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METHOD FOR OBTAINING JOMINY HARDENABILITY CURVES FROM THE MODELING OF CONTINUOUS COOLING DIAGRAMS OF MEDIUM CARBON AND LOW-ALLOY STEELS

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Abstract. *The hardness of steels can be increased by quenching heat treatment whereby the material is austenitized and then submitted to fast cooling. The material hardness will be related with the generated microstructure, which can be predicted by knowing its transformation diagrams. The experimental determination of this diagrams is sometimes difficult and laborious. In this study, a mathematical model was applied to determine the continuous cooling transformation curves from the steels chemical compositions and based on the austenite decomposition kinetics reaction. The model was applied to AISI 1045, 4140 and 4340 steels which allowed the determination of the phases volume fraction for each cooling rate. The thermal cycles prediction allowed the calculation of Jominy hardenability curves. The model validation was made trough experimental analysis such as dilatometry, metallography and hardenability Jominy tests. The experimental data associated with the used methodology endorsed the validity of the mathematic model for the medium carbon and low-alloyed steels.*

Keywords: *Hardenability, Jominy Test, CCT Diagram, Mathematical Modeling.*

1. INTRODUCTION

The improving in mechanical resistance of steels has been studied due the continuous development of new alloys. Heat treatments allows the obtaining of phase transformation diagrams that allow to correlate microstructures with time and temperature. For this, computational mathematical models have been developed to enable the prediction of these diagrams. Such models can provide powerful tools to understand the factors that control quality and performance of final products.

The aim of this work is to apply of the mathematical models for Time Temperature Transformation (TTT) and Continuous Cooling Transformation (CCT) diagrams for steels with different hardenability and chemical compositions. As a validation to these model, it were measured the equilibrium transformation temperatures Ae1 e Ae3 through the dilatometry test and it was also carried out hardenability curves generated through the Jominy test. This test allows to

know the constituents volume fraction and hardness for comparing to the virtual hardenability curves. The mathematical model adopted was developed by Victor Li et al. (1998).

2. MATERIALS

This method comprises obtaining the TTT and CCT diagrams as well as the hardenability curves. The steels AISI 1045, 4140 e 4340 were analyzed whose chemical compositions are shown in the Tab. 1 and are in accordance to NBR 87/2000 standard.

Table 1. Chemical Composition Steels 1045, 4140 e 4340 (wt %)

Steel	C	Mn	Si	Ni	Cr	Mo	W	Cu	Al	V	S	P
1045	0,48	0,75	0,35	-	-	-	-	-	-	-	0,05	0,04
4140	0,38	0,81	0,28	0,11	0,98	0,22	0,003	0,11	0,05	0,003	-	-
4340	0,41	0,74	0,25	1,72	0,77	0,27	0,007	0,07	0,03	0,002	-	-

3. MATHEMATICAL MODEL

The model applied was developed for low-alloy steels so that the sum of alloying elements should be lower than or equal 5%. The austenite grain size has a strong influence on the calculation of hardness, positioning of the start and end curves transformation as well as influences the steel hardenability prediction. For the grain size was adopted the method proposed by Andrés and Carsi (1987) which by tests ranging the time and temperature at various austenitizing and tempering treatments in commercial structural steels, obtained various results for this parameter.

The mathematical model of the reaction kinetics for austenite decomposition was defined by Victor Li et al. (1998) as shown in Eq. (1):

$$\tau(X,T) = \frac{F(C,Mn,Si,Ni,Cr,Mo,G)}{T^n exp(-Q/RT)} S(X) \tag{1}$$

The parameter τ(X,T) is the transformation reaction kinetics, F is a function which correlates the steel chemical composition with austenite grain size G, Q is the activation energy of the diffusional reaction, n is a constant of undercooling determined by the effective diffusion mechanism (n = 2 for volume and n = 3 for boundary diffusion), R is the constant of the gases (1,98 cal/mol.K) and T is the reference temperature.

The function S(X) represents a sigmoidal transformation rate observed during isothermal phase growth as shown by Victor Li et al. (1998) in the Eq. (2) and represents an approximation of the behavior of phase transformations.

$$S(X) = \int_0^x \frac{dX}{X^{0,4(1-X)}(1-X)^{0,4X}} \tag{2}$$

X is the percentage of product formation in the phase transformation.

