Proceedings of COBEM 2009
Copyright © 2009 by ABCM

20th International Congress of Mechanical Engineering
November 15-20, 2009, Gramado, RS, Brazil

ANALYSYS OF CONSTRUCTION STEEL BARS HEAT TREATMENT

Fábio Eduardo Baggio, fabio.baggio@hotmail.com
Luís Mauro Moura, luis.moura@pucpr.br
Pontifical University Catholic of Paraná - PUCPR
Imaculada Conceição, 1155, Prado Velho, Curitiba, PR

Abstract. *The purpose of this work is to present a numerical model used to obtain the cooling rate of the steel bars. Using the cooling rates and the Time Temperature Transformation (TTT) diagrams concomitantly the microstructure formation and their influence on the final mechanical properties of the steel bars can be determined.*

Keywords: *Steel Thermal Treatment, Thermex, Thempcore, steel bars*

1. INTRODUCTION

The development of the controlled cooling systems in lamination processes has as objective the reduction in the cost of the construction steel bars manufacture. Currently, the majority of the steel plants uses this technology in its productive process. Until the 70's it had one strong trend in the European market directed to the quality and performance in the steel manufacture process. The main characteristics were referring to the strength, toughness and weldability of the. Simon *et al*. (1984) verified that with the increase of the resistance of the steel bars it is observed consequent reduction of the steel bars destined to the civil constructions reducing the final cost of the buildings.

The steel bars controlled cooling systems consist of a thermal treatment of the steel bar on the last pass in the lamination set. The steel bar pass through a system of water cooling, occurring a superficial thermal treatment. The steel bar surface is submitted to an quick cooling over its surface. The surface microstructure transformation is from austenite to martensite, while the center microstructure remains austenitic. After pass from water cooler jet the center and surface temperature of the bars are equalized and the bars are cooling until the ambient temperature, Fig. 1 - annealing.

The metallurgic transformations associates to the heat transfer process result in mechanical properties that is strongly dependent of process parameters. These can be function of different factors, since the steel chemical composition, lamination speed, geometric parameters, inlet temperature bar and so on.

Through the diagrams of Isothermal Transformation or Temperature-Time-Transformation(TTT), and the cooling rates of the steel bars it can be possible identified the metallurgic transformations. For slow cooling rates it can be observed the formation of a structure ferrite + perlite, throughout all the bar section. As represented in Fig. 1, during phase 1, the tempering surface bar results on a martensite structure, whereas the nucleus remain austenitic.

Phase 2 is characterized by the ending of martensite formation in the surface layer and the temperature surface become to be heating by the nucleus bar, that temperatures remain high. In such a way, the tempering layer of the bar starts a auto-annealing treatment, that will go to transform the martensite structure, in annealed martensite structure or fine perlite. This annealed martensite does not present the fragility of the martensite and it reaches high limits of deformation and resistance. The amount of transformed martensite grows of the center for the extremity of the bar. Simon *et al*. (1984) and Economopoulos *et al*. (1975), affirm that when the bar leaves the cooling system, appears a gradient of temperatures throughout the transversal section The heat proceeding from the center of the bars tempering its superficially, occurring the auto-annealing. Finally, outside of the cooling system jet, the bar will cool until the ambient temperature.

Rodrigues *et al*., 1992 verified the existence of the interdependence between these parameters. The annealing temperature is the variable of control process since it has a direct influence in the mechanical properties of the steel. They present the increase of the mechanic resistance with the decrease of the annealing temperature, or increase of the water flow during the cooling of the steel bars. It can also be observed the flexibility of the manufacture process to diameters between 16 and 28 mm.

Economopoulos *et al*., (1975) verified that the ductibility of the annealed martensite decrease if the annealing temperature decreases, however, without compromising the material to superficial cranks. Phase 3, Fig. 1, begin when the surface temperature is practically equalized with the nucleus temperature until the temperature of the bar reaches about 100ºC or less, when cooling process is finished. In this phase the final structure is a fine granulation of perlite + ferrite.

Alves Filho (2004) obtained the experimental results for the final steel bar microstructure. He analyzed different diameters under different operation conditions, like bar temperature, lamination speed, water pressure. Figure 2 presents a typical result obtained by the author. It can be observed the annealing martensite structure close the surface and the perlite and ferrite in center of the bar. Figure 3 presents the hardness obtained for the steel bars function of the radios.

