A STUDY OF THE PARTITION OF ELEMENTS BETWEEN AUSTENITE AND FERRITE IN CONDITIONS SIMILAR TO THE TREATMENT OF TRIP STEELS[1]

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Abstract

The thermomechanical treatment of the TRIP (TRansformation Induced Plasticity) steels involve intercritical annealing followed by cooling to the austempering temperature. The composition of TRIP steels is adjusted in order to optimize the resulting multi-phase microstructure. Significant work is underway to evaluate the possibility of replacing silicon with other elements, such as aluminum, for instance. The correct understanding of the processes occurring during all stages of the heat treatment of these steels is a critical part of this evaluation. In this work, attempts to describe the transformations during the intercritical annealing and the cooling to the austempering temperature using computational thermodynamics (Thermo-calc) and diffusion simulation (DICTRA) are described. The results of calculations are compared with available experimental data and the limitations and the potential of using this approach in the alloy design of TRIP steels are discussed.

Key-words: Thermodynamics; TRIP; Steel; Diffusion; Modeling.

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1 INTRODUCTION

The last decades have seen a dramatic increase in the demand of higher strength steels with good formability for use in the transportation industry. The need for steels with strengths in the range of 500 to 1000MPa without sacrifice of formability has lead to the development of several options in alloy design.(1-3) One of the most successful of these developments, TRIP (Transformation Induced Plasticity) steels, are based on two important concepts in materials science, namely a) the use of the strain induced austenite to martensite transformation to increase strain hardening coefficient and delay the onset of unstable deformation (necking) and b) formation of an in-situ multi-phase composite, with an adequate combination of phases with different strength and plasticity. To this mean, the thermomechanical treatment of the TRIP steels involve measures required to achieve an adequate combination of ferrite, bainite, austenite and martensite both after rolling in the steel mill and after forming in the part produced. The established heat treatment involves intercritical annealing followed by cooling to the austempering temperature (Figure 1). During intercritical annealing the predominant phase in the final product (ferrite) is formed, and carbon is partitioned to the austenite present at the selected temperature. Judicious selection of parameters is essential to achieve a) the proper amount of ferrite and b) the desired enrichment in carbon of the austenite present at this point of the treatment. Subsequently the steel is cooled to an austempering temperature where bainite is formed and carbon is again partitioned to the retained austenite. The extent of this partitioning will define the amount of retained austenite and martensite formed on cooling from the austempering temperature. Ideally this austenite should, at this point, be conditioned in such a way that it will a) transform to martensite during forming and b) have a transformation behavior such that the transformation will be distributed along the range of strains associated with forming. To achieve this, hence, the composition of TRIP steels must be adjusted in order to optimize the resulting multi-phase microstructure.(4-5)

Most commercial TRIP steels have compositions based on significant silicon additions. Table I presents some typical compositions and heat treatment cycles of TRIP steels. One of the reasons for the use of silicon is the effect in preventing the formation of cementite, thus making viable the enrichment of austenite in carbon. Silicon however causes the formation of adherent scale during rolling and the resulting surface is usually not adequate to use in exposed parts in automotive applications. Furthermore, silicon can be a problem for the galvanizing process (6). Significant work is underway to evaluate the possibility of replacing silicon with other elements that would have similar effect on the phase equilibria and transformations, such as aluminum, for instance.(6-8) The correct understanding of the processes occurring during all stages of the heat treatment of these steels is a critical part of this evaluation. In this work, attempts to describe the transformations during the intercritical annealing and the cooling to the austempering temperature using computational thermodynamics (Thermo-calc)(9) and diffusion simulation (DICTRA) are described. The results of calculations are compared with available experimental data and the limitations and the potential of using this approach in the alloy design of TRIP steels are discussed.

