

## ENCIT-2018-0338

# COOLING SIMULATION OF A CARBON-STEEL ABNT 1025 USING THE FINITE DIFFERENCES METHOD

**William Denner Pires Fonseca**

State University of Campinas, Street Mendeleev, 200, Campinas, SP - Zip code 13083-860  
fonsecawdp@gmail.com

**Pedro Felipe Lavra Dias**

State University of Maranhão, University City Paulo VI – Tirirical, São Luís  
pedrodias@aluno.uema.br

**Lourival Matos de Sousa Filho**

State University of Maranhão, University City Paulo VI – Tirirical, São Luís  
lourivalfilho@professor.uema.br

**Abstract.** *The present study aims the modelling, elaboration and implementation of a computational algorithm to calculate the bidimensional and transient temperature distribution using rectangular coordinates in order to analyze the microstructural comportment of the carbon steel ABNT 1025. The heat conduction equation is spatially discretized by the Finite Differences Method and the Explicit Method was used to discretize time. Using MATLAB as software, the matricial solution of the linear systems were done by the Jacobi's method. Initially, many tests were done in order to verify the computational mesh and time-step independency and secondly how the temperature field works for two different states of cooling. By the end, it is verified by the cooling curves compared with the steel Isothermal Time Transformation (ITT), which microstructural phase is formed. It is important to affirm that these results are extremely important to the confiability of the steels microstructures.*

**Keywords:** *Steel cooling process, thermal treatment, numerical analysis.*

## 1. INTRODUCTION

Recently the interest about the environment impacts are being emerged by the industries as an important factor to their production activities. As a result, it is necessary to optimize the manufacture processes in order to guarantee the product quality besides sustainability. Besides that, the industries seek to use the energetic resources and materials in a rational way, avoiding waste. This way, new opportunities are opened in the engineering field, requiring from the professionals a new way of understanding the area, knowing neither the optimization techniques or numerical modelling and simulations.

Binele (2009) affirms that the computers evolution in an exponential way are allows the solution of more complex problems using numerical techniques. Another factor is related with the projects' costs since it is completely possible to replace hours of laboratories' experiments into computers simulations, decreasing the costs and using these experiments only to perform projects in a better way.

According to Kang et al., (2004) and Calvalcante et al., (2010), the thermal treatments in different types of alloys are one of the most discussed topic in materials and mechanical engineering recently. This appears in order to preview the microstructural alterations and consequently the mechanical properties of these materials.

In this context, the present paper seeks the modelling, elaboration and implementation of a computational algorithm to calculate the bidimensional and transient temperature of the ABNT 1025 steel, using the finite differences and explicit methods to analyze the conditions imposed.

## 2. MATHEMATICAL FORMULATION AND NUMERICAL METHOD

### 2.1 Physical model and mathematical formulation

The sketch of the problem is shown in Fig. 1. The energy equation is used in the bidimensional – x and y directions, conservative, transient, without heat generation and constant properties form. The problem consists into the cooling process of the ABNT 1025 steel.

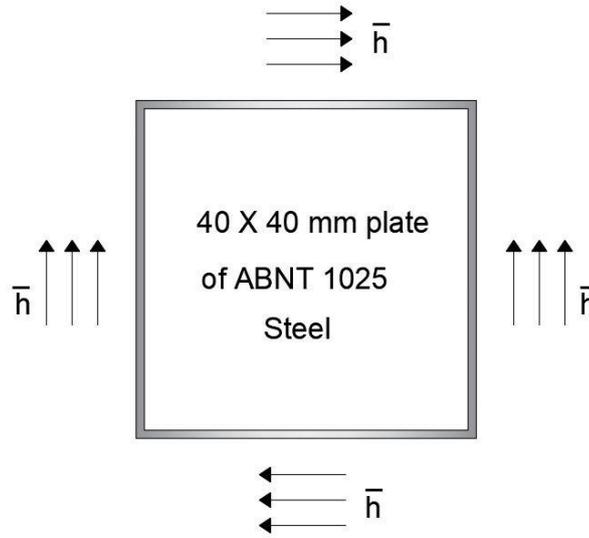


Figure 1. Problem illustration

This way, Çengel (2012) presents the heat conduction energy equation for our purpose, Eq. (1):

$$\alpha \frac{\partial^2 T_{(x,y,t)}}{\partial x^2} + \alpha \frac{\partial^2 T_{(x,y,t)}}{\partial y^2} = \frac{\partial T_{(x,y,t)}}{\partial t} \quad (1)$$

Where:  $\alpha = \frac{k}{\rho c_p}$  is the thermal diffusivity.