The resultant set of reaction equations for ferrite (τ_F), pearlite (τ_P) and bainite (τ_B), respectively, are shown in the Eq. (3), (4) and (5):

$$\tau_F = \frac{FC}{2^{0,41G}((Ae_3 - T)^3 exp(-27.500/RT))} S(X) \tag{3}$$

$$\tau_P = \frac{PC}{2^{0,32G}((Ae_1 - T)^3 exp(-27.500/RT))} S(X) \tag{4}$$

$$\tau_B = \frac{BC}{2^{0,29G}((B_S - T)^2 exp(-27.500/RT))} S(X) \tag{5}$$

The value of the functions FC, PC and BC are defined in terms of the alloying elements (in wt.%), as proposed by Victor Li et al. (1998):

$$FC = exp\,(1{,}00 + 6{,}31C + 1{,}78Mn + 0{,}31Si + 1{,}12Ni + 2{,}70Cr + 4{,}06Mo \tag{6}$$

$$PC = exp\,(-4{,}25 + 4{,}12C + 4{,}36Mn + 0{,}44Si + 1{,}71Ni + 3{,}33Cr + 5{,}19\sqrt{Mo}\,) \tag{7}$$

$$BC = exp\,(-10{,}23 + 10{,}18C + 0{,}85Mn + 0{,}55Ni + 0{,}90Cr + 0{,}36Mo\,) \tag{8}$$

The parameters Ae1, Ae3 and Bs (in °C) represent the lower equilibrium temperature between bainite, ferrite and austenite, the upper equilibrium temperature between ferrite and austenite and the isothermal initiation temperature for austenite–bainite transformation on cooling, respectively. The values of Ae1 and Ae3 were calculated from the empirical formulae proposed by Trzaska (2007), these equations are appended.

$$Ae1 = 739{,}3 - 22{,}8C - 6{,}8Mn + 18{,}2Si + 11{,}7Cr - 15Ni - 6{,}4Mo - 5V - 28Cu \tag{9}$$

$$Ae3 = 937{,}3 - 224{,}5C^{\,0{,}5} - 17Mn + 34Si - 14Ni + 21{,}6Mo + 41{,}8V - 20Cu \tag{10}$$

$$Bs = 637 - 58C - 35Mn - 15Ni - 34Cr - 41\,Mo \tag{11}$$

The values of Ae1 and Ae3 obtained by mathematical model were confirmed experimentally through dilatometry tests for each steel.

The start transformation temperature of martensite Ms, proposed by Victor Li et al. (1998) is shown by Eq. (12). The value of Ms (in °C) was defined in terms of the alloying elements (in wt.%).

$$Ms = 539 - 423C - 30{,}4Mn - 17{,}7Ni - 12{,}1Cr - 7{,}5Mo + 10Co - 7{,}5Si \tag{12}$$

The mathematical model of hardenability curves is based on the calculation of hardness using the mixture rule to predict the hardness for Jominy test sample. Equation (13) shown by Victor Li et al. (1998) will serve as the basis for the calculations:

$$H_v = X_M Hv_M + X_B Hv_B + \left(X_F + X_P\right) Hv_{F+P} \tag{13}$$

Where H_v is the Vickers hardness, X_M, X_B, X_F e X_P are the volume fraction of martensite, bainite, ferrite and pearlite, respectively. Hv_M, Hv_B e $Hv_{(F+P)}$ are the hardness of martensite, bainite and the mixture of ferrite and pearlite, respectively. Hardness prediction is based on Victor Li et al. (1998) and chemical composition of the steel as well as the cooling rate as shown in Eq. (14), (15) and (16):

$$Hv_M = 127 + 949C + 27Si + 11Mn + 8Ni + 16Cr + 21\,logV_r \tag{14}$$

$$\begin{aligned} Hv_B = {} & -323 + 185C + 330Si + 153Mn + 65Ni + 144Cr + 191Mo + \\ & + \left(89 + 53C - 55Si - 22Mn - 10Ni - 20Cr - 33Mo\right) logV_r \end{aligned} \tag{15}$$

$$Hv_{F+P} = 42 + 223C + 53Si + 30Mn + 12{,}6Ni + 7Cr + 19Mo + \left(10 - 19Si + 4Ni + 8Cr + 130V\right) logV_r \tag{16}$$

Vr is the cooling rate at 700 °C/s.
The hardenability curves were also checked experimentally through real Jominy tests in each sample.

