

BAINITE FORMATION AT LOW TEMPERATURES IN A HIGH C-Si STEEL AND ITS MECHANICAL BEHAVIOR¹

José Alberto da Cruz Junior²

Icaro Portela Pinheiro³

Thiara Francis Mateus Rodrigues³

Virgínia Dutra Costa Viana³

Dagoberto Brandão Santos⁴

Abstract

A significant amount of stabilized austenite can be obtained in high carbon steels containing high amounts of Mn and Si (1.5-2%). At relatively low temperatures the bainite plates formed are extremely thin, making the material very strong. In this study, the influence of the thermal cycle of austempering on the mechanical behavior of a spring steel (0,56%C-1,43%Si-0,58%Mn-0,47%Cr), with TRIP effect, was investigated. The thermal cycle consisted of heating two groups of hot-rolled steel at austenite field, at 900°C for 300 s, and quickly transferring it to a metallic bath maintained at 220°C or 270°C, respectively, for different isothermal treatment times. The samples were then tested in tension and their microstructures were examined by optical and scanning electron microscopy. According to the results the samples treated at 220°C showed higher elongation, yield point and tensile strength than those maintained at 270°C. The high level of strength and ductility is due to a mixture of martensite and very fine bainite formation.

Key words: Bainite; TRIP effect; Retained austenite.

¹ *Technical contribution to the 18th IFHTSE Congress - International Federation for Heat Treatment and Surface Engineering, 2010 July 26-30th, Rio de Janeiro, RJ, Brazil.*

² *Graduate student at Metallurgical and Materials Engineering Department – UFMG*

³ *ABM Member – Undergraduate student at Metallurgical and Materials Engineering Department – UFMG*

⁴ *ABM Member – Associate Professor at Metallurgical and Materials Engineering Department – UFMG*

1 INTRODUCTION

Free carbides bainite steels with high strength and toughness have been currently designed using models based only on the theory of phase transformation.^[1] These steels follow a conventional process, achieving significant combinations of strength and toughness, comparable to those martensitic steel quenched and tempered.

The microstructure responsible for these mechanical properties consists of thin sheaves of bainitic ferrite separated by regions of austenite enriched in carbon. This austenite can then be transformed to martensite due to TRIP effect.

The TRIP effect (Transformation Induced Plasticity) originally published by Zackay et al.,^[2] is the retained austenite transformation into martensite during plastic deformation, promoting a mechanical strength increase and ductility.

The original microstructure of TRIP steel consists of polygonal ferrite, bainite and a significant amount of retained austenite. Varying the steel chemical composition or modifying the parameters of the transformation process, the volume fraction of each constituent can be varied, causing significant changes in mechanical properties. In a recent study of Soliman et al.,^[3] a methodology was introduced to control these steel properties, using bainitic transformation in two steps to create bimodal bainite in the microstructure. The authors^[3] used the dilatometric curves to show that when the partially processed material is treated at lower temperatures austenite decomposition occurs, which produce a second bainite generation. In the second step, the process is interrupted at intervals of longer times as the bainite transformation temperature becomes lower. The decomposition of austenite into bainite can be controlled by adjusting the time of isothermal transformation.

Both, upper and lower bainite, consist of aggregates of ferrite plates separated by regions called residual phases. According to the chemical composition, temperature and time of isothermal transformation, these phases may be composed of non-transformed austenite or constituents formed subsequently to the bainitic ferrite, such as martensite and carbides.^[4] After Bhadeshia et al.,^[5] the microstructure resulting when using alloy steel with silicon or aluminum, transformed into upper bainite, has no carbides. The carbon partitioning to the residual austenite is not precipitated as cementite, making the austenite stabilized at room temperature. The microstructure consists of fine plates of bainitic ferrite separated by regions of carbon-enriched austenite and martensite.

The steel presented in this work is used in industrial practice as quenched and tempered at 450°C. However, heat treatment using only the austempering can reduce the costs in large-scale production.

Therefore, this work, inspired by the favorable results of Badeshia et al.,^[5] Wang et al.^[6] and Soliman et al.,^[3] aimed to investigate the influence of isothermal treatment on microstructure formation to obtain low temperature bainite. Afterwards, to compare the mechanical behavior with a high carbon and silicon steel, containing manganese and chromium, quenched and tempered at 450°C.

