

COB-2023-1701 ANALITICAL FORMULATION AND MICROSTRUCTURAL TRANSFORMATIONS IN INDUCTION HEATING

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Abstract. *Induction heating is a contactless heating method widely employed in various industries. This article discusses on the mathematical formulation using finite volumes for heat transfer in axially symmetric geometries, specifically using cylindrical coordinates. The article highlights the microstructural transformations that occur during induction heating processes and their influence on material properties. Analytical cases for axially symmetric systems with internal heat generation are presented with microstructural analysis and the influence of magnetic fields on microstructure change. The article concludes with a comprehensive understanding of the mathematical formulation for austenitic transformations in induction heating processes.*

Keywords: *Axisymmetric Geometries, Analytical Solution, Induction Heating, Heat Transfer*

1. INTRODUCTION

Induction heating in axially symmetric geometries is a contactless heating method widely used in the industry. This process utilizes alternating electric currents to generate heat in conductive materials, such as cylindrical or conical metal parts. An induction coil is designed to conform to the shape of the part, enveloping it and forming an induction-part assembly. When an alternating current is applied to the coil, a varying magnetic field is generated, inducing electric currents in the parts. These currents predominantly circulate in the radial direction, creating a magnetic flux pattern around the central axis of the part. Eddy currents generate heat through Joule heating in the conductive material, enabling rapid and efficient heating.

Induction heating in axially symmetric geometries offers several advantages. First, it allows selective heating of specific areas of the parts, concentrating the heat where it is needed. Additionally, it is a fast and efficient method, providing high heating rates. The temperature distribution can be precisely controlled by adjusting the power and frequency of the induced current. This enables efficient and high-quality mass production of cylindrical or conical parts. This process is widely applied in different industrial sectors, such as automotive, aerospace, metallurgical, and general manufacturing. It is used in heat treatments like quenching and tempering to improve the mechanical properties of parts. It is also employed in brazing and welding of cylindrical or conical components, ensuring a strong and durable joint.

In induction heating in axially symmetric geometries, it is crucial to use appropriate induction coils for each part shape. These coils are designed considering the specific requirements of the process, such as the desired temperature distribution along the part. With a correct coil design, uniform and controlled heating can be achieved, ensuring consistent and high-quality results.

The reproducibility and consistency of results are strong points of induction heating in axially symmetric geometries. Through numerical simulations and precise process control, highly reproducible results can be obtained. Once the correct parameters are established, the same thermal conditions can be reproduced in different heating cycles, ensuring mass production with consistent and repetitive quality.

The field of materials and the use of the Continuous Cooling Transformation (CCT) diagram play a fundamental role in predicting microstructure in heat treatments. The relationship between the possibility of reproducing the same thermal conditions in different heating cycles and achieving mass production with consistent and repetitive quality is directly linked to the control of material microstructure. (Rudnev *et al.*, 2017)

When it comes to heat treatments such as quenching and tempering, it is essential to achieve the desired microstructure to obtain appropriate mechanical properties in the material. The CCT diagram is a tool that provides information about phase transformations occurring in a material as a function of time and temperature. Based on this diagram, it is possible to determine the necessary thermal conditions to achieve the desired microstructure.

In summary, the relationship between the possibility of reproducing the same thermal conditions in different heating cycles in induction heating in axially symmetric geometries and the field of materials using TTT (Time-Temperature-Transformation) diagrams and CCT diagrams lies in the prediction of microstructure in heat treatments. This relationship allows for the control of phase transformation in materials, ensuring mass production with consistent and repetitive quality, and optimizing production processes based on simulations.

2. Axisymmetric Thermal Analysis

2.1 Mathematical Development

Heat transfer is an essential phenomenon in many processes and systems, and understanding its mathematical formulation is crucial for conducting accurate analyses and simulations. In this context, the use of a control volume in cylindrical coordinates is particularly useful when dealing with problems that exhibit axial symmetry, such as tubes, cylinders, or cylindrical shells. Let's explore the mathematical formulation for a numerical case of heat transfer using this coordinate system.