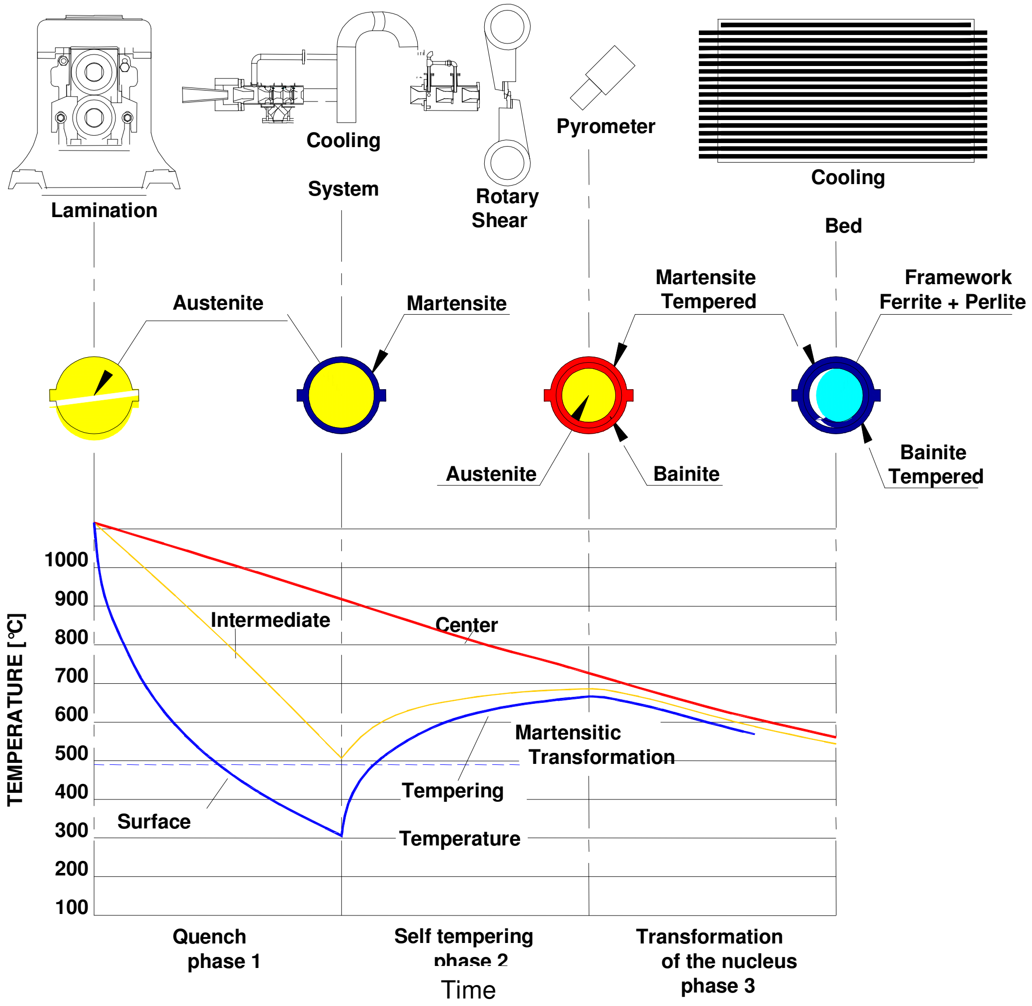
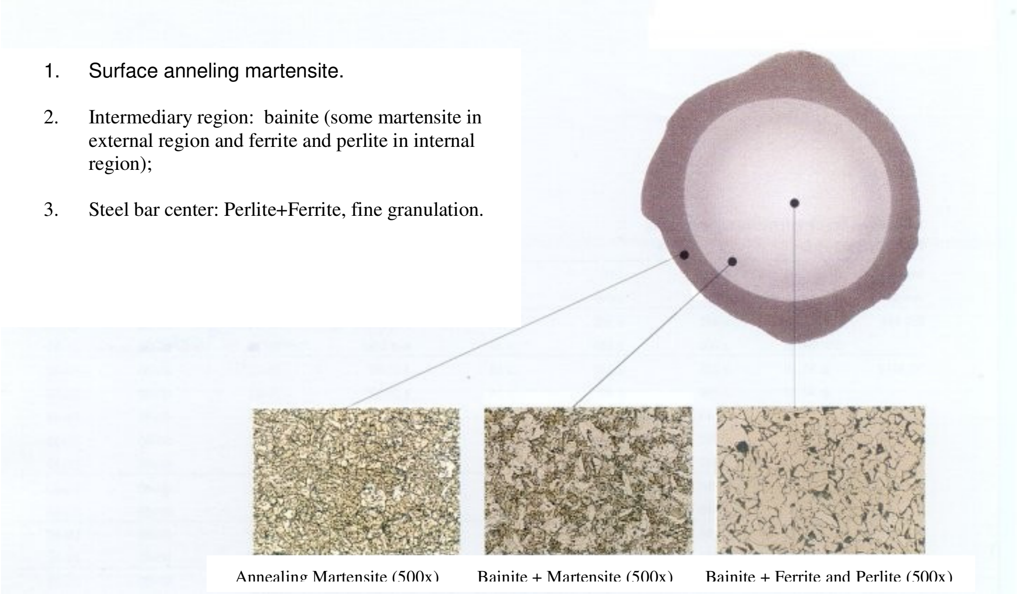