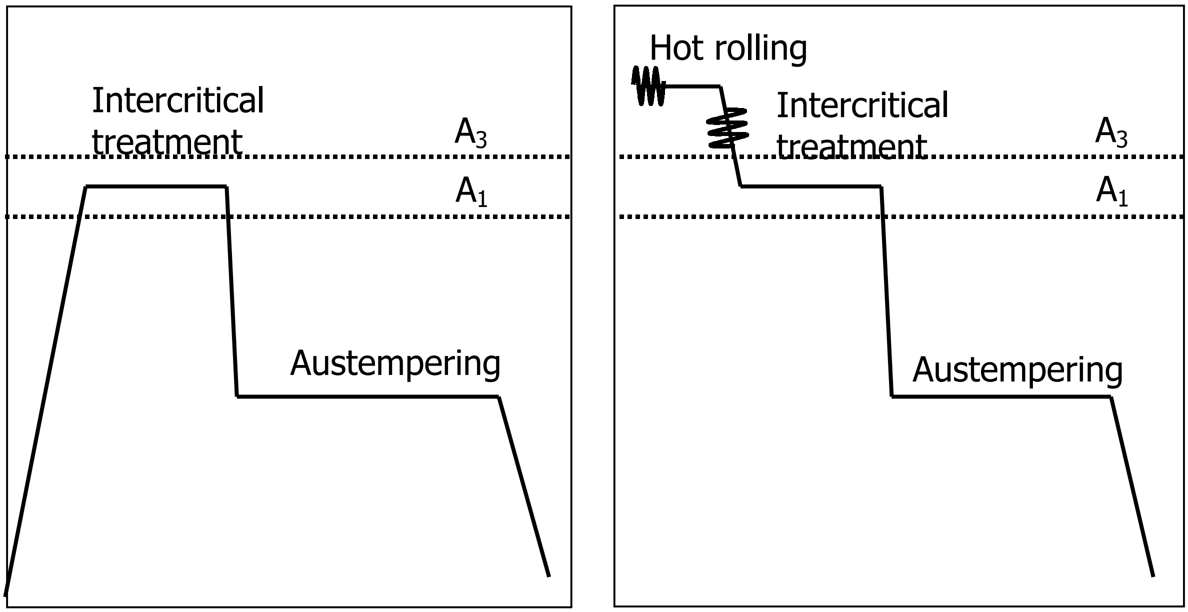

Figure 1. Schematic heat treatment cycles (simplified) for the production of TRIP steels. An intercritical treatment and a holding time at a temperature in the austempering range are the critical steps for the conditioning of the retained austenite.

Table I. Tipical compositions and processing conditions for some TRIP steels

Steel	**%**				**Intercr. treatment**		**Austempering**	
	C	**Mn**	**Si**	**Al**	**T(°C)**	**t (s)**	**T (°C)**	**t (s)**
92Matsumura B1 (4)	0.39	1.2	1.16		770	300	350-450	1800
92Matsumura B2	0.38	1.2	1.46		790	300	350-450	
92Matsumura B3	0.39	1.2	1.99		810	300	350-450	
96MinoteA (10)	0.19	1.51	1.45		750-875		300-500	
96MinoteB	0.21	1.54	1.53		750-875		300-500	
99DemeyerA (6)	0.19	1.57	1.46		770	120-240	400-450	
99DemeyerB	0.31	1.57	0.34	1.2	800	120-240	400-450	
00Sugimoto (11)	0.20	1.51	1.51		780		400	1000
01JacquesAl1 (12)	0.11	1.55	0.06	1.5	750	240	375	0-2000
01JacquesSi1 (12)	0.11	1.53	1.5		750	240	375	0-2000
98Samajdar (13)	0.11	1.53	1.5		750			
97Zarei (14)	0.19	1.54	1.50					
02Jiao (15)	0.2	1.55	1.55	Mo 0.3				
99JacquesHSi (16)	0.29	1.40	1.5		760	360	360 410	
99JacquesLSi (16)	0.29	1.3	0.38				370 430	

2 FACTORS IN ALLOY DESIGN AND PROCESSING

2.1 Equilibrium evaluation

Since high silicon is detrimental to surface quality and to galvanizing, other elements that would prevent carbide formation and provide the required changes in transformations are required. Aluminum has been identified as a cost effective candidate.

The intercritical treatment, holding temperature and composition must be adjusted to achieve the desired fraction of ferrite (BCC), the dominant phase in the microstructure. The fraction of ferrite formed depends, evidently, both on the thermodynamics and on the kinetic aspects of the intercritical treatment.

Figure 2 shows the calculated effect (all calculations performed using Thermo-calc and TCFE3 Database,(17) except otherwise indicated) of the main alloy elements on the 1053K (780 °C) isotherm. It is interesting to note that the carbon solubility in ferrite (BCC) at this temperature is essentially unchanged by the substitutional alloying additions, whereas the composition of austenite (FCC) is dramatically affected. Furthermore, the fractions of phases present changes considerably due to these changes.