Hahn and Ozisik (2012); Carslaw and Jaeger (1959) present analytical solutions for axially symmetric cases with internal heat generation. Dalir and Nourazar (2014) also developed a solution with internal generation, but Hahn and Ozisik (2012) better approach the desired concepts as they derive their solution from a fundamental problem with characteristics close to the induction process. Equation 1 proposes the starting point for formulating transient problem at Figure 1

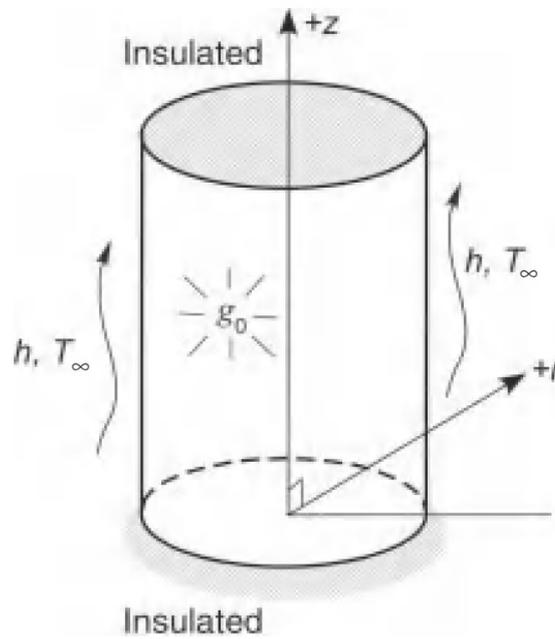


Figure 1. axisymmetrical case with internal generation. (Hahn and Ozisik, 2012)

$$\frac{\partial^2 \Psi}{\partial r^2} + \frac{1}{r} \frac{\partial \Psi}{\partial r} + \frac{\partial^2 \Psi}{\partial z^2} = \frac{1}{\alpha} \frac{\partial \Psi(r, t)}{\partial t} \quad (1)$$

where Ψ is the homogenous form of the PDE, and α is the thermal diffusivity. At the end of the analytical solution process, the temperature result is obtained.

$$T(r, z, t) = \sum_{n=0}^{\infty} \sum_{m=1}^{\infty} \left[C_{nm} J_0(\beta_m r) \cos \eta_n z e^{-\alpha \lambda_{nm}^2 t} \right] + \frac{bg_0}{2h} + \frac{g_0}{4k} (b^2 - r^2) + T_{\infty} \quad (2)$$

The transient analytical solution, which describes the behavior of the non-steady-state heat transfer system, provides a reliable reference for validating the numerical simulation. This analytical solution is obtained by solving partial differential equations that describe the underlying physical phenomenon. (Jain *et al.*, 2009)

However, When considering heat transfer in solids, it is important to take into account the microstructural changes that can occur during the process. One of these changes is phase transformation, which can occur without a physical state change. During the transformation, atomic rearrangements take place that can release or absorb latent heat. This latent heat directly influences the temperature increase of the material, even when the heat flux is kept constant. (Davies and of Electrical Engineers., 1990)

In addition to the latent heat of microstructural transformation, another relevant phenomenon is the reduction of magnetic permeability with temperature. Ferromagnetic materials, such as ferrite and austenite, exhibit a magnetic permeability that varies with temperature changes. This variation directly affects the material's ability to conduct magnetic flux and can be considered in numerical modeling. (Zinn and Semiatin, 1988)

The phase change from ferrite to austenite can also be investigated through numerical solutions. According to Porter and Easterling (1992) the phase transformation of a material, as in this case, is directly related to temperature. Mathematical models that describe the kinetics of phase transformation can be incorporated into numerical solutions to predict the evolution of the austenite fraction over time and the resulting changes in the material's magnetic properties.

The validation of numerical simulations is an essential process to ensure the reliability of results obtained through computational methods. In the context of heat transfer in a control volume, comparing the numerical solution with the transient analytical solution is a common way to validate the model. Jain *et al.* (2009) provides an analytical solution for validating numerical cases in multiple layers in an axially symmetric scenario.