Figure 1. Temperature bars to differents radius for the tempering process. (Alves Filho, 2004)



1. Surface anneling martensite.
2. Intermediary region: bainite (some martensite in external region and ferrite and perlite in internal region);
3. Steel bar center: Perlite+Ferrite, fine granulation.

Annealing Martensite (500x)

Bainite + Martensite (500x)

Bainite + Ferrite and Perlite (500x)

Figure 2. Transversal section of steel. Regions affected by the tempering process. (Alves Filho, 2004)

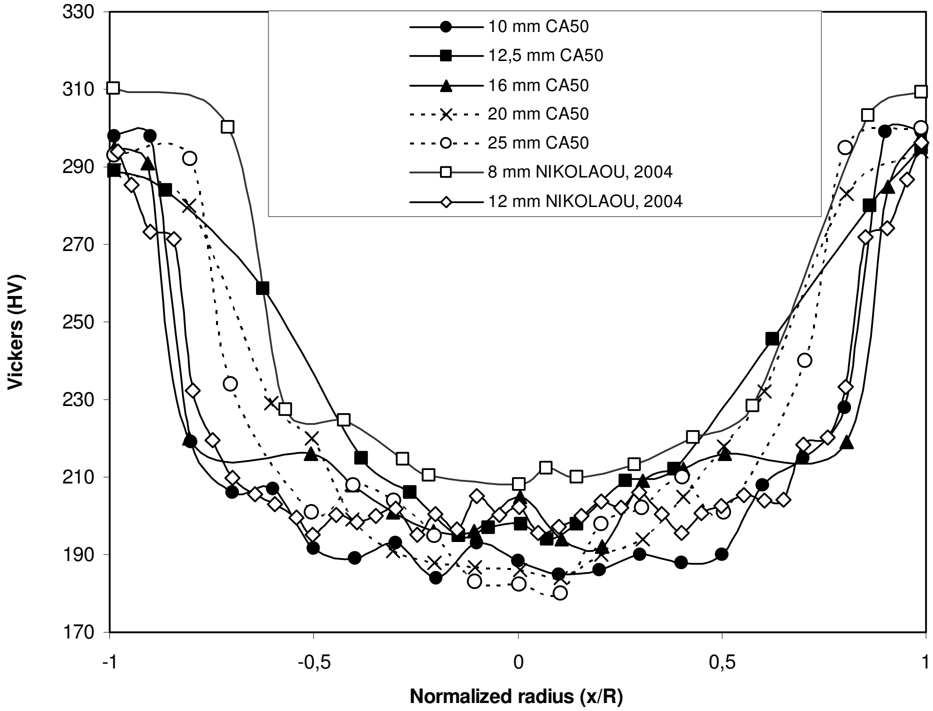


Figure 3. Steel bar hardness CA50 – NBR7480. (Alves Filho, 2004)

The development of the mathematical models to predict the thermomechanical parameters associated with the steel bars manufacture process are important to reduce the necessity of the experimental analysis and consequently the costs. For this reasons, in continuity of Alves Filho (2004) work, it is presented and analyzed a model of numerical simulation for the curves of the steel bars cooling. This will allow determining which microstructure of the steel bars will result. This numerical model was elaborated by the method of finite volumes, using FORTRAN language.