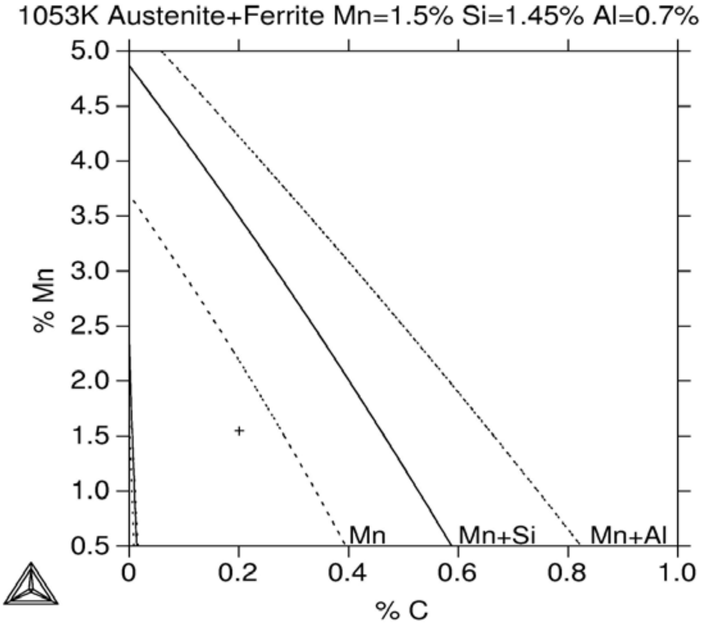

Figure 2. Calculated 1053K (780 °C) isotherm for a TRIP steel composition, considering the individual effects of the substitutional alloying elements. The symbol + indicates the steel composition. The amount of equilibrium ferrite at the intercritical temperature and the amount and composition of equilibrium austenite can be adjusted via temperature and composition.

2.2 The formation of intercritical austenite

Processing schemes for TRIP steels include the possibility of direct cooling from rolling to intercritical treatment. In these conditions, ferrite growth from austenite must be considered. Although this treatment is seldom considered from a kinetic point of view in the conventional heat treatment of steel, some interesting observations can be derived from the analysis of the kinetics of these diffusion processes. Once a certain intercritical treatment temperature is selected for a given steel composition, the equilibrium phase fraction is defined (see Figure 3a). Simulation of diffusion growth of ferrite from austenite in these conditions, for a viable TRIP steel composition show that depending on the selected temperature, ferrite growth kinetics from austenite can exhibit a clear change from a fast process to a quite slow growth.

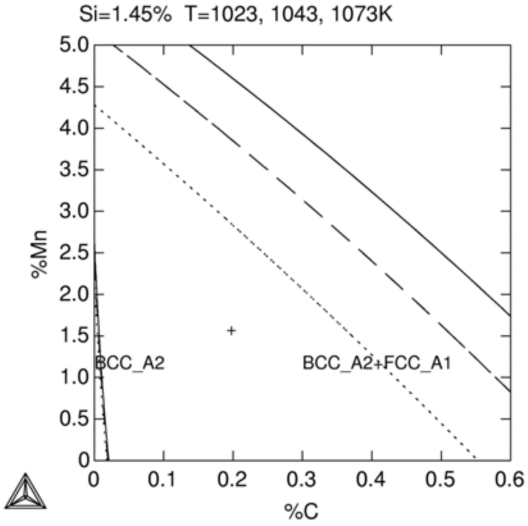

Figure 3a. Effect of intercritical treatment temperature on the phase fractions of BCC and FCC for a 1.45% TRIP steel. . The symbol + indicates the steel composition used in Figure 3b.