2.2 Boundary Condition

2.2.1 Internal Generation

Magnetic permeability is a property of materials that describes their ability to conduct magnetic flux. Materials with high magnetic permeability, such as iron, have a stronger response to the applied magnetic field, while materials with low magnetic permeability, such as aluminum, have a weaker response.

The presence of materials with different magnetic permeabilities can complicate the accuracy and efficiency of the simulation. When simulating induction heating, it is necessary to take into account the differences in magnetic permeabilities of the materials involved. The magnetic fields generated by the induction system can behave differently in different materials, resulting in non-uniform heat distributions, reduced heating efficiency, and varying depths of heat generation. (Kagimoto *et al.*, 2010)

Davies and of Electrical Engineers. (1990) determines the magnetic field penetration in a workpiece under induction heating. Despite the difficulties in estimating the magnetic permeability of different alloying elements and different structures, the author proposes a reasonable approximation that can be calculated using Eq.3.

$$\left(\frac{2 \cdot \text{Electrical Resistivity}}{\text{Angular Frequency} \times \text{Magnetic Permeability}} \right)^{\frac{1}{2}} \quad (3)$$

Often, the metallic alloys found in industrial processes can exhibit a combination of different elements, resulting in complex magnetic properties. These alloys may display nonlinear magnetic behaviors, which can further complicate the accurate simulation of the induction heating process. (Davies and of Electrical Engineers., 1990)

In addition to the different magnetic permeabilities of materials and alloys, the control volume simulation of an industrial induction heating process should also take into account the magnetic permeability change of steel resulting from alterations in physical phases and microstructure.

Steels, for example, are ferromagnetic alloys commonly used in industrial induction heating processes. These steels can undergo physical phase changes, such as the transition from solid to liquid state, when subjected to high temperatures. This phase change can significantly affect the magnetic permeability of the material. However, for the induction hardening process, we can disregard the changes in magnetic and thermal properties related to the material's melting.

Furthermore, the microstructure of steel also plays a crucial role in magnetic permeability. For instance, the transformation from ferrite, a ferromagnetic phase, to austenite, a less induction-susceptible phase, can occur when steel is heated to high temperatures. This change in microstructure can lead to a significant reduction in the magnetic permeability of the steel. (Davies and of Electrical Engineers., 1990)

Austenite has a relatively weaker magnetic response compared to ferrite. This is because austenite has a face-centered cubic crystal structure in which the magnetic moments are more disordered and less efficiently aligned. Therefore, the transition from ferrite to austenite results in a decrease in magnetic permeability.

When simulating an induction heating process in which physical phase changes or microstructural transformations occur in steel, it is crucial to consider these alterations in magnetic permeability. Simulation models should incorporate information about the magnetic properties of different phases and microstructures of steel at different temperatures.

2.2.2 Convection

In the case of an induction hardening system with an axially symmetric workpiece, there are two relevant boundary conditions for the cooling of the workpiece: natural convection by air on the outer surface and forced convection with a jet of cooled water. Let's address each of them separately.

Natural convection by air occurs on the outer surface, and since the length is much larger than the diameter, the North and South boundaries are considered isolated. This initial consideration of the influence of air on the cooling rate can be made because the workpiece is initially at a higher temperature than the ambient.

In a subsequent stage, when the heated workpiece is subjected to forced convection with a jet of cooled water, the cooling is intensified. The cooled water is applied directly onto the workpiece, promoting more efficient heat transfer.

The cooling rate in this stage is determined by the velocity and temperature of the water.