The boundary conditions in all faces were a third order condition (Eq. 2). These were applied to simulate the environment cooling through the plate.

$$k \frac{\partial T}{\partial (x, y)} = \bar{h}(T - T_\infty) \quad (2)$$

The thermophysical properties of the material and the dimensionless parameters of the fluid flow imposed by the algorithm were:  $k = 51,9W/mK$ ,  $\rho = 7832Kg/m^3$ ,  $\alpha = 18,8 \cdot 10^{-6}m^2/s$ ,  $\beta = 11,7\mu m/mC$ . In order to obtain the medium convection coefficient, Incropera (2015) affirms that for non-natural convection the convection coefficient can be adopted as  $\bar{h} = 30W/m^2K$ . The plate initial temperature was  $840^\circ C$  and the temperature of tangent fluid through the plate was  $27^\circ C$ .

## 2.2 Numerical method

The discretization of the conduction heat transfer equation and of the boundary conditions were developed by the finite differences method, demonstrated by Darrell et al., (2006). The problem adopted a bidimensional mesh that covers all the rectangular coordinates of the plate.

Starting from the conduction heat transfer equation, Eq. (2), and applying the Taylor's series expansion we get the same above mentioned terms into these discretized equations:

$$\frac{\partial^2 T_{(x,y,t)}}{\partial x^2} = \frac{T_{(x+1,y,t)} + T_{(x-1,y,t)} - 2T_{(x,y,t)}}{\Delta x^2} \quad (3.1)$$

$$\frac{\partial^2 T_{(x,y,t)}}{\partial y^2} = \frac{T_{(x,y+1,t)} + T_{(x,y-1,t)} - 2T_{(x,y,t)}}{\Delta y^2} \quad (3.2)$$

$$\frac{\partial T_{(x,y,t)}}{\partial t} = \frac{T_{(x,y,t+1)} + T_{(x,y,t)}}{\Delta t} \quad (3.3)$$

Replacing the above expressions into equation (1), the general discretized equation is given by:

$$T_{(x,y,t+1)} = \alpha \frac{\Delta t}{\Delta x^2} [T_{(x+1,y,t)} + T_{(x-1,y,t)} - 2T_{(x,y,t)}] + \alpha \frac{\Delta t}{\Delta y^2} [T_{(x,y+1,t)} + T_{(x,y-1,t)} - 2T_{(x,y,t)}] + T_{(x,y,t)} \quad (4)$$

The discretization of the boundary conditions, Eqs. (5.1 – 5.4), are given by:

$$-k \frac{T_{(x-1,y,t)} - T_{(x,y,t)}}{\Delta x} = \bar{h}(T_{(x,y,t)} - T_{\infty}) \quad (5.1)$$

$$-k \frac{T_{(x+1,y,t)} - T_{(x,y,t)}}{\Delta x} = \bar{h}(T_{(x,y,t)} - T_{\infty}) \quad (5.2)$$

$$-k \frac{T_{(x,y-1,t)} - T_{(x,y,t)}}{\Delta y} = \bar{h}(T_{(x,y,t)} - T_{\infty}) \quad (5.3)$$

$$-k \frac{T_{(x,y+1,t)} - T_{(x,y,t)}}{\Delta x} = \bar{h}(T_{(x,y,t)} - T_{\infty}) \quad (5.4)$$

It is important to affirm at this point that for each boundary grid point it was replaced the proper boundary condition term. For example, to the left and upper vertex grid point only the terms  $T_{(x-1,y,t)}$  and  $T_{(x,y-1,t)}$  of equations (5.1) and (5.3) respectively were replaced into Eq. (4).

In a first moment, the computational mesh was analyzed in order to guarantee the numerical results. For this study, 441, 961 and 1681 grid points were tested, and the Fig. 2 shows these results and proves that is not a significantly difference among the results. This way, the mesh with 441 grid points was used for the study to prevent a higher computational effort.