2. HEAT TRANSFER MODEL

With the objective to simulate the heat transfer of the steel bar tempering a mathematical model for the problem is proposed in order to be solved by the method of finite volumes. The conduction equation considered an advective term to take in account the displacement of the steel bar, Fig. 4 is express as,

$$\nabla^2 T = V\rho c_p \frac{dT}{dx} \tag{1}$$

Equation (1) can be written in cylindrical coordinates as,

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial x}\right)=\rho V c_p \frac{\partial T}{\partial x} \tag{2}$$

where k is thermal conductivity of the steel, ρ is the specific mass of the steel and c_p is the specific heat of the steel.

Figure 4 presents the boundaries conditions. The term Thermex is used to the water cooler jet, with dimension $l_{thermex}$, and the convective effect for phase change is considered by the convection coefficient, h_1. After to leave the Thermex the bar still remains for a distance, $l_{externo}$, changing heat with air to a convection coefficient, h. The bar enters in the Thermex to a temperature, T_o, and constant speed, V.

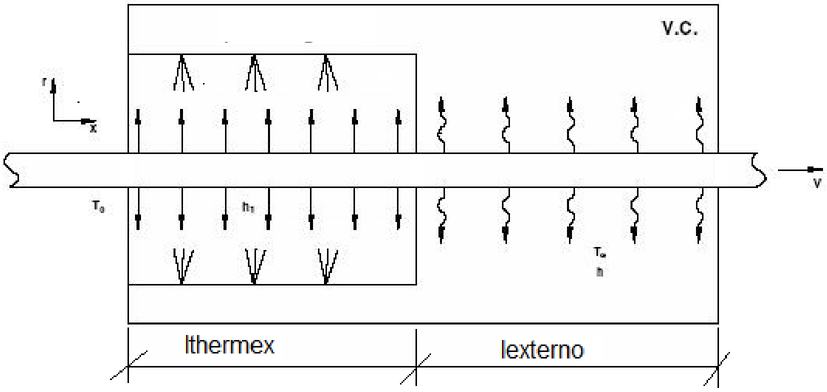


Figure 4. Boundary conditions to the problem.

Mathematically, the boundary conditions can be written as:

$$\text{(I)} \qquad r = 0 \rightarrow q = -k\frac{dT}{dr}\Big|_{r=0} = 0 \tag{3}$$

$$\text{(II)} \qquad r = R \rightarrow \begin{cases} q = -k\dfrac{dT}{dr}\Big|_{r=R} = h_{thermex}\left(T_s - T_\infty\right), \rightarrow\ p / x \le l_{thermex} \\ q = -k\dfrac{dT}{dr}\Big|_{r=R} = h_{ar}\left(T_s - T_\infty\right) \rightarrow\ p / l_{thermex} < x < L \end{cases} \tag{4}$$

$$\text{(III)} \qquad x = 0 \rightarrow T_w = T_{conhecido} \tag{5}$$

$$\text{(IV)} \qquad x = L \rightarrow q = -k\frac{dT}{dx}\Big|_{x=L} = h_{ar}\left(T_e - T_\infty\right) \tag{6}$$

The Finite Volume formulation is applied to Eq. (2) and boundary conditions Eqs. (3) to (6). The volumes are represented on Fig. 5.

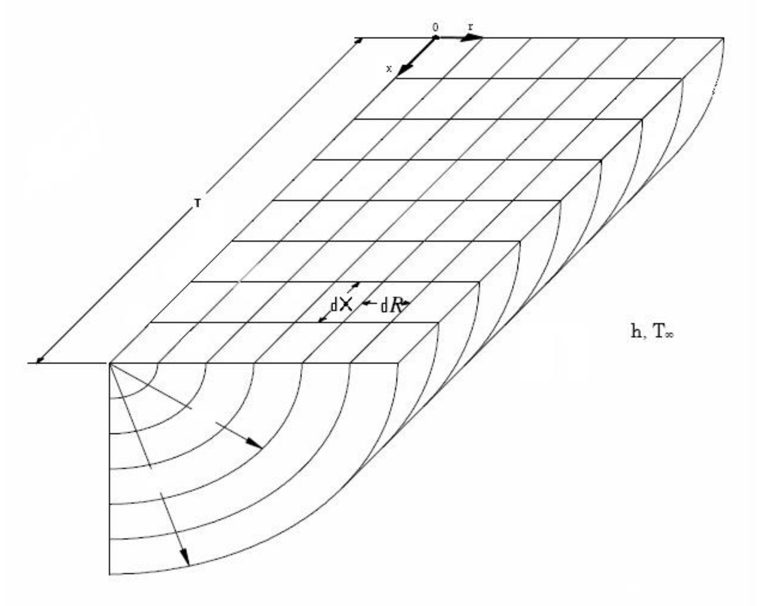


Figure 5. Domain of the volume control volumes.