2 EXPERIMENTAL PROCEDURE

The chemical composition of the investigated steel is shown in Table 1, and the transformation temperatures, Ac1 and Ac3, estimated by empirical formulas and by the IT diagram of steel, shown in Figure 1. These data are detailed in the work of Santos et al.^[7]

The samples of steel with 8 mm in diameter, whose the original microstructure is shown in Figure 1, were machined to reduced tensile size specimens with 4 mm in diameter and 25 mm of gage length. Then, they were austenitized at 900°C and quickly transferred to a heat bath of an alloy Sn60-Pb40, which has a melting point below 200°C. At the end of schedule time of heat treatment, the samples were air cooled. The samples remained in the furnace for austenitizing for 300 s, timed from the moment the sample-furnace system reached equilibrium. The bath was held in a crucible of stainless steel AISI 304. During the austempering mechanical agitation were not made and temperature monitoring was performed by a type K probe thermocouple. Four isothermal treatments were held with each group of samples whose temperatures and their times are presented in Table 2.

Table 1. Chemical composition of steel used (wt%)

Aço	C	Mn	Si	Cr	Ac ₁ (°C)	Ac ₃ (°C)
C-Mn-Si	0,56	0,58	1,43	0,47	768	810

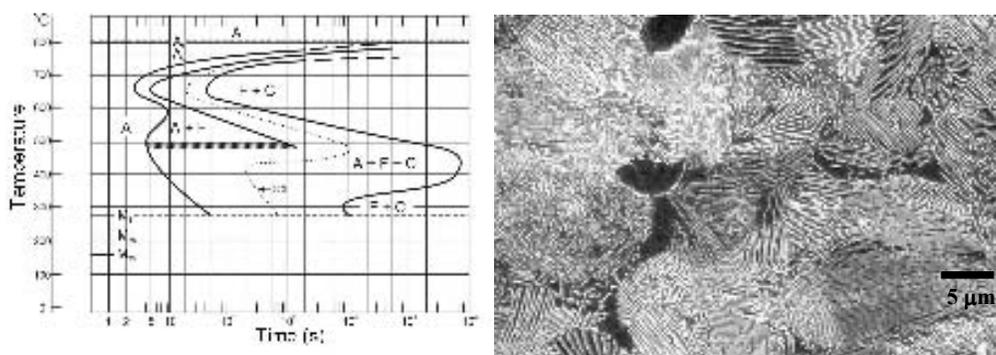


Figure 1. IT diagram of a steel with similar chemical composition to this work (a). Scanning electron micrograph the steel as received hot rolled. Etched with nital 2%. Fine pearlite and pro-eutectoid ferrite - Vv pro-eutectoid ferrite 6.3%, HV = 324 (b).

Table 2. Conditions of isothermal treatments

Samples	Temperature (°C)	Time (h)
A/E	222/271	0,5
B/F	221/272	2
C/G	221/274	24
D/H	225/269	48

Samples of the same steel were quenched in oil and tempered at 450°C for 1h in order to compare their mechanical properties with austempered samples.

After the thermal cycles, the specimens were subjected to tensile testing in triplicate for each treatment applied. The test was performed at room temperature with a cross head speed of 1 mm/min using a Instron machine, model 5582. Were determined the yield limit, tensile strength and total elongation. Then, the samples were prepared by the conventional metallographic method for analysis. The etch was carried out using 2% nital reagent. The microstructural analysis was reported by optical microscopy and scanning electron microscopy.

Vickers microhardness measurements were performed with a load of 2.9 N (300 g) in samples treated at 220°C and 270°C.

The retained austenite volume fraction was quantified using X-ray diffraction, by the method of direct comparison.^[8] This method uses the integration of most intensive peaks of austenite, characterized by the planes (111), (200), (220) and (311), and ferrite, planes (110), (200), (211) and (220). The X-ray data diffraction was also used to determine the carbon concentration in retained austenite according to equation (1).^[8]

$$C_{\gamma} = (a_{\gamma} - 3.578) / 0.033 \quad (1)$$

C_{γ} is the carbon concentration in retained austenite in %wt and a_{γ} is its lattice parameter in Å.