4. RESULTS AND DISCUSSION

Dilatometry tests was carried out to validation the mathematical model for TTT diagrams prediction. It was possible to verify experimentally temperatures Ae1 and Ae3 for each steel, comparing the experimental results and calculated data. The Fig. 1, 2 and 3 represent experimental data for each steels.

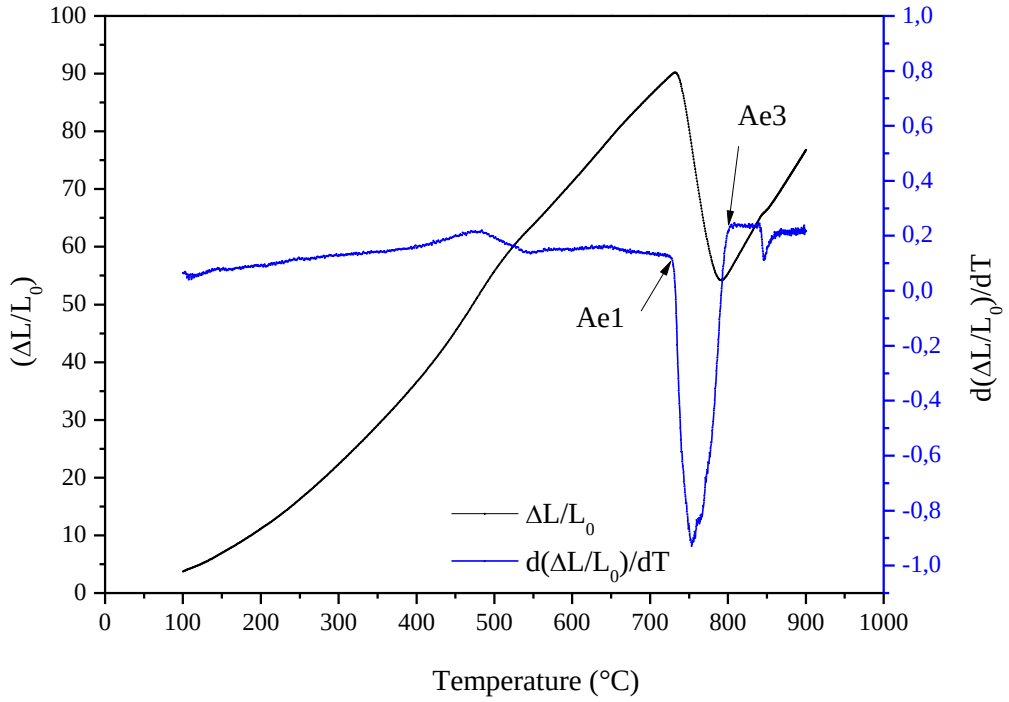

Figure 1. Temperatures Ae1 and Ae3 measured by dilatometry test of AISI 1045 steel.