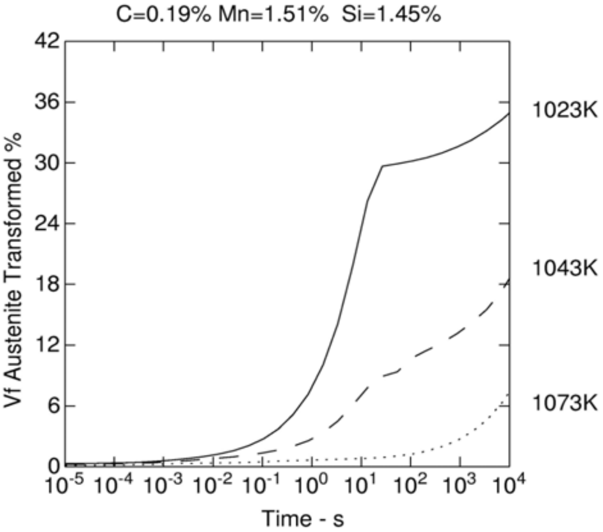

Figure 3b. Decomposition of austenite at different intercritical temperatures. Changes in the intercritical temperature have an effect on kinetics. Kinetics change during growth. See text for discussion.

The reason for this change in ternary and higher order systems is well established(18) and is associated to tie-line selection during growth. The main hindrance to the diffusion growth of ferrite from austenite is the redistribution of the relatively slower moving substitutional elements. If the alloy composition is such that a tie-line can be selected by system in which only carbon needs to be partitioned between the phases (see Figure 4a), growth can proceed at a rate limited by carbon diffusion. This can be termed non-partition, local equilibrium growth (NP-LE). When the system cannot use such a tie-line, growth must proceed at a slower rate, limited by the redistribution of substitutional solutes (P-LE), as indicated in Figure 4a. As the compositions of the phases adjust to the growth process, different tie lines must be choose by the system in such a way that eventually growth might change from NP-LE to P-LE, causing a significant reduction in the transformation kinetics.

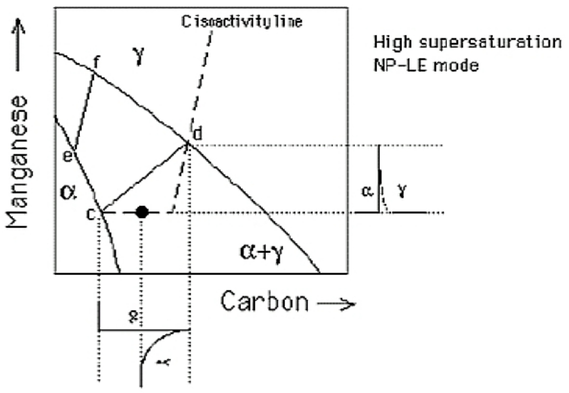

Figure 4a. Fast growth can occur with the selection of a tie line associated to partitionless growth with respect to the substitutional element(s) (NP-LE) (19)

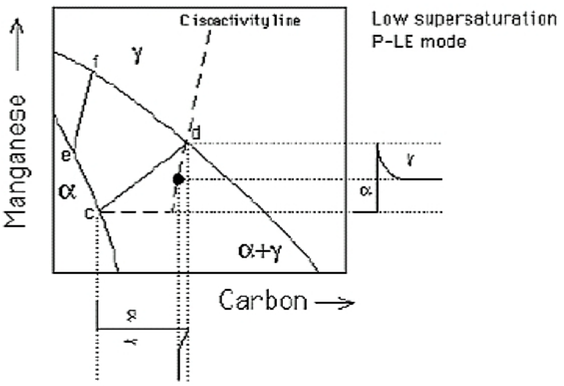

Figure 4b.Slower growth, as substitutional element(s) must partition between austenite and ferrite (P-LE) (19)

Conversely, when the processing includes cooling and coiling after rolling, followed by the intercritical heat treatment, the formation of austenite from the previous room temperature microstructure must be considered. Figure 5 presents the evolution of the formation of austenite from a ferrite plus cementite microstructure. It is apparent that the presence of the fine carbide-ferrite agglomerate will enhance the formation of austenite. The modeling can predict considerably well the real behavior reported by Samajdar e co-workers (13).