3 RESULTS AND DISCUSSION

3.1 Effect of Time and Temperature Treatment on the Microstructures

Scanning electron micrographs samples quenched and quenched tempered at 450 °C for 1h, are shown in Figure 2.

After austenitizing at 900°C for 300 s, the sample quenched contains a small amount of ferrite in a completely martensitic microstructure. The presence of ferrite indicates an incomplete austenitizing, despite the high temperature used.^[9] Moreover, the sample quenched and tempered displays needlelike on the microstructure, with the presence of some carbides. This happens because the tempering temperature increase favors the martensite decomposition into ferrite and cementite.^[10]

In Figure 3 optical micrographs of etched samples with 2% nital and treated at 220 and 270°C are illustrated. It is observed in micrographs in Fig. 3 predominantly martensite microstructure with the presence of retained austenite and bainite. Wang et al.,^[6] obtained for a steel with similar chemical composition to that used in this study (0.59%C, 1.61%Si, 0.56%Mn, 1.01%Cr, 0.13%V , 0.02%Al, 0.012nP, 0.011% S), microstructure like that shown in Figure 3.

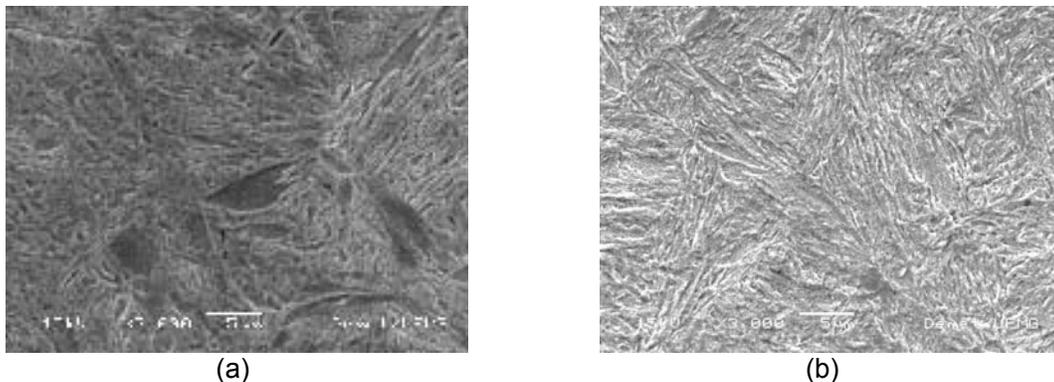
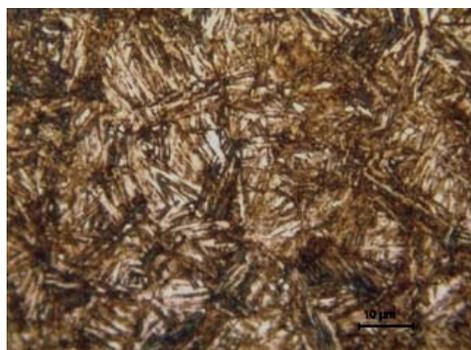
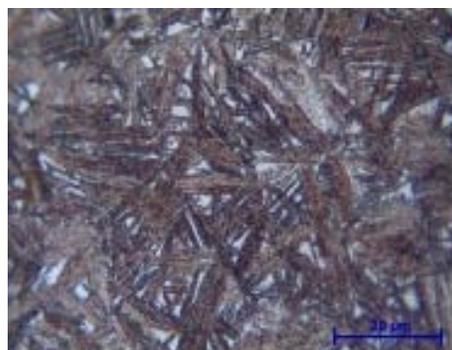


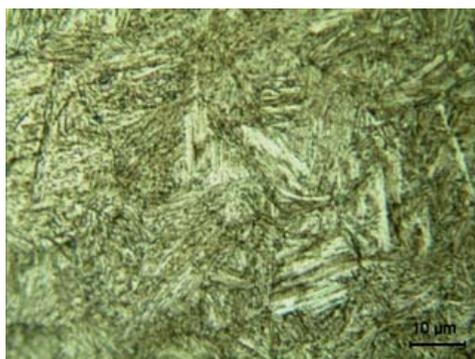
Figure 2. Scanning electron micrograph of the samples after austenitizing at 900°C and (a) quenched, HV = 884 (b) quenched and tempered at 450°C for 1h, HV = 565.