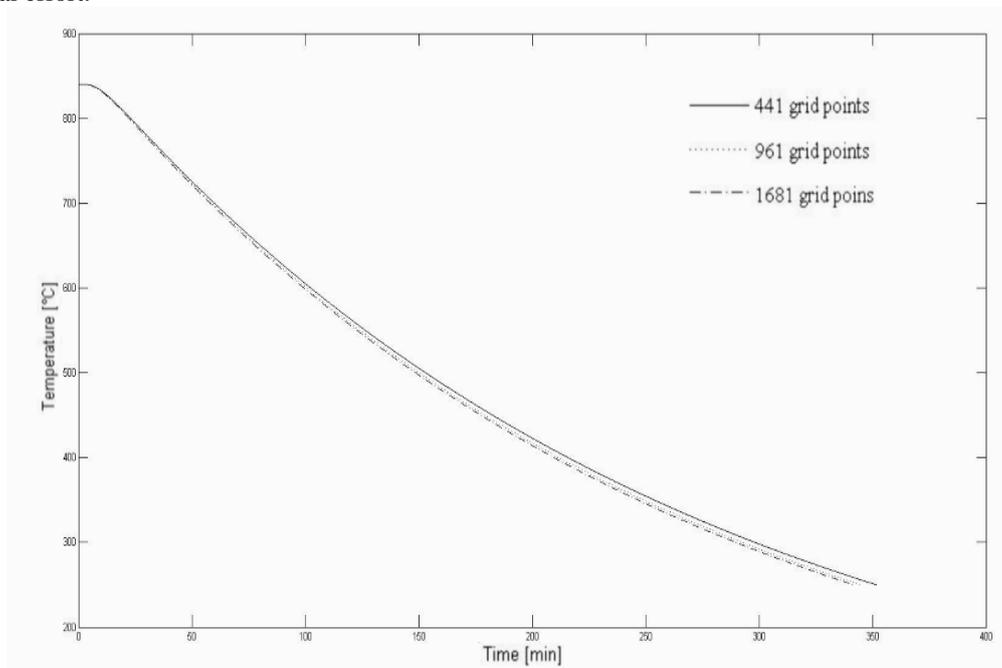


Figure 2. Optimized computational mesh

Simulations to verify the influence of the time-step into the results were done. This way it was used time-steps of  $\Delta\tau = 0,01$  and  $\Delta\tau = 0,02$ , choosing  $\Delta\tau = 0,02$ , since it has similar results with the first one and demand lower computational effort. Figs. 3 and 4 present this information.

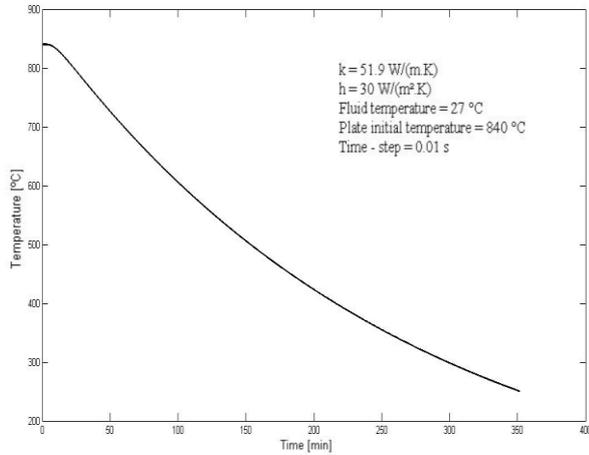


Figure 3. Optimized time step,  $\Delta\tau = 0,01$

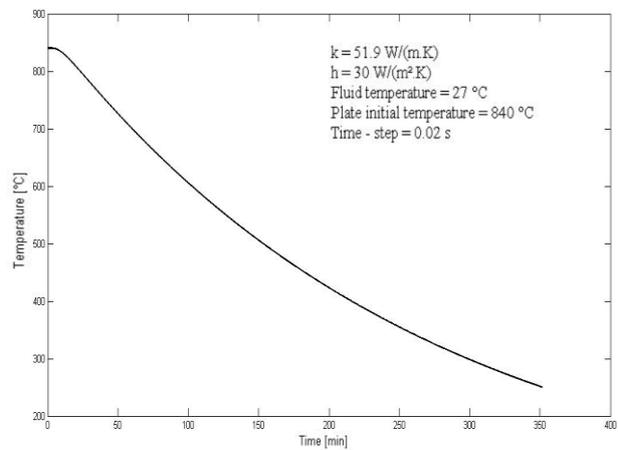


Figure 4. Optimized time step,  $\Delta\tau = 0,02$

### 3. RESULTS AND DISCUSSION

From the numerical method applied to the governing equations it was possible to get the results. This part of the paper aims to validate the numerical method proposed by the analyses of the temperature field in comparison with the material cooling curve.