Cooling Intensities				
Quenchant	Quenchant Temperature		Velocity	Cooling Intensity
	°C	°F	m/s	W/(m ² °C)
Pure water	32	90	0	5000
			0.51	12,000
	55	130	0	1000
25% Polyvinyl pyrrolidone			0.76	10,500
	43	110	0	3500
			0.76	7500
Conventional oil	65	150	0.51	3000
Air	27	80	0	200
			5.08	350

Figure 2. Industrial reference values for convection.(Rudnev *et al.*, 2017)

During the quenching process, a phase transformation occurs in the workpiece from austenite to martensite. Austenite is a high-temperature solid phase with a face-centered cubic crystal structure, while martensite is a high-hardness phase with a body-centered tetragonal crystal structure. The phase transformation occurs when the workpiece is rapidly cooled. (Porter and Easterling, 1992)

The cooling rate is crucial for the proper formation of martensite. Slower cooling rates can lead to the formation of other phases, such as pearlite or bainite, which have different mechanical properties compared to martensite. Therefore, precise control of the cooling conditions is essential to achieve the desired properties in the tempered workpiece.

2.3 Microstructural Transformation

The Continuous Cooling Transformation (CCT) diagram is a valuable tool in the steel industry as it provides information about the microstructural transformations that occur in steel during cooling. However, accurately representing the reality of induction processes can be challenging due to the lack of isothermal maintenance of the workpiece.

When applying an induction process, the workpiece is rapidly heated using a high-frequency alternating electromagnetic field. This heating is localized, meaning it only affects a specific region of the workpiece while the rest remains relatively cool. As a result, there is a significant variation in temperature along the workpiece, creating a non-uniform thermal gradient.

This lack of uniformity in the workpiece temperature during the induction process makes it challenging to accurately represent the microstructural transformations on the CCT diagram. The CCT diagram assumes that the workpiece undergoes uniform and isothermal cooling, which is not the case in induction processes. Figure 3 illustrates a representation of a CCT diagram for two cases, showing the possible changes in microstructure on the surface and core of the workpiece.(Porter and Easterling, 1992)

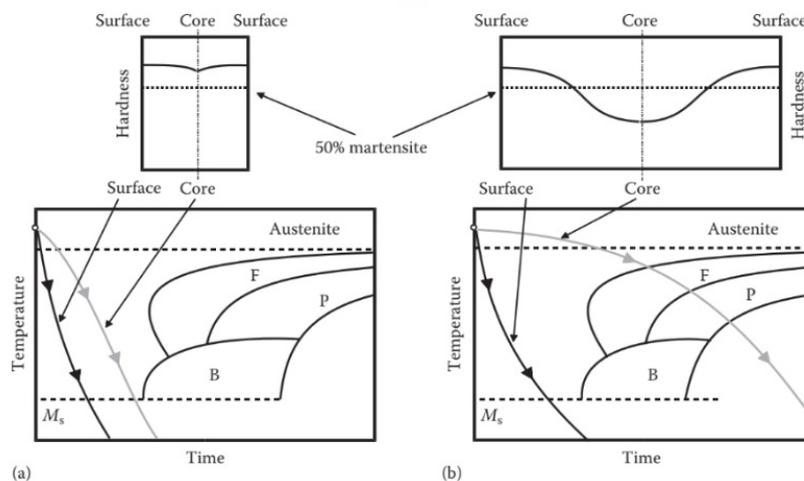


Figure 3. CCT diagrams illustrating microstructural transformations during cooling processes in the surface and core. (Rudnev *et al.*, 2017)

Additionally, Rudnev *et al.* (2017); Porter and Easterling (1992) point out that the addition of alloying elements to steels can alter the configuration of the CCT diagram. These alloying elements, such as chromium, molybdenum, and nickel, have the effect of delaying the transformations from austenite to pearlite and bainite, favoring the formation of

martensite during rapid cooling.

Martensite is a highly desirable phase in many hardened steel applications as it exhibits high strength and hardness. In induction hardening processes, where cooling is rapid and non-isothermal, the CCT diagram is more appropriate than the TTT (isothermal transformation) diagram as it takes into account the non-uniform cooling.

The CCT diagram provides information about the transformations that occur at different cooling rates, allowing for the appropriate selection of cooling parameters to achieve the desired properties. In this way, it is possible to control the formation of martensite during the induction process, optimizing the heat treatment to attain the desired mechanical properties in the region affected by induction.