The discretization equations obtained by finite volume method are:

$$\frac{k_w}{\delta x_w \delta x_p}\left(T_w - T_p\right) + \frac{k_e}{\delta x_e \delta x_p}\left(T_e - T_p\right) + \frac{k_s r}{\dot{r}\,\delta r_s \delta r_p}\left(T_s - T_p\right) + \frac{k_n}{\dot{r}\,\delta r_n \delta r_p}\left(T_n - T_p\right)\left(r_p + \delta r_p\right) + V\rho c_p \frac{\left(T_w - T_p\right)}{\delta x_w} = 0 \qquad (7)$$

where $\dot{r}$ corresponding to the center of the volume and r corresponding to the surface of the volume.

To solve the equations obtained by this formulations it was used the TDMA method, Maliska (1995).

3. RESULTS

The thermophysical properties, k, c_p, h, and ρ were obtained by the Unterwiser *et al.* (1998) results. Using these value it was proposed a formulation to thermal conductivity by:

$$k = A + B1 \cdot Temp + B2 \cdot Temp^2 \qquad (8)$$

To temperatures equal or less than 800ºC is used:

$$A = 51.78061$$
$$B1 = -0.01232 \qquad (9)$$
$$B2 = -2.43506 \cdot 10^{-5}$$

For the temperatures greater than 800ºC is used:

$$A = 34.2 \qquad (10)$$
$$B1 = -0.02325$$
$$B2 = 1.625 \cdot 10^{-5}$$

Figure 6 presents the thermal conductivity values representation for Eq. (8).

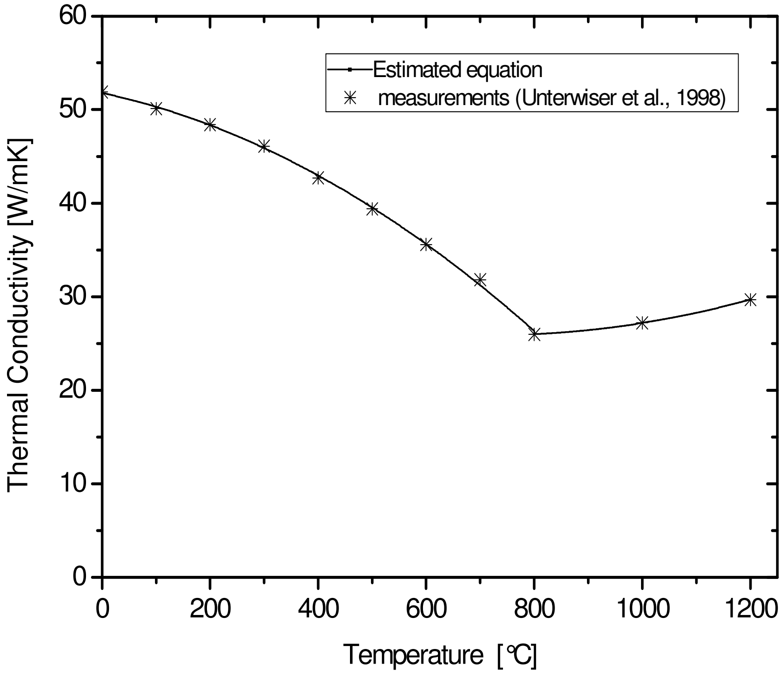


Figure 6. Thermal conductivity values representation for Eq. (8) to low Carbon steel (Unterwiser *et al.*, 1998).

The specific heat capacity, c_p, is also represented like a function:

$$c_p = A + B1 \cdot Temp + B2 \cdot Temp^2 \tag{11}$$

To temperatures less than 675ºC is used:

$$\begin{aligned} A &= 483{,}9243 \\ B1 &= 0.04455 \\ B2 &= 7{,}23086 \cdot 10^{-4} \end{aligned} \tag{12}$$

For the temperatures equal or greater than 675ºC and less than 775ºC is used:

$$\begin{aligned} A &= -111595{,}5 \\ B1 &= 310{,}76 \\ B2 &= -0{,}2136 \end{aligned} \tag{13}$$

For the temperatures equal or greater than 775ºC is used:

$$\begin{aligned} A &= 1756 \\ B1 &= -1{,}04 \\ B2 &= 0 \end{aligned} \tag{14}$$

Figure 7 presents the specific heat capacity values representation for Eq. (11).