The Fig. 5 shows the temperature field as a function of the rectangular coordinates. The stop criterion was the temperature of 720 °C at the center of the plate. This criterion was used since Callister Jr (2012) affirms that at this temperature it is possible to visualize the phase transformation of the material, from austenite to ferrite and cementite.

As can be observed by the temperature field (Fig. 5) and the isothermal curve (Fig. 6), the plate cooling occurs from the exterior to the interior once the boundary conditions are given by the natural convection at each side of the plate. In this sense it is possible the formation of austenite in the interior of the plate. Another relevant aspect is that for this condition, the cooling time is 55.306 minutes.

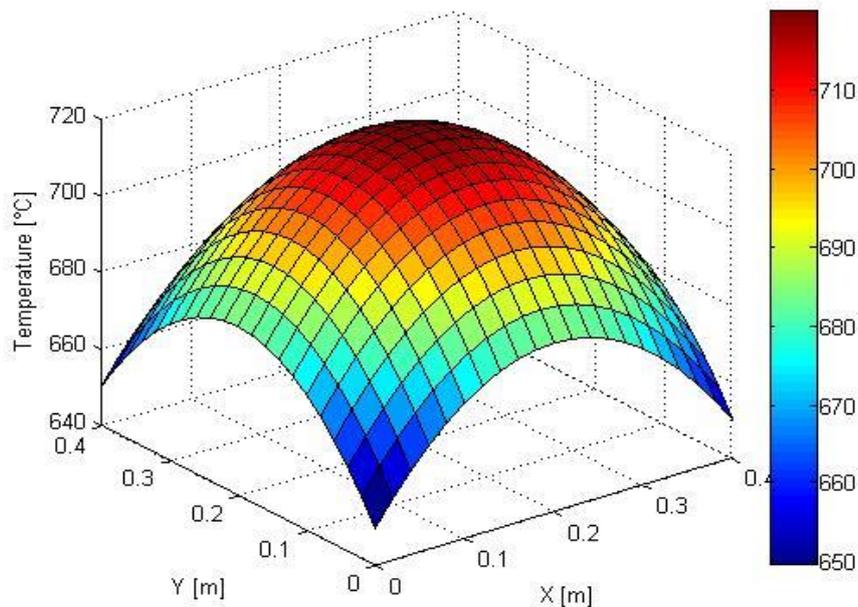


Figure 5. Field temperature for  $T = 720\text{ }^{\circ}\text{C}$