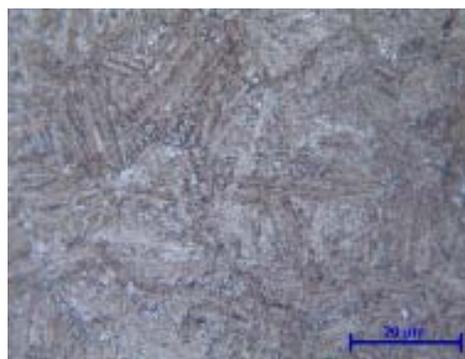
(a)



(c)



(b)



(d)

Figure 3. Optical micrograph of the samples after austenitizing at 900°C and bath: at 220°C for (a) 0,5h, (b) 48 h at 270°C for (c) 0,5h, (d) 48h, followed by cooling air. They were etched with 2% nital.

The authors^[6] described the bainitic ferrite in the form of thin sheaves of lath with approximately 100 nm thickness, arranged in different crystallographic orientations that appear in a dark color. Among these sheaves would be the martensite and austenite in lighter colors.

Comparing the microstructures for different temperatures and processing times, it is observed that the samples treated at 270°C contain a greater amount of untransformed phase (retained austenite) and that it decreases with increasing processing time and temperature. As lower is the transformation temperature, as greater the bainitic ferrite formation. This is because as the temperature decreases, the concentration of carbon in austenite, corresponding to the curve T_0' , increases. During the process, the adifusional growth of bainite results in increased free energy released by the austenite.^[11] At T_0' the transformation stops, as ferrite and austenite reaches the same composition and equal free energies.

The result of the low temperature processing is the reduction in the sizes of the sheaves of bainitic ferrite, which leads to an increase in the strength and toughness.^[5] When temperature decreases, the austenite yield strength becomes higher. This promotes an increase in resistance to interface movement during the bainitic ferrite formation, resulting in very fine sheaves.^[12]

Figure 4 shows scanning electron micrographs of samples austempered at 220 or 270°C.