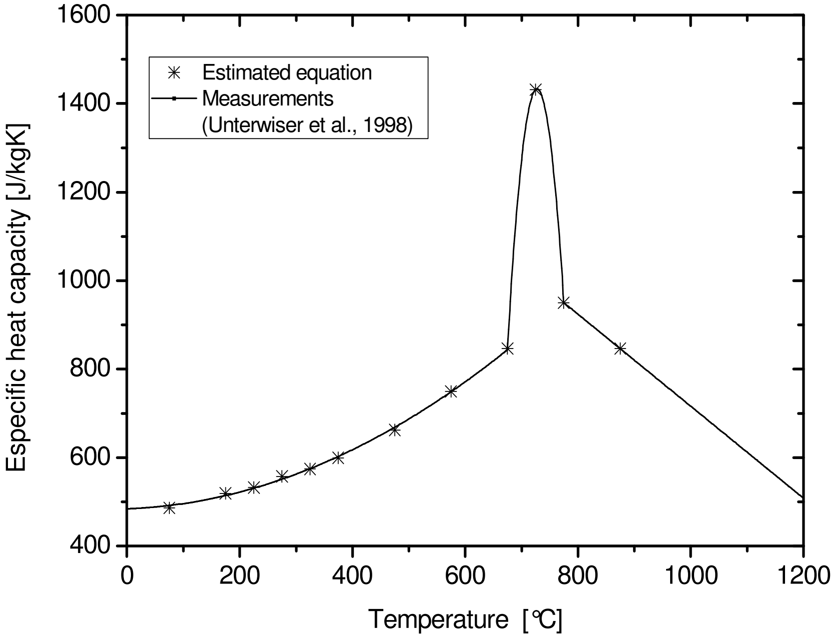


Figure 7. Specific heat capacity values representation for Eq. (8) to low Carbon steel (Unterwiser *et al*., 1998).

The values of the convective heat transfer, h, are used for jet cooling inside the Thermex ($1 \cdot 10^4 W/m^2K$ <h< $5 \cdot 10^4 W/m^2K$) and air-vapor cooling for outside the Thermex (h=$10 W/m^2K$).

It was used a diameter of 10 mm like the measures of Alves Filho (2004). The length bar is 10 m and the Thermex length is 2 m. The mass specific is $7779{,}49 kg/m^3$. The inlet temperature is 1000ºC and the outlet temperature is 30ºC. The maximum speed attained by the bar is 4 m/s.

Firstly, in Fig. 8, is presented the calculated temperature profile function of the length bar to a convective coefficient in the Thermex domain, $1 \cdot 10^4 W/m^2K$. The equalization temperature is around 700ºC. Figure 9 present the same case to the temperature profile function of the radius.

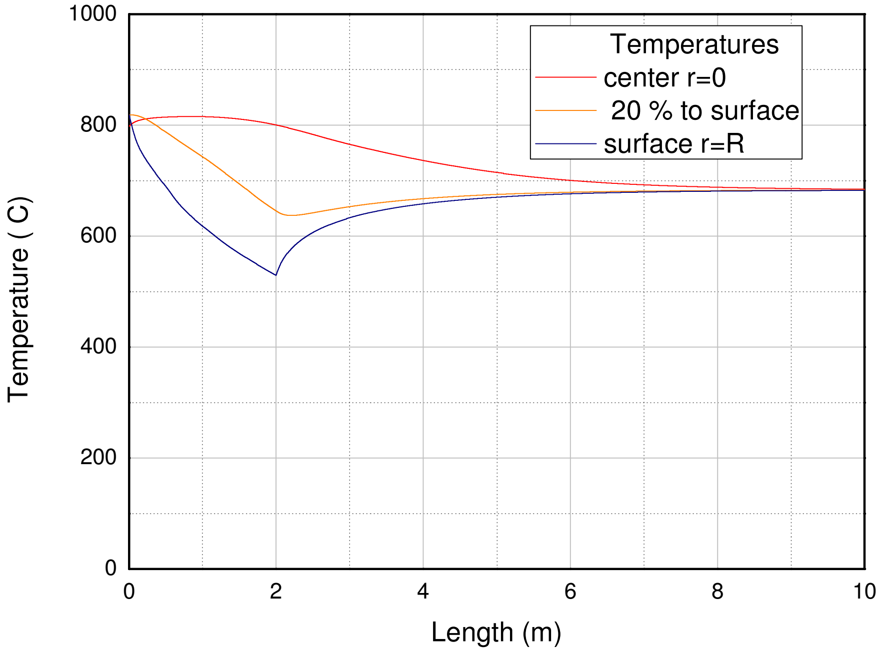


Figure 8. Calculated the temperature profile function of the length bar, $h = 1 \cdot 10^4 W/m^2 K$.