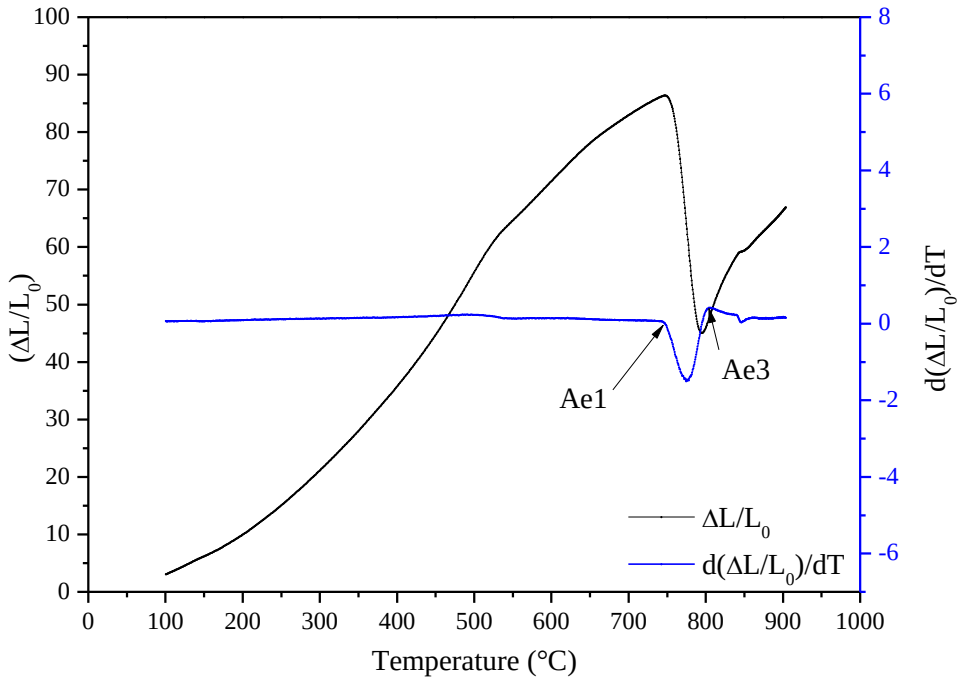

Figure 2. Temperatures Ae1 and Ae3 measured by dilatometry test of AISI 4140 steel.

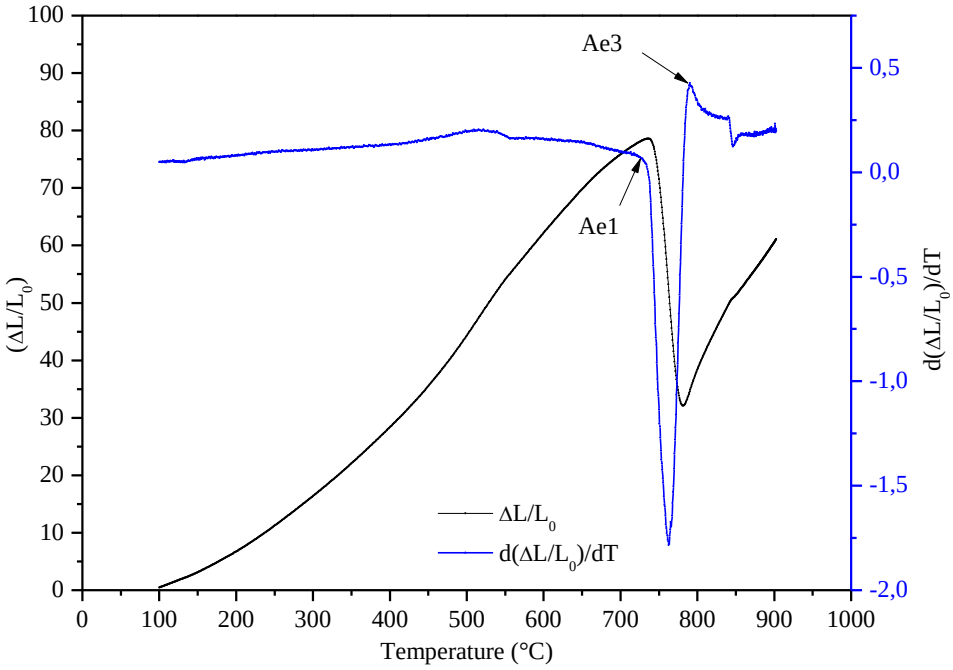

Figure 3. Temperatures Ae1 and Ae3 measured by dilatometry test of AISI 4340 steel.

The values measured by dilatometry and the values calculated temperatures Ae1 and Ae3 for different steels were compared, as shown in Tab. 2. It is possible to verify that they are in agreement.