2.3.1 Numerical Solution for Microstructural Change

The Avrami equations are widely used to describe microstructural transformations in steels, especially those occurring during the quenching and tempering process. These equations are applied to determine the transformed fraction as a function of time and temperature. They provide valuable information about the transformation kinetics and enable the prediction of microstructure evolution over time. The Avrami equation, represented in Eq. 4 is based on the assumption that the transformation rate is proportional to the amount of untransformed phase and the rate of nucleation of new phases.

$$f(t) = 1 - e^{(-kt)^n} \quad (4)$$

Where:

$f(t)$ represents the transformed fraction at time t ;

k is the transformation rate constant;

n is a parameter that depends on the transformation mechanism and varies according to the structure geometry and reaction conditions.

Equation 4 presented involves the parameter "n," which is a numerical exponent ranging from -1 to 4. This value of "n" represents the relationship between the nucleation rate and temperature. It is important to note that as long as the nucleation mechanism remains unchanged, the value of "n" remains independent of temperature. On the other hand, the parameter "k" is influenced by the nucleation and growth rates, making it highly temperature-sensitive. (Porter and Easterling, 1992)

During induction heating, the heating rate is quite rapid, which can result in higher transformation rates compared to other heating methods. However, the transformation rate will also depend on the diffusion capability of elements in the steel, which is influenced by temperature. At higher temperatures, elements have greater mobility, favoring diffusion and, consequently, accelerating the microstructural transformation.

By plotting the transformed fraction as a function of time for a fixed temperature, we can observe the transformation rate over time. Initially, the transformation rate may be slow, but as time increases, the transformation rate accelerates, and the transformed fraction increases rapidly. Again, this behavior is consistent with the Avrami equation, where the transformation rate is proportional to the amount of untransformed phase, as can be observed in Fig. 4.

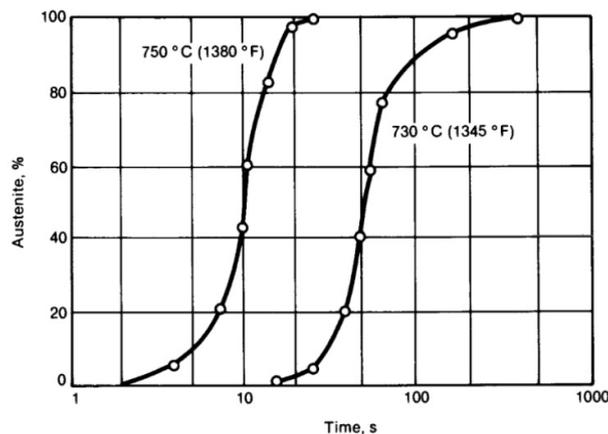


Figure 4. TTT for the austenitization process (Zinn and Semiatin, 1988)

It is important to note that the transformation kinetics during induction heating in steels can be complex, as the temperature distribution within the workpiece may be non-uniform due to various factors such as workpiece geometry and magnetic properties. Therefore, to fully understand the transformation rates during induction heating, it is necessary to carefully consider all these aspects and conduct specific experimental studies and numerical simulations for each case. (Davies and of Electrical Engineers., 1990)

The Avrami relation to austenitization graphs in terms of temperature and time is related to the transformation from an initial phase to the austenitic phase in steels. During the austenitization process, the steel's crystal structure transitions from an initial phase, typically ferritic or pearlitic, to the austenitic phase.

When plotting austenitization graphs in terms of temperature and time, it is common to observe a curve representing the transformed fraction as a function of time for a fixed temperature. These graphs can be interpreted based on the principles of the Avrami equation.

3. RESULTS AND DISCUSSIONS

The enthalpy of transformation values shown in Figure 5, were used as input values. It was considered, therefore, that the amount of energy would be equivalent for the reverse process since the studied piece begins with a completely ferritic structure.