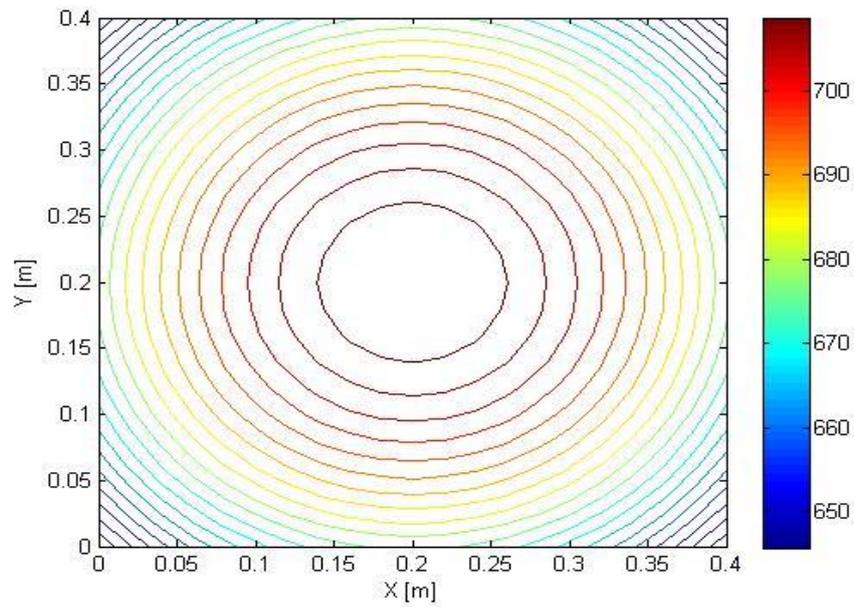


Figure 6. Isothermal curve,  $T = 720\text{ }^{\circ}\text{C}$

Continuing with the cooling temperature evolution, it is seen that for 250 °C (Figs. 7 and 8) in the center point of the plate the microstructural characteristics of the plate remains the same of the previous ones. According to Mei & Costa (2010), this temperature is relevant for the formation of ferrite and cementite and consequently perlite. To this simulation the cooling time was 351.67 minutes.

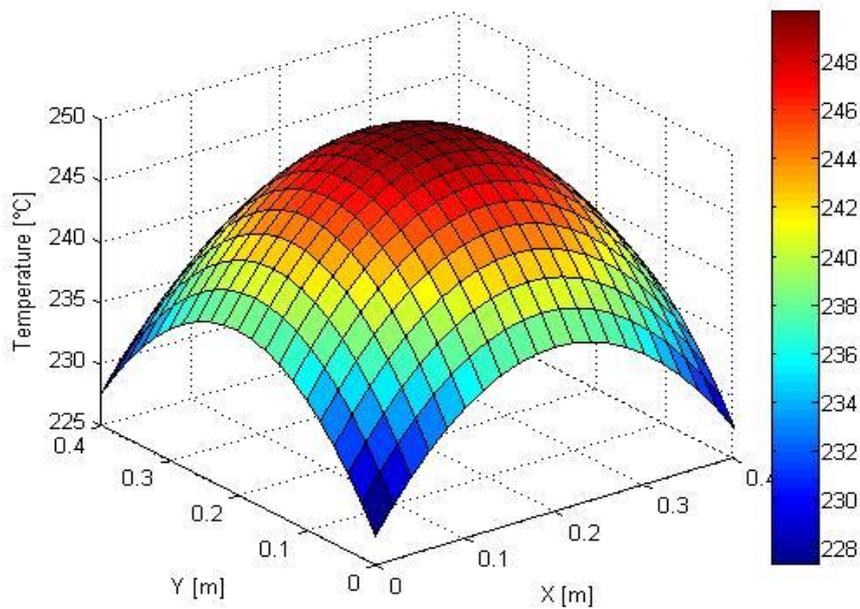


Figure 7. Field temperature for  $T = 250\text{ }^{\circ}\text{C}$

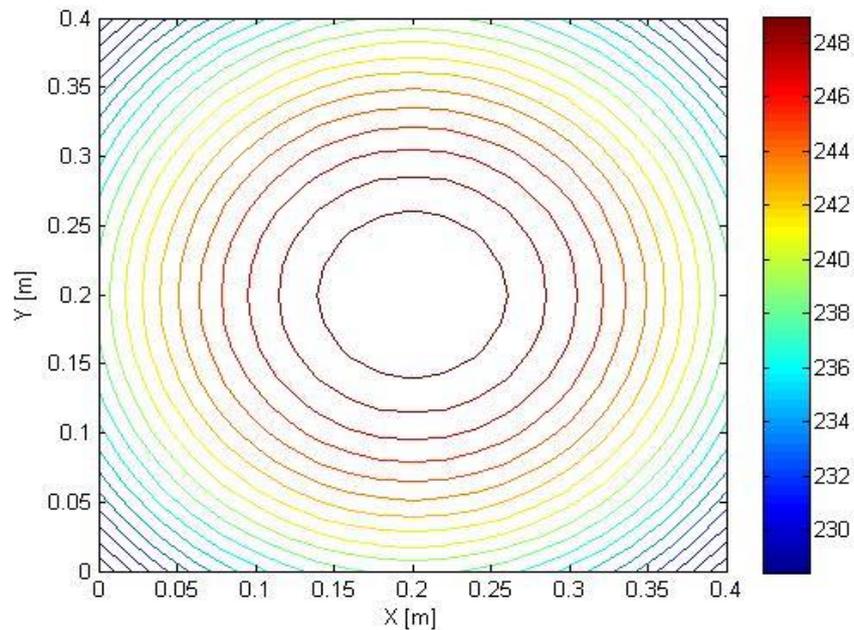


Figure 8. Isothermal curve,  $T = 250\text{ }^{\circ}\text{C}$

According to the ITT curve and the result obtained, it is confirmed the formation of ferrite and perlite. This can be verified by the metallography (Fig. 10).