Table 2. Comparison among experimental and calculated temperatures Ae1 e Ae3

Steel	1045		4140		4340	
Temperature (°C)	Ae1	Ae3	Ae1	Ae3	Ae1	Ae3
Experimental	729,62	780,91	738,62	797,99	710,94	771,3
Calculated	729,47	796,95	745,98	802,79	722,37	789,34

The model proposed by Victor Li et al. (1998) allows the prediction of TTT diagrams and once the cooling conditions are known, the same model could be implemented to obtain the CCT diagrams. The predicted TTT diagram for steels AISI 1045, 4140 and 4340 are shown in the Fig. 4, 5 and 6, respectively, and comparing them to diagrams already presented in Atlas and literature, they are consistent. Slight variations are due to empirical variables considerable in the model. The curves represent the beginning of phase transformation to form 0,1% of constituent.

For all the steels presented in this work it has been carried out the Jominy tests to validate the model. The hardenability curves experimentally measured was compared with the calculated and they are shown in the Fig. 7, 8 and 9.

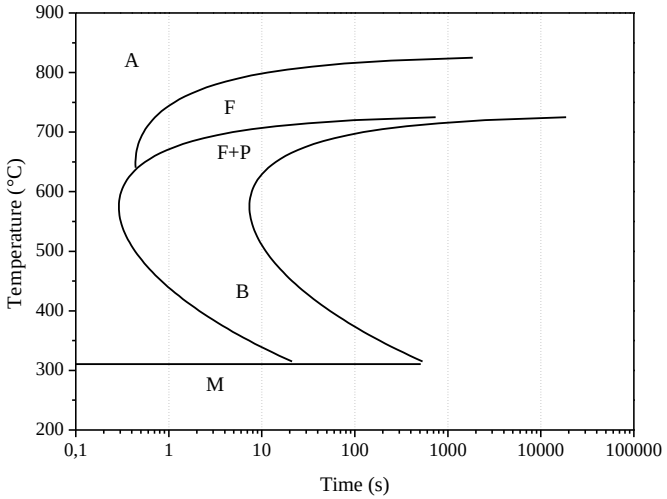

Figure 4. Calculated TTT diagram for AISI 1045 steel. Constituents considered include: austenite (A); ferrite (F); pearlite (P); bainite (B) and martensite (M)

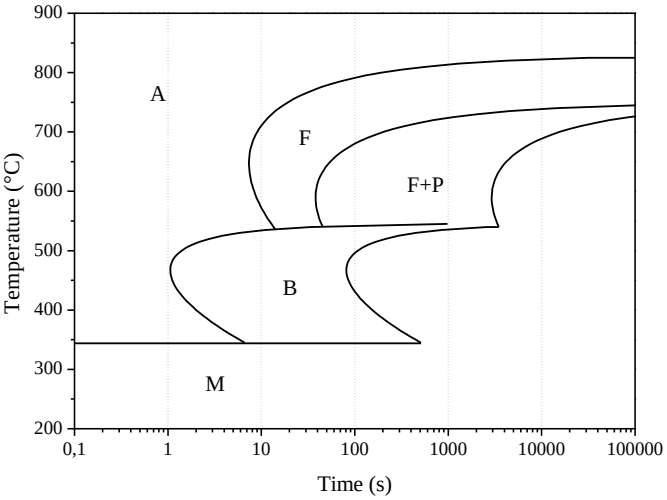

Figure 5. Calculated TTT diagram for AISI 4140 steel. Constituents considered include: austenite (A); ferrite (F); pearlite (P); bainite (B) and martensite (M)

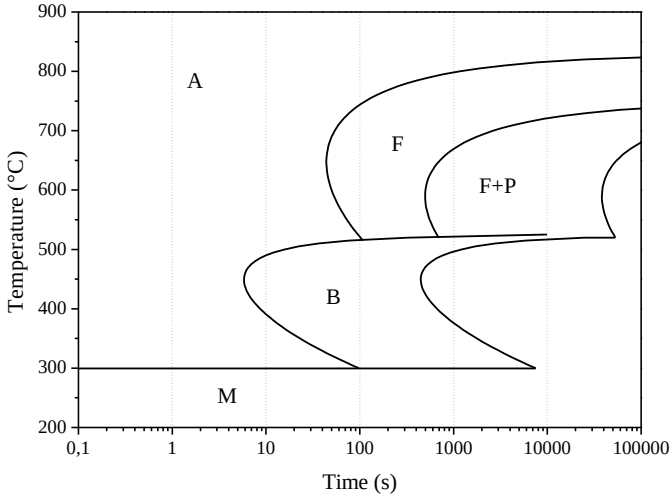

Figure 6. Calculated TTT diagram for AISI 4340 steel. Constituents considered include: austenite (A); ferrite (F); pearlite (P); bainite (B) and martensite (M)

