Cinética da formação de austenita a altas velocidades de aquecimento

The kinetics of austenite formation at high heating rates

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Resumo

Foi estudada por dilatometria a variação das temperaturas críticas para a formação de austenita, com o aumento da velocidade de aquecimento. A análise foi realizada a velocidades de aquecimento entre 10 e 90°C/s. Foram propostas equações empíricas para o cálculo de Ac_3, em função da velocidade de aquecimento. O aumento da velocidade de aquecimento não afetou Ac_1, mas Ac_3 aumentou em 115°C. As equações propostas se revelaram de uso mais geral, uma vez que também previram os resultados obtidos em trabalhos para outros aços com altos coeficientes de correlação.

Palavras-chave: Austenitização, cinética, aquecimento rápido, dilatometria.

Abstract

The variation in critical temperatures for the formation of austenite when increasing the heating rate was studied by dilatometry. The analysis was performed at heating rates between 10 and 90°C/s. Empirical equations are herein proposed for calculating Ac_3 with respect to the heating rate. The results showed that an increase in the heating rate had no influence on Ac_1, but Ac_3 increased 115°C. The equations proved to be of a more general use, as they also predicted the results of works on other steels with high values of correlation coefficients.

Keywords: *Austenitization, kinetics, fast heating, dilatometry.*

1. Introduction

The formation of austenite in steels is employed in various industrial processes. Therefore austenitization is still a largely studied phenomenon, since the grain size and its distribution directly influence the final mechanicalt properties obtained (Morito et al., 2006). At continuous heating, the heating rates significantly alter the temperatures of steel processing and, consequently, its microstructures. Danon et al. (2003) studied the influence of the heating rate and austenitization temperature on the heterogeneous growth of austenitic grains in martensitic steels, and noted that the heating rate used to reach the austenitic phase had a strong influence on the austenitic grain size distribution.

Another important aspect to be considered is related to the type of steel because different original microstructures and different levels of carbon and alloy elements influence the austenitic microstructure produced, as well as the products of its tempering and annealing (Krauss, 1990; Oliveira et al., 2007).

Oliveira et al. (2007) observed that an increase in the heating rate increases the rate of austenite formation and affects its critical temperatures in low-carbon steel, for heating rates between 0.1 and 16°C/s.

In some industries, due to the short treatment period and the ability to treat specific parts of the pieces, thermal treatment by electromagnetic induction is employed. In this process, because of losses from the Joule effect and hysteresis, an induced electrical current heats the piece to be treated. Usually the heating rates are extremely high, and may exceed 200°C/s (Rudnev et al, 2003). Therefore, when electromagnetically induced thermal treatments are used, besides checking the previous microstructure and chemical composition, it is necessary to verify the critical temperatures for austenite formation to determine the heating rate that will be employed. Consequently, an examination of the influence of high heating rates at critical temperatures in the austenite formation is fundamental.

Dilatometric techniques have been used to study austenite formation under continuous heating, since during the steel's transformation phases , there is some volume variation due to changes in the crystalline structure (Garcia de Andrés et al., 1998).

This research investigated the influence of the variation of high heating rates at the starting and final temperatures of austenite formation, as well as its influence on the transformation period, in order to simulate thermal treatment conditions by electromagnetic induction.

2. Materials and experimental procedure

The material studied in this research was the SAE4130 steel, produced by V&M of Brazil S.A. The chemical composition of this steel, given in % by weight, was of 97.8Fe, 0.29C, 0.52Mn, 0.013P, 0.003S, 0.19Si, 0.01Ni, 0.97Cr, 0.16Mo and 0.008Cu. The steel microstructure at delivery condition was obtained by optical microscopy, on a sample etched with nital 2%.

The tests were conducted in an Adamel Ihomargy type LK02 dilatometer. The samples were cut from laminated and drawn tubes, with 0.6mm thickness, 2mm width and 12mm length. The critical starting and ending temperatures of austenite formation were determined by dilatometric curves. The critical temperatures were obtained for the heating rates of 10, 30, 50, 70 and 90°C/s.

3. Results and analysis

The original steel microstructure is composed of ferrite and pearlite, with a volumetric ferrite fraction of $V_{\alpha 0}$=(48 ± 0.6)%, and a structure of bands, which is due to the laminating and drawing processes used for the manufacturing of the tubes from which the samples were taken.