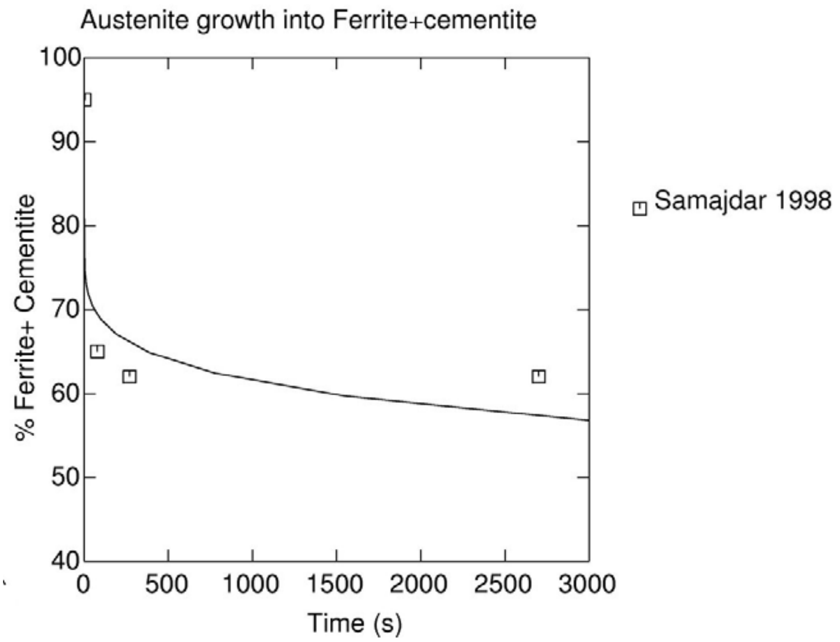

Figure 5. Kinetics of austenite formation from ferrite+ cementite during intercritical annealing at 750 °C.

2.3 The austempering treatment

The microstructure formed during intercritical annealing is composed of ferrite and austenite. This austenite is considerably richer in carbon when compared to the average steel composition. This enrichment, however, is not, in general, sufficient to guarantee the "optimized mechanical stability of the retained austenite"(5) viz. a sufficiently low M_s, so that a significant volume fraction of austenite is retained at room temperature, to be transformed during deformation.

Understanding what happens during the austempering treatment is not an easy task. As time at the austempering temperature increases, the amount of bainite formed increases and the carbon content of the austenite increases. As a result, the amount of martensite that will be formed on cooling decreases.

The presence of elements that inhibit the formation of carbides (Si, Al or P, mostly) is critical in this step, in order to properly enrich the austenite in carbon. If the formation of austenite was assumed to be displacive(5) or too fast for appreciable diffusion of carbon to occur, the maximum carbon content it could inherit from the austenite would be given by the T_o composition, when $G_{□}=G_{□}$, as indicated in the calculated diagram in Figure 6. However, as this bainite is held at the austempering temperature in contact with austenite, the carbon content in these phases is not in equilibrium. Hillert and co-workers (20) have demonstrated that for the usual dimensions of the bainite plates, carbon can redistribute quite fast, in order to establish carbon equilibrium between these phases. More recently, these calculations were repeated for the specific case of TRIP steel by Van Doren and co-workers,(21) as shown on Figure 7. Although it has been suggested that the T_o curve should represent the limit for carbon enrichment of the austenite, the redistribution of carbon to reach "constrained carbon equilibrium"(CCE)(22) should not be limited by this composition, but rather by the CCE condition for the given austempering temperature. Figure 6 indicates that the final austenite carbon content exceeds in many cases the calculated T_o carbon content, suggesting that this may, indeed be the case. If so, to reach the "ideal" carbon content for the proper stabilization of the retained austenite, not only the austempering temperature, but also the relative phase fractions, will play a role in reaching the ideal microstructure.