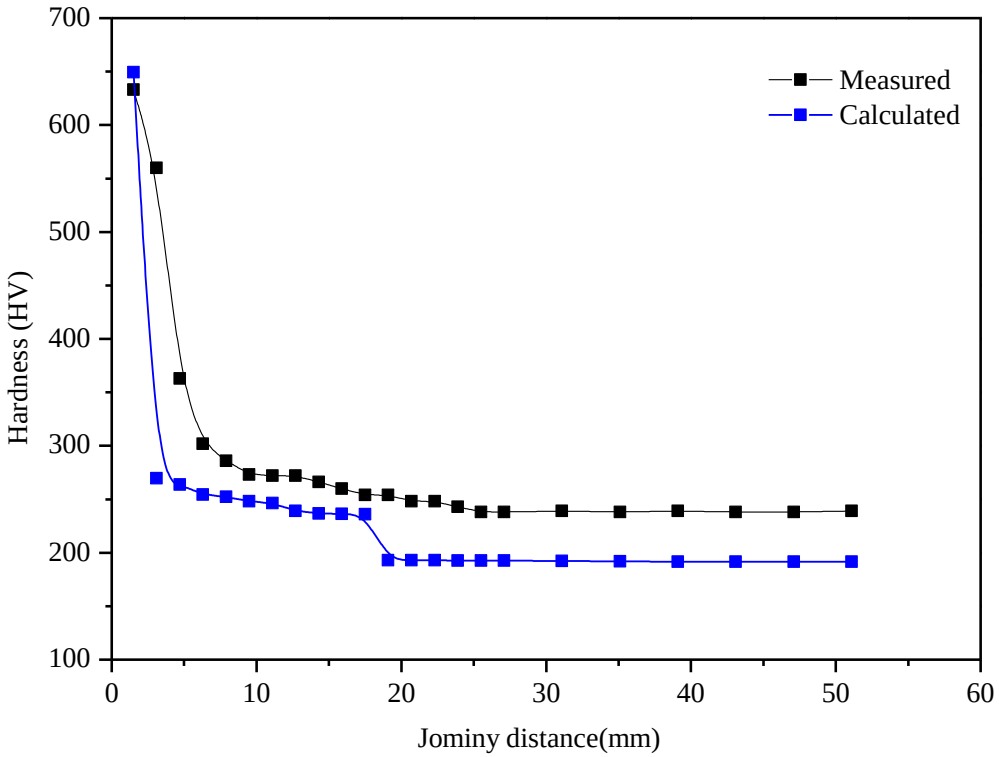

Figure 7. Predicted and measured Jominy hardness curves of AISI 1045 steel.