Transformação	ΔH_i^L	Calor Latente associado(J/m ³)
austenita→ferrita	ΔH^F	$5,95 \times 10^8$
austenita→bainita	ΔH^B	$5,12 \times 10^8$
austenita→perlita	ΔH^P	$5,26 \times 10^8$
austenita→martensita	ΔH^M	$3,14 \times 10^8$

Figure 5. Latent heats of transformation of austenite into its respective decomposition products. (Bortoleto, 2010)

Austenitization is a diffusion-controlled phase transformation. The diffusion of carbon and alloying elements within the material is inherently temperature-dependent. Elevated heating rates can hinder the efficiency of element diffusion, leading to alterations in the kinetics of the austenitization process. Slower heating rates facilitate improved element diffusion, contributing to a more uniform and controlled phase transformation.

The heating rate directly influences grain structure. Rapid heating may encourage grain growth, resulting in uneven austenitization and, consequently, an irregular microstructure. In contrast, slower heating rates promote finer and more uniform grain structures, a desirable characteristic for various material applications.

As shown in the figure 6, maximum heating rates of 1.5 °C/s are achieved during the initial stages of heating. These heating rates are considered high as they, to a certain extent, facilitate diffusional processes; however, the rate in question exceeds the diffusion limits. Nevertheless, phase transition temperatures are not reached during the initial moments.

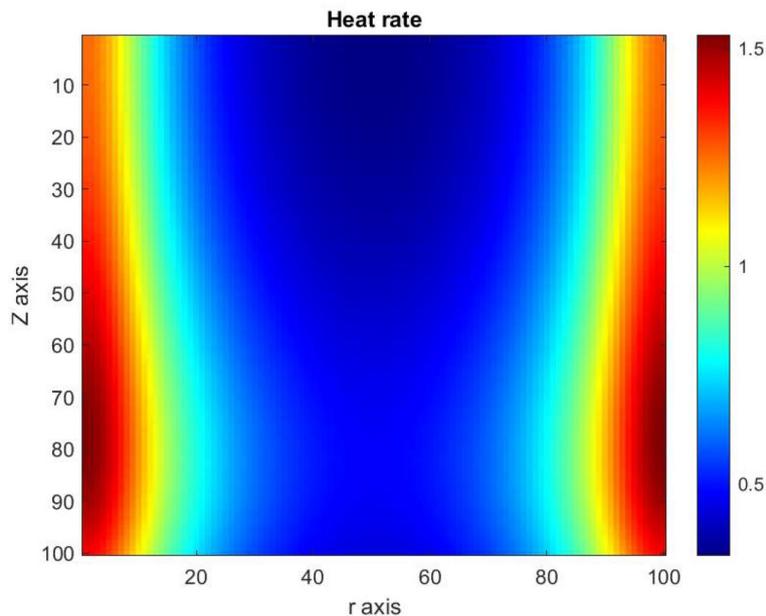


Figure 6. Heat rate per control unit.

As depicted in the figure 7, the average heating rate of the process is slightly above 0.12 °C/s. According to Napitupulu (2017), these values fall within the austenitic grain growth zone. Heating rates exceeding 0.125 °C/s are considered high and, instead of favoring grain growth, promote nucleation. Therefore, to refine the austenite grains and achieve an improved final martensitic outcome following treatment, it is advisable to further increase heating rates in the final stages of heating, close to the austenitization temperatures.