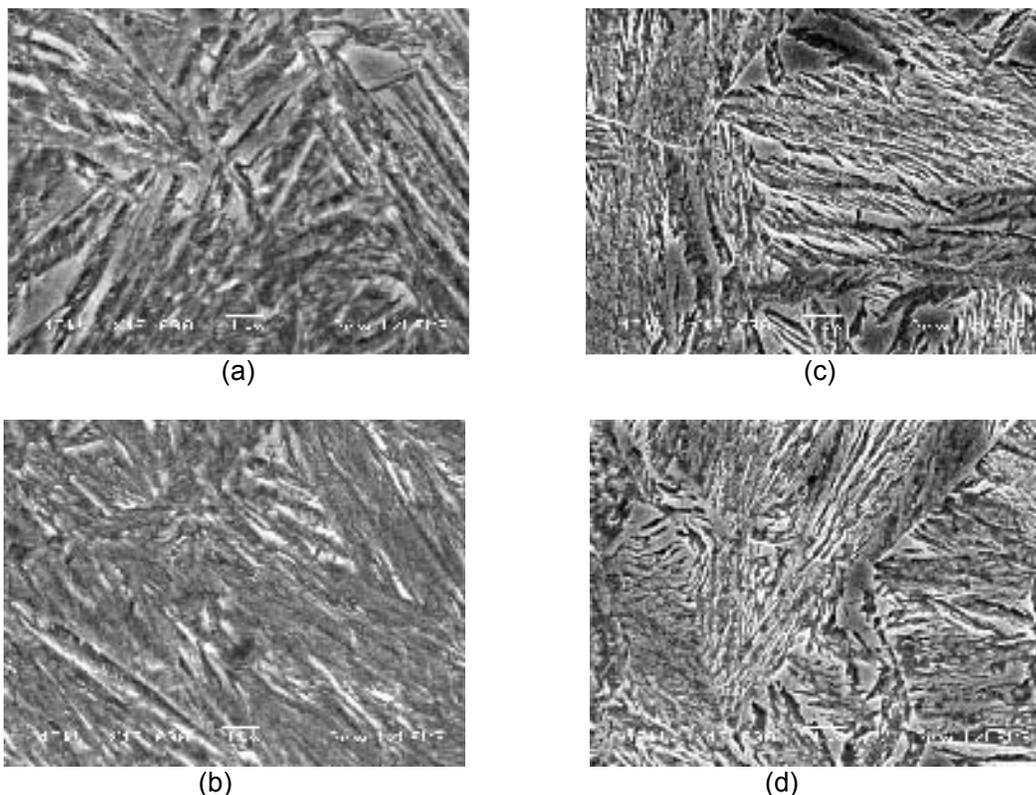


Figure 4. Scanning electron micrograph of the samples after austenitizing at 900°C and transformed at 220°C for (a) 0,5h, (b) 48h and 270°C for (c) 0,5h, (d) 48h, followed by air cooling. Etched with nital 2%.

According to the microstructures of the samples austempered at 220 and 270°C, the bainitic microstructure, which corresponds to the crosshatched regions, is presented as fine as characterized by Soliman and Palkowski.^[13]

The IT diagram in Figure 1 shows that about 50% of the microstructure corresponds to the martensite constituent to samples isothermally treated at 220°C. Moreover, the tests performed at 270°C, precede the start martensite transformation (M_s), so the presence of martensite in the microstructure is due to a transformation during cooling and after the end of isothermal treatment. The residual austenite present in microstructure after first cooling (from austenitizing temperature) will be transformed into bainite during the isothermal treatment. The bainitic ferrite formation from the residual austenite is a slow process and the amount formed increases with time processing.

The austenite lattice parameter extrapolation method (Eq. (1)) was used to estimate the carbon concentration and the amount of retained austenite present in the microstructure. The data are recorded in Table 3.

Table 3. volume fraction of retained austenite and carbon concentration (between parentheses - wt%) under isothermal treatments conditions

Volume fraction and carbon content (wt%) in the retained austenite				
Temperature (°C)	Time (h)			
	0,5	2	24	48
220	12,5 (2,31)	10,8 (0,52)	9,2 (2,87)	8,8 (1,0)
270	11,1 (2,54)	12,5 (2,27)	14,3 (2,13)	7,3 (2,94)

According to Table 3, the fraction of retained austenite and the carbon concentration are higher for the sample treated at 270°C. This occurs because the amount of bainite formed is lower for higher processing temperatures and carbon can diffuse more intensely.

The austenite stability in steel is controlled by the bainitic transformation, since the formation of bainite sheaves enriches with carbon the retained austenite. It can transform into martensite during the cooling until room temperature after the isothermal treatment. The capacity of the transformation will decrease as the carbon content in retained austenite increase, because martensitic transformation starting temperature (M_s) becomes lower.

3.2 Effect of Time and Transformation Temperature upon the Mechanical Properties

Figure 5 represents the microhardness of the samples as a function of temperature and isothermal transformation time, compared to microhardness of the sample tempered at 450°C.

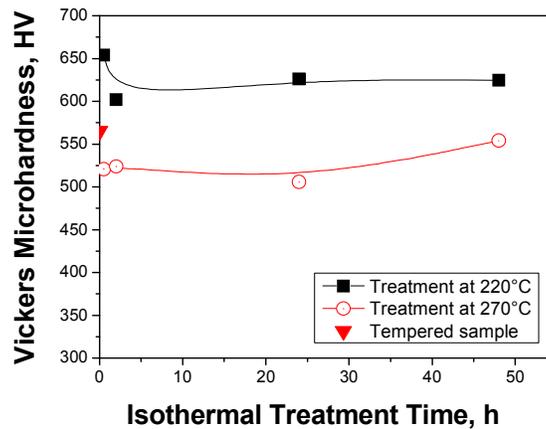


Figure 5. Microhardness of the samples as a function of temperature and time of isothermal transformation.

The tempering temperature of 450°C was chosen for comparing the results with austempered samples. This temperature is used in industrial practice, generating a microhardness Vickers of 565.