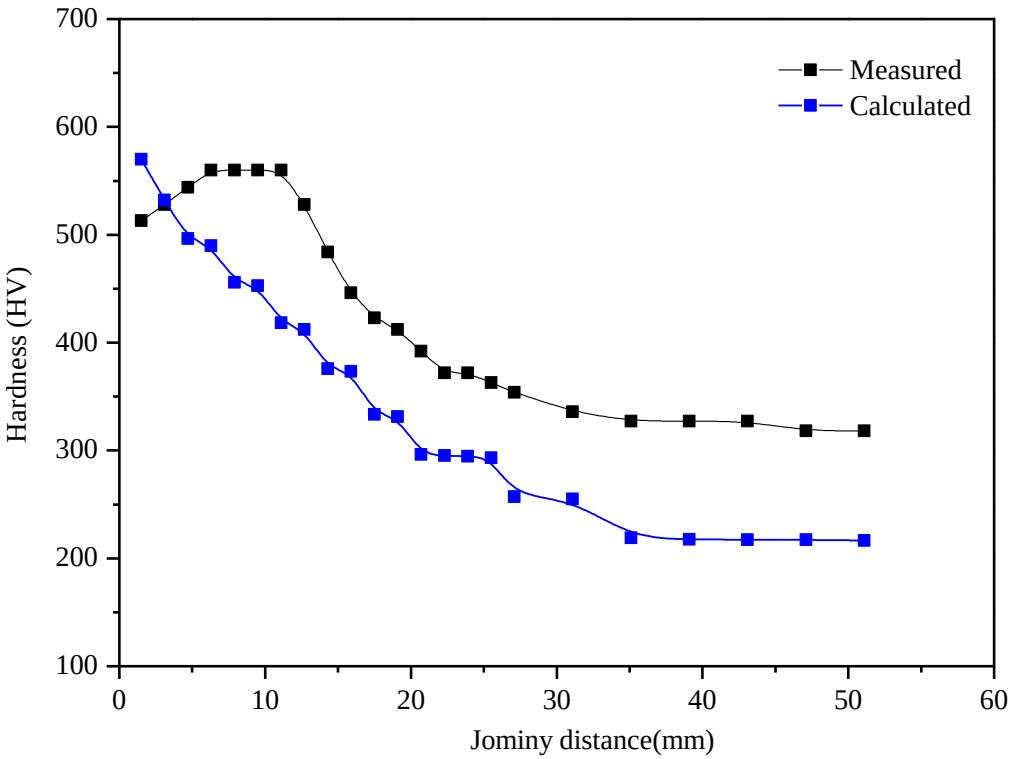

Figure 8. Predicted and measured Jominy hardness curves of AISI 4140 steel.

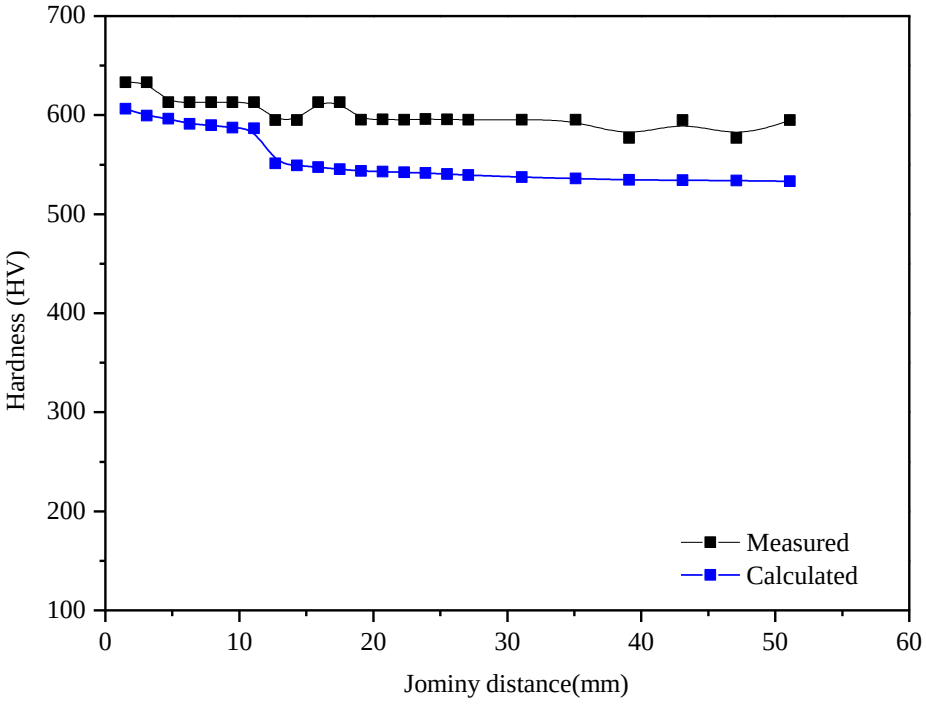

Figure 9. Predicted and measured Jominy hardness curves of AISI 4340 steel.

5. CONCLUSION

The prediction of TTT diagrams for AISI 1045, 4140 e 4340 steels was carried out using the model proposed by Victor Li et al. In order to validate the model dilatometry and Jominy test were made for obtaining the phases temperature transformation and hardenability curves, respectively. According to these results, the mathematical modeling proved to be adequate for these steels with different chemical compositions, compared to those proposed by the referenced authors.

6. ACKNOWLEDGEMENTS

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