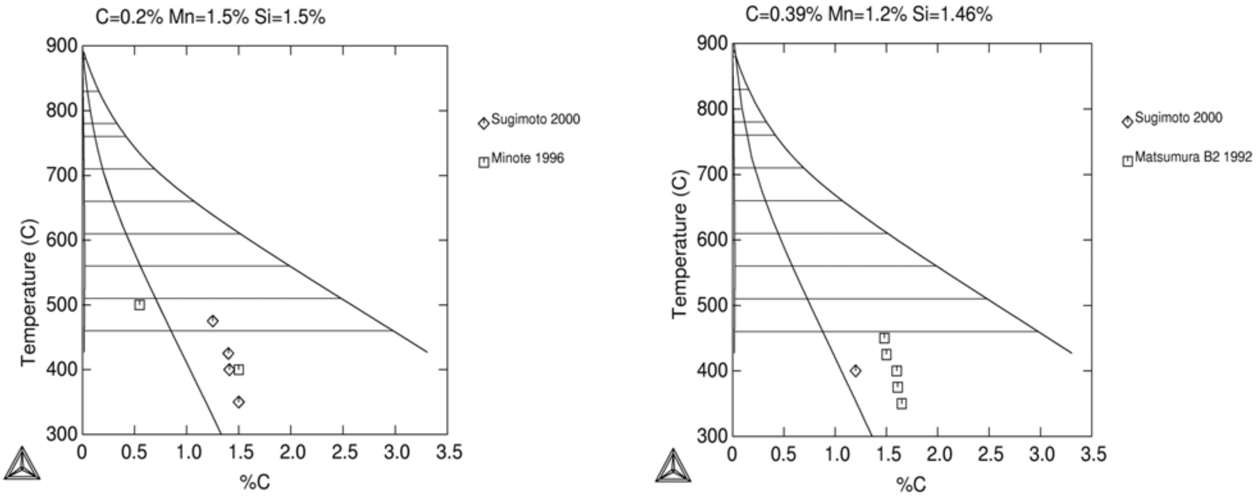

Figure 6. Calculated para-equilibrium diagram (BCC and FCC) with superimposed T_o curves. Results(4,10-11) are carbon content of retained austenite for TRIP steels with given compositions after austempering at indicated temperatures.

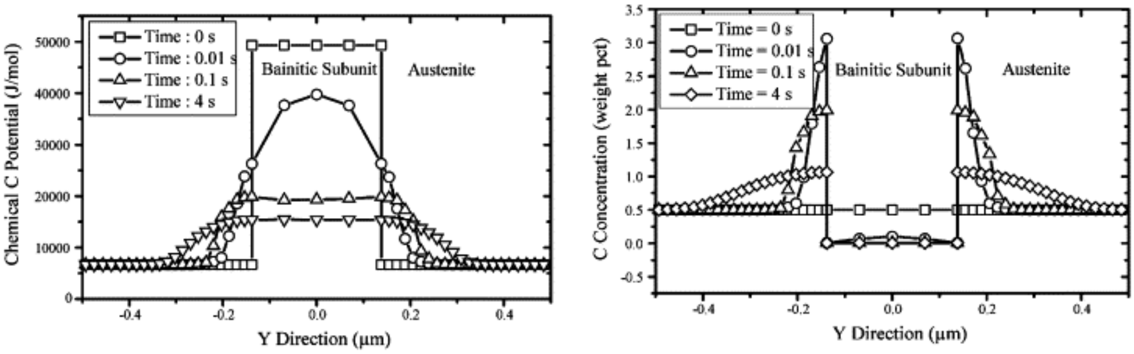

Figure 7. Evolution of carbon chemical potential (left) and composition (right) with time at 400 °C during austempering treatment of a C-Mn-Si TRIP steel.(21).

3 CONCLUSIONS

Computational thermodynamics and diffusion modeling can be useful in the selection of conditions for heat treatment of TRIP and dual phase steels, as well as on improving the understanding of the processes involved.

These tools can also be used to evaluate alloying options and alternatives.

More effort is needed in order to improve the understanding of the transformations occurring during austempering.

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ESTUDO DA PARTIÇÃO DOS ELEMENTOS ENTRE AUSTENITA E FERRITA EM CONDIÇÕES SIMILARES AO TRATAMENTO DE AÇOS "TRIP"

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Resumo

O tratamento termomecânico dos aços TRIP envolve um tratamento intercrítico seguido de resfriamento até a temperatura de austempera. A composição dos aços TRIP é ajustada para otimizar a estrutura multi-fásica resultantes. Um esforço significativo de pesquisa vem sendo desenvolvido para avaliar a substituição do silício por outros elementos, tais como o alumínio, por exemplo. A compreensão exata dos processos que ocorrem durante todas as etapas do tratamento termomecânico destes aços é uma parte critica desta avaliação. No presente trabalho são apresentados resultados de modelamento visando descrever as transformações que ocorrem no tratamento intercrítico e no resfriamento subseqüente, empregado termodinâmica computacional (Thermo-calc) e simulação difusional (DICTRA). Os resultados destes cálculos são comparados com os dados experimentais disponíveis e discute-se as limitações e potencial do emprego destas técnicas no projeto de liga de aços TRIP.

Palavras-chave: Termodinâmica; Transformação de fases; Difusão; Modelamento; Aço; TRIP.

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