It can be seen in the Figure 5 that the microhardness is higher for the sample treated at 220°C for 0.5 h (≥ 650 HV). This result, as reported by Santos et al.,^[13] is due to the difference between the volume fraction of martensite and bainite. In this case, there is greater amount of MA constituent, probably because there is no treatment time sufficient for a considerable bainite reaction progress. In addition, the yet existing austenite may not be enriched in carbon sufficiently to remain stabilized at room temperature, and then it is transformed into martensite.

However, for the samples treated at 270°C, the microhardness results were lower than the sample quenched and tempered, due to a smaller amount of fine bainite present.

The microhardness difference between the samples treated at 220°C for times of 0.5 h and 2 h due to the early stages of processing, when changes begin to occur in the fractions of bainite, martensite and retained austenite. Previous researches show a minimum point in the graphs for samples treated in the range of 200 to

250°C.^[14] Firstly, the microhardness decreases because the fraction of bainite increases more than martensite. Values grow back when the fraction of fine bainitic ferrite increases, reaching very high microhardness measures comparable to a mixture of martensite and austenite.^[14,15]

The mechanical properties results of tensile test are plotted in Fig. 6. There is a greater proximity between the yield strength and the tensile strength for the sample quenched and tempered and the austempered sample for 0.5 h at 220°C in Figure 6(a), which indicates lower ductility. This is demonstrated by the total elongation, which for these two samples showed a value slightly smaller than the other. This low ductility is an outcome of a greater fraction of martensite present in the microstructure.

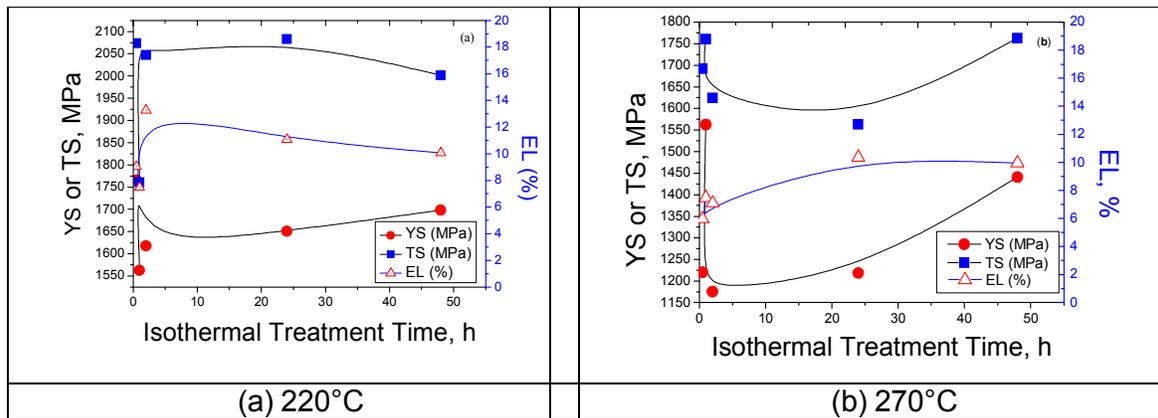


Figure 6. Results of mechanical properties as a function of temperature and time of treatment. (a) 220°C, (b) 270°C, compared with sample quenched and tempered.

In the samples austempered at 220°C for a time above 2 h, the mechanical behavior did not show a great variation. The yield strength increased slightly and the tensile strength remained stabilized, resulting in a slight total elongation reduction.

Samples heat treated at 270°C (Fig. 6(b)) have lower mechanical properties compared with the specimen treated at 220°C, due to a lower amount of fine sheave ferrite bainitic and martensite.

An important aspect that must be observed in Fig. 6(b) is the decrease of the yield strength and tensile strength for samples treated at 270°C until the time of 24 h. This is a result of increased bainite amount in relation to martensite as a function of time. These properties restart to increase for times longer than 24h, when the amount of fine bainitic ferrite increases.

4 CONCLUSION

- The samples treated at 220°C for 0.5 h showed mostly martensite in the microstructure, as well as lower presence of bainite and retained austenite. This justifies the different mechanical behavior of this sample for the others.
- The samples austempered at 220°C for 2 h, did not show significant variation in mechanical behavior. Putting on question the need for a longer heat treatment, which increases the processing cost.
- Comparing the samples austempered at 220°C for time over 2 h with the sample quenched and tempered at 450°C for 1 h, they showed stable tensile strength in the range of 2000 against 1700 MPa, yield strength in the range of

1700 against 1550 MPa, and finally, an total elongation in the range of 12% versus 7% for quenched and tempered sample.