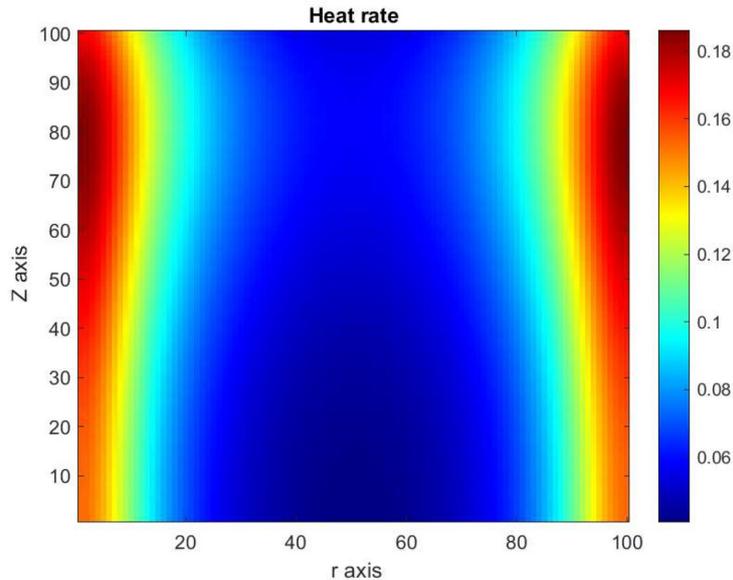


Figure 7. Mean heat rate per control unit.

Controlled heating rates are of paramount importance in some industrial processes, where the goal is to achieve a desired depth of case hardening. Rapid heating rates may impede adequate carbon diffusion, resulting in insufficient hardening, making the selection of an appropriate heating rate a critical consideration. (Hart-Rawung *et al.*, 2023)

The relationship between heating rate and austenitization kinetics is a fundamental parameter in the realm of materials science and metallurgy. It significantly influences microstructure, mechanical properties, and the overall performance of materials. Engineers and metallurgists must meticulously consider the heating rate when designing heat treatment procedures to attain desired material characteristics and ensure the quality and reliability of the final product.

The disparities and imprecisions intrinsic to diffusional microstructural formation prediction formulas, particularly those advanced by Avrami, have long stood as fundamental tools in the realm of materials science. Essential for forecasting the evolution of microstructures during diffusional transformations, Nevertheless, these conventional models often struggle to accommodate the nuanced variations seen in real-world scenarios. One prominent factor contributing to these disparities is the reliance on isothermal temperatures in these predictive models. This simplification, while practical for theoretical considerations, may not sufficiently capture the complexity of temperature gradients present during actual processes. As a result, these inaccuracies inherent in predictive models can have far-reaching implications. (Hawbolt *et al.*)

It is known that ferrite and perlite have a stronger magnetic interaction than austenite, so when exposed to a strong magnetic field, it can affect the driving force for microstructural generation. As studied by Garcin *et al.* (2010), the change in the transformation temperature is proportional to the intensity of the magnetic field.

The presence of magnetic fields increases the growth of ferrite grains by approximately 1/10, as reported by Enomoto *et al.* (2001). It can be inferred that the energy required for the transformation from ferrite to austenite is proportionally impeded by the applied magnetic field. The author also established that this relationship is linear, and the heating rate near the transformation temperatures influences the rate of growth and transformation of the grains under investigation.

Further investigation into the effects of magnetic fields on grain growth and phase transformation reveals intriguing insights. The linear relationship between magnetic field strength and grain growth implies that higher magnetic field intensities correspond to more pronounced impediments in the ferrite-to-austenite transformation. This phenomenon highlights the sensitivity of the transformation process to external magnetic influences.

Additionally, the interplay between the heating rate and the magnetic field warrants deeper exploration. It becomes evident that the rate of heating in proximity to the transformation temperatures significantly affects the growth and transformation kinetics of the grains. Slower heating rates offer more time for the magnetic field to exert its influence, potentially leading to a more substantial impact on the transformation process.

Recognizing that three domains are inherently interconnected, them being the thermal, the microstructure and the mechanical, the significance of simultaneously considering all aspects in materials modeling and simulation must be emphasized. Neglecting any one of these spheres can lead to suboptimal predictions and potentially inaccurate assessments of materials behavior. By embracing a holistic approach that integrates thermal, microstructural, and mechanical parameters, not only the precision of simulations is enhanced but also gain a deeper understanding of the underlying mechanisms governing material performance. (Bortoleto, 2010)

4. ACKNOWLEDGEMENTS

The authors would like to thank LETA and its members for their support in the development of this work. We also thank Gerdau Summit for making this work possible through funding.

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