scope of the conducted research

The primary objective of this dissertation was to investigate the phenomena occurring during the induction heating of multilayer materials joined by explosive welding, with particular emphasis on their specific structural characteristics and material properties varying as a function of temperature. Owing to the limited number of publications in this research area, the study has a pioneering character and comprises both numerical modelling and experimental investigations.

The secondary objectives included a literature review, sample selection, acquisition of material characteristics (e.g. B-H curves), development of numerical models in the ANSYS environment, as well as the design and construction of dedicated measurement setups. Both systems incorporating ferromagnetic layers and those without such layers were considered, which enabled an assessment of the influence of these features on the accuracy of process representation. The knowledge gained during the conducted research was subsequently applied to the design of multilayer material systems and induction heating configurations for specific industrial applications.

## Research methodology

Coupled numerical simulations based on the finite element method constituted the primary analytical tool. Accordingly, the developed numerical models employed two modules of the ANSYS software suite, namely Maxwell 3D and Fluent. In the former, simulations of the eddy current loss distribution were performed, while in the latter the heat transfer and temperature distribution within the analysed sample were calculated. The coupled simulations enabled the incorporation of temperature-dependent material properties, thereby allowing the characteristic behaviour of ferromagnetic materials associated with the Curie temperature to be taken into account.

Due to the lack of available B-H curve data for the applied AISI 410S stainless steel, the B-H characteristics were determined independently as part of additional experimental investigations. Furthermore, an original method was developed to describe changes in the shape of the B-H curve as a function of increasing temperature, including the determination of the

Curie temperature. The investigated multilayer materials were divided into two groups: systems without ferritic layers and systems incorporating ferritic layers. The gradual increase in model complexity enabled the calibration of partial models based on experimental measurements and the successive improvement of simulation accuracy at subsequent stages.

In the experimental part of the study, measurement-based validation was performed with respect to the temperature distribution on the sample surface as well as pointwise temperature measurements for each developed numerical model. Three temperature measurement methods were employed in the experiments:

- type K thermocouples, used as the reference measurement,
- an industrial pyrometer,
- a thermal imaging camera.

The collected results were compared with those obtained from numerical simulations, and their accuracy and validity were assessed. In addition, the influence of the sample surface condition on the accuracy of non-contact temperature measurements was examined.

## Conducted research

Three main research pathways were defined in this study, directly related to the previously identified material groups:

a) numerical modelling and experimental validation of multilayer systems without ferritic layers,
b) numerical modelling and experimental validation of multilayer systems incorporating ferritic layers,
c) analysis of the influence of the thickness of the heat-distributing layer on the temperature distribution.

For the first stage of the research, material systems with diverse material properties and geometrical configurations were selected in order to verify the correctness of the numerical models under various conditions. In the experimental setup, an excitation coil with a geometry resembling a flattened cylinder was used. Based on measurement validation, the developed numerical models demonstrated high accuracy, reaching errors as low as 1% for selected cases. An additional numerical analysis of parameter distributions across the sample cross-section was also performed, revealing a number of atypical behaviours of the observed parameters. An attempt to explain these phenomena was undertaken within the study.

The next stage of the study involved an attempt to model the induction heating of a multilayer material containing ferritic layers. Owing to the pronounced skin effect in ferritic materials, it was necessary to implement additional discretisation strategies and geometric simplifications in order to obtain a computational mesh of sufficient resolution to ensure reliable simulation results. Furthermore, based on the conducted literature review, it was observed that such materials may undergo changes in their magnetic properties as a result of large plastic deformations. Consequently, the influence of the explosive welding process on the variability of the B–H curve was examined. Measurement-based validation of the numerical models confirmed the correctness of the adopted assumptions, and the model achieved the expected level of accuracy. The proposed numerical model remained valid over the entire analysed range, including the correct representation of the loss of magnetic properties above the Curie temperature.

As part of the research, an analysis was also carried out to assess the influence of the thickness of the heat-distributing layer on the final temperature distribution on the sample surface. Given the application-oriented nature of the study, these considerations were aimed, among other aspects, at limiting unnecessary costs. Numerical and experimental investigations were again performed for three variants of the functional layer thickness, demonstrating that an increased thickness improves the temperature uniformity on the sample surface, while simultaneously increasing the manufacturing cost of the material. The conducted analysis made it possible to identify a compromise between thermal efficiency and the economic feasibility of the proposed solution.

The study also addressed the problem of designing induction coils for three-dimensional geometries using multilayer materials, taking into account geometric and technological constraints in real-case applications. The influence of coil turn arrangement on heating efficiency and the distribution of eddy current losses was analysed. On this basis, solutions ensuring effective and uniform heating were proposed.

## Practical aspects of the conducted research

The applied objective of this study was the development and implementation of solutions enabling the practical use of induction heating in multilayer materials joined by explosive welding. Based on validated numerical models and an analysis of the thermo-electromagnetic properties of these materials, three industrial applications were designed and realised: a wax melter, a WOK-type vessel, and a boiler for alcohol distillation. Each of these devices exploits the advantages of the multilayer structure, including the effective heating of the ferromagnetic layer and the high thermal conductivity of the copper layer, which made it possible to achieve a more uniform temperature distribution, higher energy efficiency, and improved operational performance. Consequently, the results of this work have a direct impact on engineering practice, supporting the development of real heating devices and confirming the usefulness of the proposed models in the design of induction heating systems.

## Summary

The dissertation confirms the high applicability of induction heating as a modern, energy-efficient technology of increasing industrial relevance. The conducted analysis demonstrated that, in the case of multilayer materials—particularly those joined by explosive welding—accurate modelling requires the consideration of temperature-dependent material properties. The developed and validated numerical models enabled a reliable representation of the heating process, including the influence of geometry and layer composition on the distribution of eddy currents and temperature. Experimental validation showed a high level of agreement between numerical predictions and measured results. Significant phenomena occurring at the interfaces between material layers were also identified, affecting the penetration depth of the electromagnetic field and the localisation of eddy current losses. The obtained results therefore constitute not only a scientific contribution but also a foundation for the design of efficient heating devices and for further research and development activities.