Employing Andrews' equations, Ac_1 and Ac_3 values for the SAE4130 steel in this research, at slow heating, are: Ac_1=739°C and Ac_3=814°C. At continuous heating and at high heating rates, dilatometric tests were performed to determine the temperatures Ac_1 and Ac_3. Figure 1 displays the dilatometric curves, where ΔL=f(T) for the continuous heating and high heating rates of the steel under study, and the derivatives of the dilatometric curves, dΔL/dT=f(T), highlight the great differences among the final temperatures of austenite formation, Ac_3, under varying heating rates.

In Figure 1, with a low heating rate of 10°C/s, it is possible to identify the starting temperature of the ferrite transformation into austenite (Af_i), which is of about 790°C, after the pearlite dissolution; the temperatures Ac_1 and Ac_3 are also indicated.

At continuous heating, the austenite formation rate reaches its maximum at about the final temperature of pearlite dissolution, and the increase in the heating rate raises the austenite formation rate (Oliveira, 2007). Therefore, at heating rates greater than 10°C/s, the austenite formation rate will be so high in Afi that this temperature is not easily displayed graphically. Temperatures Ac_1 and Ac_3, for each heating rate at continuous heating, are listed in Table 1.

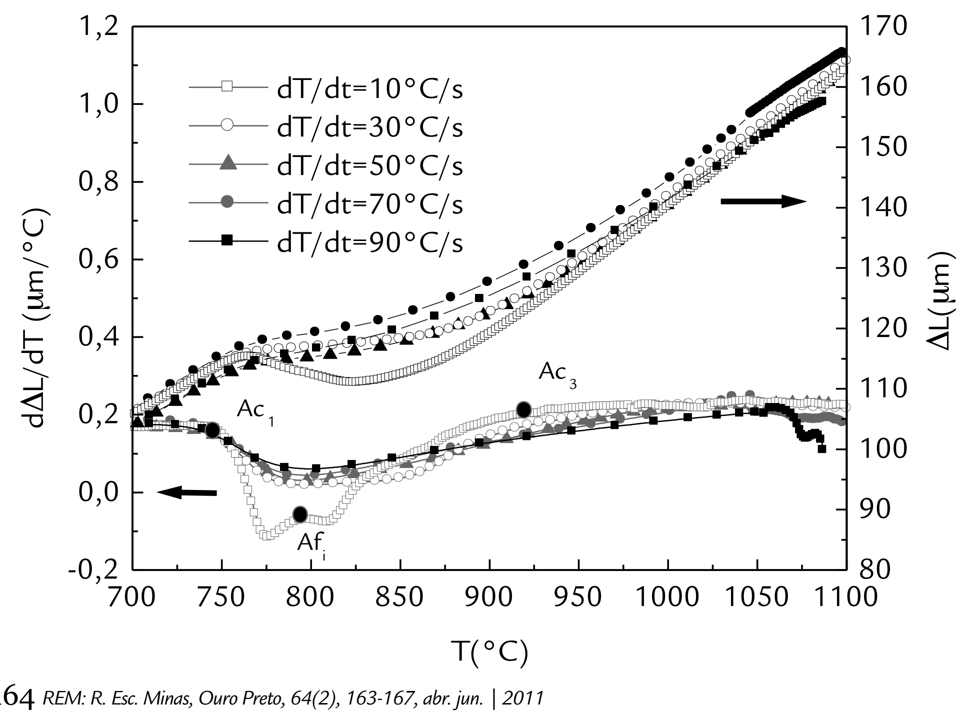

Figure 1
Dilatometric curves (ΔL=f(T)), and their derivatives (dΔL/dT=f(T)) for the SAE4130 steel, under continuous heating, at the rates of 10, 30, 50, 70 and 90°C/s.

Table 1
Critical temperatures of austenite formation of the SAE4130 steel, Ac_1 and Ac_3, for continuous heating at various heating rates.

dT/dt (°C/s)	Ac_1 (°C)	Ac_3 (°C)
10	740	920
30	744	977
50	740	985
70	738	1016
90	740	1035

Figure 2 displays the variation of temperatures Ac_1 and Ac_3, as well as the time variation for austenite formation, with respect to the heating rates of 10, 30, 50, 70 e 90 °C/s.