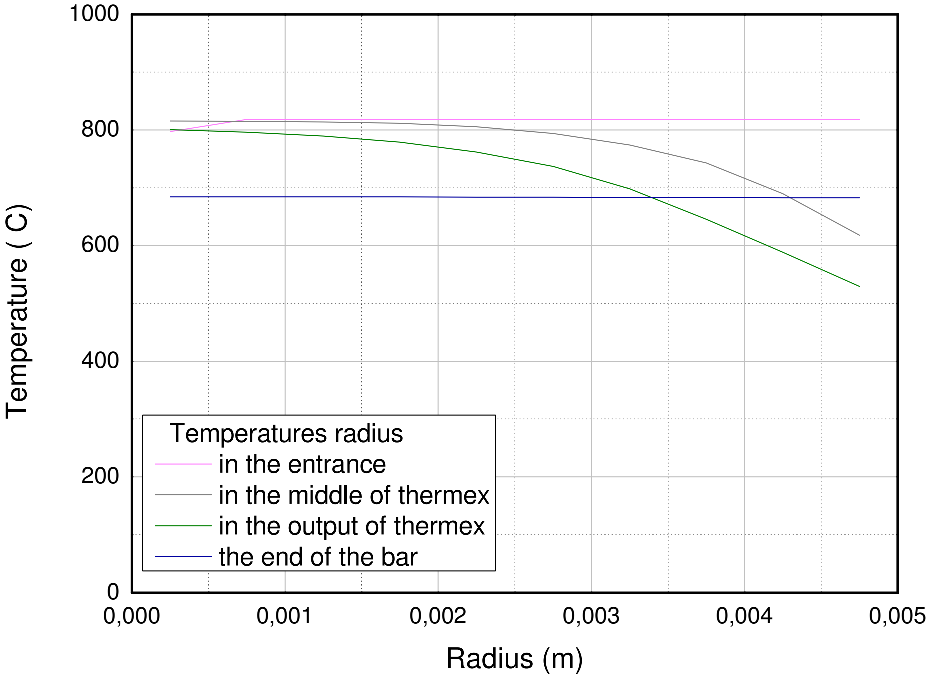


Figure 9. Calculated the temperature profile function of the radius bar, $h = 1 \cdot 10^4 W/m^2 K$.

The second analysis present the same problem changing the heat transfer coefficient to $5 \cdot 10^4 W/m^2 K$ **.** In this case these results are more similar to the experimental results and the temperature surface was obtained and demonstrated by Tamm (2003). Like the previous analysis, Figs. 10 and 11 present the results to the calculated profile function to the length and radius bar.

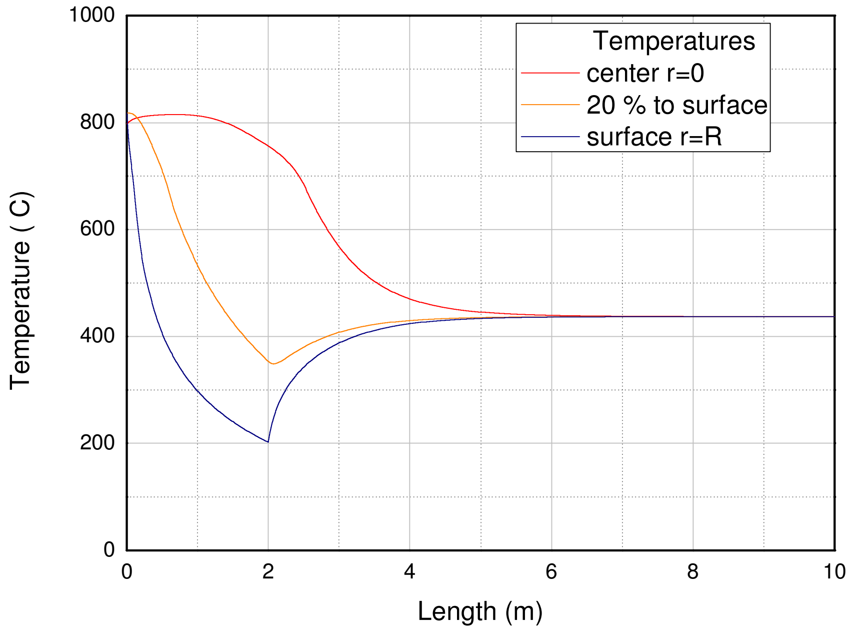


Figure 10. Calculated the temperature profile function of the length bar, $h = 5 \cdot 10^4 W / m^2 K$.