- Comparing samples treated at 220 and 270°C, the latter have lower mechanical properties, due to lower fraction of fine bainite sheaves and retained austenite films.

Acknowledgments

This study was financially supported by FAPEMIG, State Foundation for Research Development of Minas Gerais, and CNPq, National Council for Technological and Research Development.

REFERENCES

- 1 BADHESHIA, H.K.D.H. Properties of Fine-Grained Steels Generated by Displacive Transformation. *Materials Science and Engineering A*, v. 481-482, p. 36-39, 2008.
- 2 ZACKAY, V. F. PARKER, E. R. FAHR, D. BUSCH, R. The enhancement of ductility in high-strength steels. *Transactions of American Society for Metals*, v. 60, p. 252-259, 1967.
- 3 SOLIMAN, M.; LUESING, S.; ASADI, M.; PALKOWSKI, H. Thermomechanically processed TRIP-steel with bimodal bainite structure. *Italy*, 2008, p 1-10.
- 4 BHADSHIA, H.K.D.H. *Bainite in Steels*. 2^{ed}. Cambridge: IOM Communications, England 2001. 478 pp. (ISBN 1-86125-112-2).
- 5 CABALLERO, F.G.; BHADSHIA, H.K.D.H. Very Strong Bainite. *Current Opinion in Solid State and Materials Science*. n.8, p. 251–257, 2004.
- 6 WANG, T.S.; LI, X.Y. ZHANG, F.G. ZHENG, Y.Z. Microstructures and mechanical properties of 60Si2CrVA steel by isothermal transformation at low temperature. *Materials Science and Engineering A*, v. 438 – 440, p. 1124-1124, 2006.
- 7 SANTOS, D. B.; BARBOSA, R.; DUARTE, D. M.; OLIVEIRA, P. P.; PERELOMA, E. V. Produção, desempenho mecânico e caracterização microestrutural do aço alto C Si-Mn-Cr laminado a quente apresentando efeito TRIP. 44^o Seminário de Laminação – Processos e Produtos Laminados e Revestidos ABM – Campos do Jordão – SP, p. 607-619, Outubro 2007.
- 8 CULLITY, B. D., STOCH, S. R. *Elements of X-ray Diffraction*, 3^a ed. Prentice Hall, Inc., New Jersey, 2001. p. 351-355.
- 9 SANTOS, D. B., BARBOSA, R., OLIVEIRA, P. P., PERELOMA, E. V. Mechanical Behavior and Microstructure of High Carbon Si-Mn-Cr Steel with Trip Effect, *ISIJ International*, v.49, p.1592-1600, October 2009.
- 10 KRAUSS, G. *Steels: Heat Treatment and Processing Principles*.1 ed. Ohio: Materials Park, 1989. 497 p.
- 11 HONEYCOMBE, R. W. K, BHADSHIA, H. K. D. H. *Steels Microstructure and Properties*. 2 ed. London: Gray Publishing, 1995. 324 p.
- 12 SING, S. B., BHADSHIA, H. K. D. H. Estimation of Bainite Plate-Thickness in Low-Alloy Steels, *Materials Science and Engineering A*, v.245, p.72-79, June 1997.
- 13 SOLIMAN, M.; PALKOWSKI, H. Ultra-Fine Bainite Structure in Hypo-eutectoid Steels. *ISIJ International*, v. 47, n. 12, p.1703-1710, 2007.
- 14 GARCIA-MATEO, C., CABALLERO, F. G., BHADSHIA, H. K. D. H. Development of Hard Bainite, *ISIJ International*, v. 43, n. 8, p. 1238-1243, 2003.
- 15 GARCIA-MATEO, C., CABALLERO, F. G., BHADSHIA, H. K. D. H. Superbainita. Uma Nueva Microestructura Bainítica de Alta Resistencia, *Rev. Metal. Madrid*, v. 41, p. 186-193, mar. 2005.