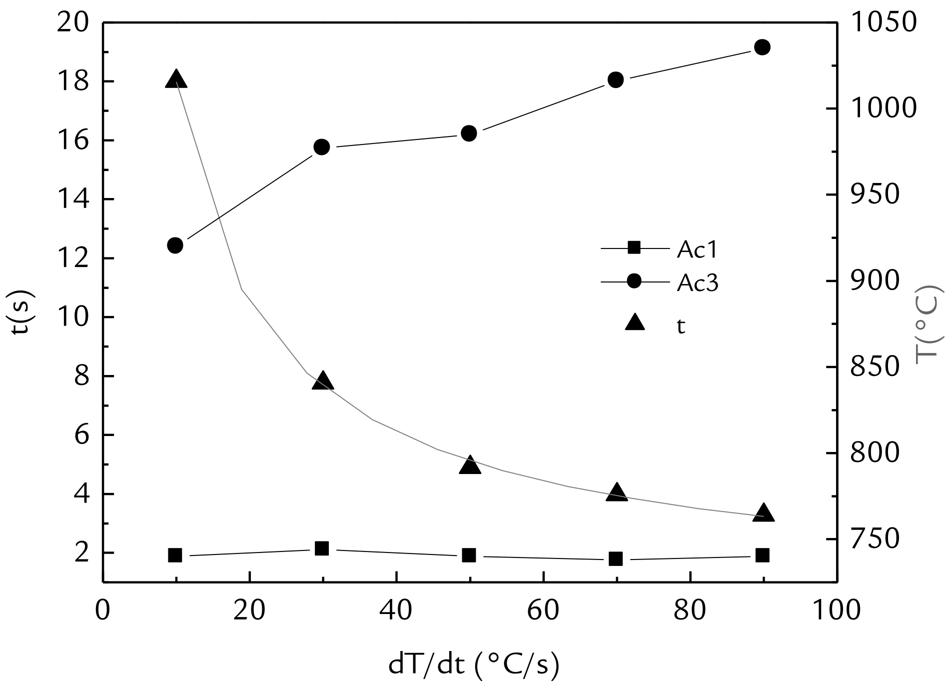

Figure 2
Variation of temperatures Ac_1 and Ac_3, together with the time variation at the end of the austenite formation, in respect to the heating rates for the SAE4130 steel.

The starting temperature of austenite formation (Ac_1), defined as the temperature at which the thermal expansion has strayed from linearity (Garcia de Andrés et al., 1998; 2002), hardly varied with the heating rate, also displayed in Figure 1. The austenite formation derived from the ferrite and pearlite microstructure begins with the pearlite dissolution, as it becomes