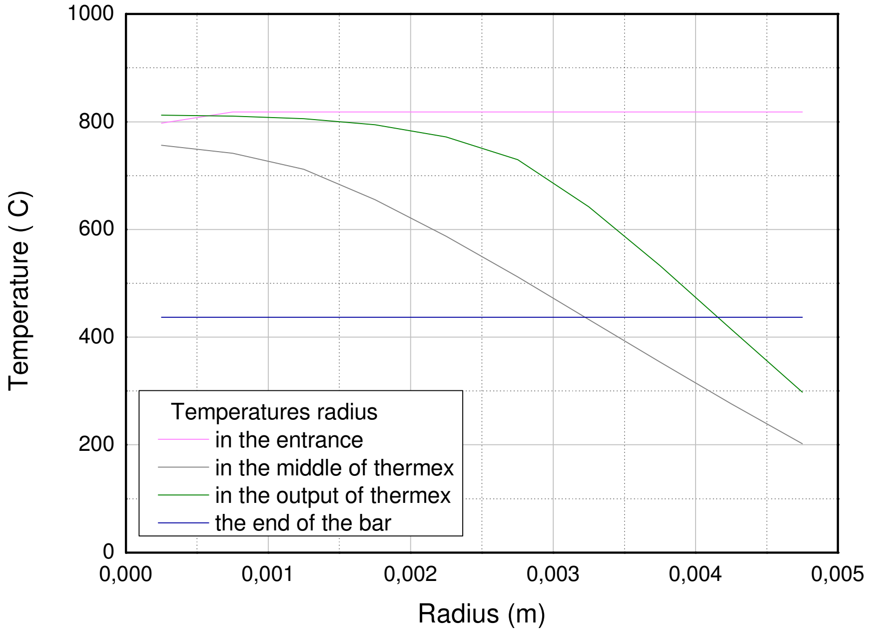


Figure 11. Calculated the temperature profile function of the radius bar, $h = 5 \cdot 10^4 W / m^2 K$.

5. CONCLUSION

A model for simulation of the thermal treatment of steel bars was presented in this work. These steel bars are used on the civil industries. The results presented in this work present are concordant with the values of Tamm (2003). Results for complete validation of the model are not available in literature. A method to obtain the cooling rate with 1 microstructure characteristics still to be implemented.

6. REFERENCES

Simon, P., Economopoulos, M. Nilles, P., 1984, “Tempcore: A new Process for the production of High-Quality Reinforcing Bars”, Iron and Steel Engineering, p. 53-57.

Economopoulos, M.; Respen, Y.; Lessel, G.; Steffes, G., 1975, “Aplication of TEMPCORE Process to the Fabrication of High Yield Strenght Concrete Reinforcing Bars”, CRM, Vol. 45, p. 01-17.

Alves Filho, C. H. M., 2004, “Análise da influência da taxa de resfriamento no gradiente microestrutural de barras laminadas a quente tratadas termicamente”. Curitiba, Dissertação de mestrado em Engenharia Mecânica. Centro de Ciências Exatas e Tecnológicas - Mestrado em Engenharia Mecânica, Pontifícia Universidade Católica do Paraná, 128 p..

Rodrigues, P.C., Celtin, P.R., Silva, A.P., Aguilar, M.T.P., 1992, “Perfil de Temperaturas em Barras de Aço para Construção Civil Fabricadas Pelo Processo Tempcore”. Congresso Anual ABM, 47^{o}, Vol.04, p. 505-521.

Maliska, C. R., 1995, “Transferência de calor e mecânica dos fluidos computacional”. Rio de Janeiro: LTC.

Unterweiser, P.M., Boyer, H.E., Kubbs, J.J., 1998, “Heat Treater´s Guide – Standard Practices and Procedures for Steel”, American Society for Metals ASM Handbook.

Tamm, H., 2003, “Manual Técnico Thermex – HSE”, Hennigsdorfer Stahl Engineering, 28p.

7. RESPONSIBILITY NOTICE

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