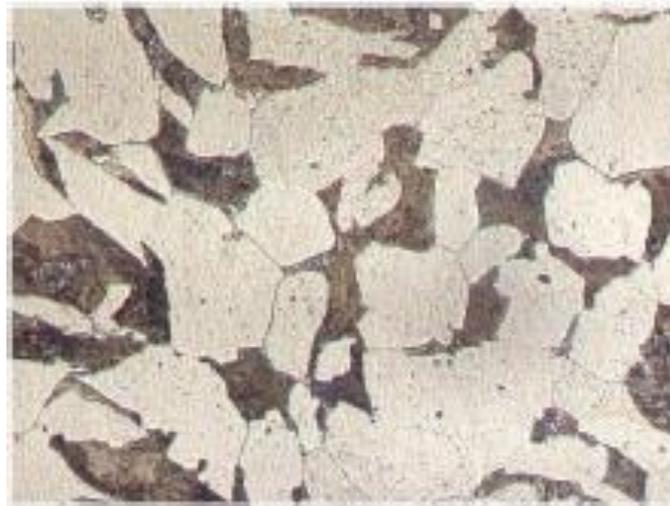


Figure 9. Micrograph of standard 1025 steel

The cooling curve represents the thermal treatment of normalization. Although it is important to affirm that the velocity of the cooling is lower than the real one since it was not considered the radiation loss. Besides that, as a boundary condition it was used an average value of heat transfer coefficient of  $\bar{h} = 30\text{ W/m}^2\text{K}$ , during all the process.

#### 4. CONCLUSIONS

The computational algorithm to calculate the bidimensional and transient conduction heat transfer equation for Cartesian geometries was done using MATLAB®. It was possible to simulate the cooling process of normalization where any material is cooled by the air. The ABNT 1025 steel was used as the material of study. The obtained results were satisfactory and the program could predict the formed microstructure.

The results of this simulation were confirmed by metallography, which demonstrated the formation of ferrite and perlite inside the treated part. As contributions for future work, it is suggested the improvement of the physical model, including heat losses by radiation and evaluation of the instantaneous coefficient of heat transfer by convection at each point of the surface. Another important extension would be the ability to treat three-dimensional systems, or with other coordinate systems, such as, cylindrical and spherical

## 5. ACKNOWLEDGEMENTS

The authors acknowledge the Foundation of Research and Scientific Development of Maranhão, FAPEMA, and for the Laboratory of Modeling and Simulation, MSILAB, from the State University of Maranhão, UEMA, for the infrastructure and scholarship to the authors.

## 6. REFERENCES

- Bergman, T.L. and Incropera, F.P., 2011. *Introduction to heat transfer*. John Wiley & Sons.
- Bezerra, A.C. et al., 2006. “*Simulação numérica da soldagem com aplicação à caracterização do comportamento dinâmico de estruturas soldadas*”.
- Callister, W., 2000. *Ciência E Engenharia de Materiais: Uma Introdução*. Grupo Gen-LTC.
- Costa, A. and Silva, P., 2010. “Mei: aços e ligas especiais”.
- Fortuna, A., 2000. *Técnicas computacionais para dinâmica dos fluidos: conceitos básicos e aplicações*. Edusp.
- Kang, J., Rong, Y. and Wang, W., 2004. “Numerical simulation of heat transfer in loaded heat treatment furnaces”. In *Journal de Physique IV (Proceedings)*. EDP sciences, Vol. 120, pp. 545–553.
- Orlande, H.R., Colaço, M.J., Cotta, R.M. et al., 2017. *Finite Difference Methods in Heat Transfer*. CRC Press.
- Yunus, A.C. et al., 2003. “*Heat transfer: a practical approach*”. MacGraw Hill, New York.

## 7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.