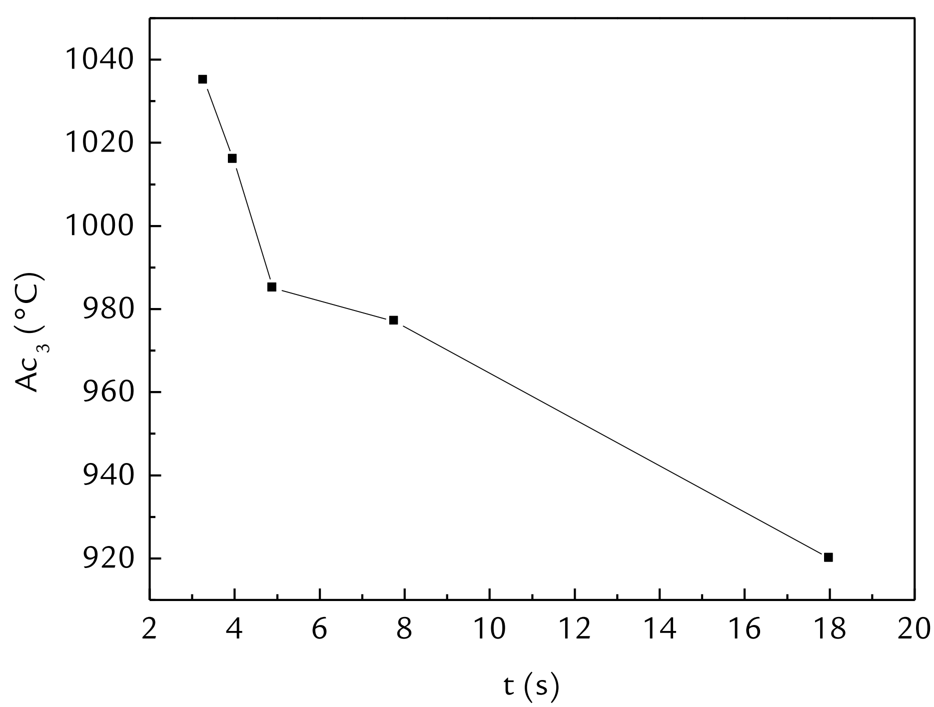

Figure 3
Temperature variation at the end of the austenite formation with respect to the transformation period, for the SAE4130 steel.

unstable at temperatures over Ac_1. The austenite nucleation occurs in the interfaces between the pearlite colonies and the ferrite-cementite interface, which implies in high formation rates, due to the narrow distances of carbon diffusion. Therefore, even with the increase in heating rates, the energy to the transformation, and consequently Ac_1, remain unaltered.

An increase is noticeable at the final temperature of austenitic transformation (Ac_3) with a raise in the heating rate. Figure 3 displays Ac_3 with respect to the transformation period. These results indicate that the increase in the heating rate reduces the austenite transformation period, hence, reducing the duration of the diffusion process, which demands greater energy for the transformation, and therefore a greater Ac_3 value.

An empiric equation is proposed, fitting the time variation at the end of the austenite formation with respect to the heating rates of Figure 2, which is expressed by:

$$t_{100} = Q\left(\frac{dT}{dt}\right)^{-g} \quad (1)$$

where t_{100} is the total time of austenite formation, Q and g are steel constants, which can depend on the starting microstructure and chemical composition. In this case, for the SAE4130 steel, Q is about 109.1 and g is about 0.78, with a correlation coefficient of 0.999. Considering that the heating rate can be calculated by:

$$\frac{dT}{dt} = \frac{Ac_3 - Ac_1}{t_{100}} \quad (2)$$

hence:

$$Ac_3 = Q\left(\frac{dT}{dt}\right)^{-g+1} + Ac_1 \quad (3)$$

The results of Oliveira et al. (Oliveira, 2007) demonstrated that for heating rates amidst 0.1°C/s and 16°C/s, temperature Ac_3 raises with the rate, while Ac_1 suffers less influence of the increase in the heating rate. The adjustment of the figures of Oliveira et al. (Oliveira, 2007) to equation 1 proves that the equation is true also for low carbon steel microalloyed with niobium of that study, with a 0.999 correlation coefficient, and the Q and g constants at 135.6 and 0.95, respectively. Therefore, for both microalloyed steels, one should merely determine the temperature Ac_1 at continuous heating to find out Ac_3 at any heating rate.

For stainless steels, the results of Danon et al. (Danon, 2003) and Garcia et al. (Garcia, 2002) demonstrated that the temperature of Ac_1 suffers a greater influence from the heating rate. In fact, equations 1 and 3 are also able to correctly describe the time variation for the transformation and for the temperature of Ac_3 in respect to the increase of the heating rate for those steels.

4. Conclusions

For heating rates of over 30°C/s, the starting temperature of the ferrite transformation into austenite (Af_1) is not easily identified by dilatometric curves. The increase in the heating rate amidst 10°C/s and 90°C/s had no influence in the starting temperature of the austenite formation (Ac_1), kept close to 740°C, but changed its final critical temperature (Ac_3), which increased from 920°C to 1035°C. The set of empirical equations proposed from the dilatometric data successfully predicted Ac_3 as a function of the heating rate between 10 and 90°C. The theoretical curves calculated from the proposed equations, for the alteration in transformation time and temperature Ac_3 with respect to the increase in heating rate and a correlation coefficient of 0.999, correspond to the experimental data obtained for the SAE4130 steel in this study, as well as to the data on steels analyzed in other studies, suggesting that it is an equation with general application.

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