

A Study of isochronal austenitization kinetics in a low carbon steel

Estudo da cinética de austenitização isócrona em um aço de baixo carbono

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Abstract

The austenite formation under isochronal conditions in Nb microalloyed low carbon steel was studied by means of dilatometric analysis and the data was adjusted to the Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation, for different heating rates and for three initial microstructures. It was shown that the kinetics of austenitization of a pearlite+ferrite structure is faster than that of martensite (tempered martensite) at a heating rate of 0.1°C/s. For heating rates higher than 0.1°C/s, the kinetics of austenitization of a martensite structure is faster than of pearlite+ferrite one. The K parameter of the JMAK equation increases with the heating rate for the three previous microstructures and it is greater for the initial microstructure composed of ferrite+pearlite. At lower heating rates, the formation of austenite in this steel is controlled by carbon diffusion, independently of the initial microstructure. At higher heating rates, the formation of austenite from an initial microstructure composed of pearlite and ferrite is controlled by interface-controlled transformation.

Keywords: *austenite formation; kinetics; low carbon steel.*

Resumo

Foi estudada a formação da austenita em condições isócronas em um aço de baixo carbono e microalloyado com Nb por meio de análise dilatométrica, com o ajuste dos dados à equação de Johnson-Mehl-Avrami-Kolmogorov (JMAK), para diferentes taxas de aquecimento e para três diferentes microestruturas iniciais. Foi mostrado que a cinética de austenitização da estrutura perlita+ferrita é mais rápida que a da martensita (martensita revenida) à taxa de aquecimento de 0,1°C/s. Para taxas de aquecimento maiores que 0,1°C/s, a cinética de austenitização da estrutura martensítica é maior que da estrutura perlita+ferrita. O parâmetro K da equação de JMAK aumenta com a taxa de aquecimento para as três microestruturas prévias e é maior para a microestrutura inicial composta de perlita+ferrita. A baixas taxas de aquecimento, a formação da austenita é controlada pela difusão de carbono, independentemente da microestrutura inicial. A altas taxas de aquecimento, a formação da austenita da microestrutura inicial composta de perlita+ferrita é uma transformação controlada pela interface.

Palavras-chave: formação da austenita; cinética; aço baixo carbono.

1. Introduction

The formation of austenite in carbon steels is an inevitable occurrence during heat treatment and the initial austenitic condition is important to the development of the final microstructure and the mechanical properties. In this sense, the mechanical properties of the steels depend on the kinetics of austenite formation; in others words, they depend on the heating rate, austenite homogeneity, austenite grain size, non-metallic inclusions and the distribution, size and chemistry of individual phases (Krauss, 1990).

In general, non-isothermal dilatometry is a powerful method for the analysis of solid-state transformation kinetics, by measuring the shifts of the temperatures of inflection points on dilatometric curves as a function of heating rate. Through

the dilatometric curves it is possible to determine the critical transformation temperatures and to establish a relationship between the volume fractions, the temperature and the composition of the phases (Almeida et al., 2010; Farahat, 2008; Oliveira et al., 2007; Garcia de Andrés et al., 2002; Zhao et al., 2001; Kop et al., 2001).

Many works studied the kinetics of austenite formation, which is influenced by chemical composition, initial microstructure and heating rate. Almeida et al. (2010), Oliveira et al. (2007) and San Martin et al. (2008) studied the non-isothermal austenite formation in low carbon steels from an initial microstructure composed of ferrite and pearlite for different heating rates. Caballero et al.

(2001) provided a model for the kinetics of austenite formation in steels with different initial microstructures: pearlite, ferrite and ferrite + pearlite. Garcia de Andrés et al. (1998), Banerjee et al. (2009) and Zhao et al. (2002) have presented models of kinetics and dilatometric behavior of austenite formation during continuous heating.

The Johnson–Mehl–Avrami–Kolmogorov (JMAK) equation (Avrami, 1939; Johnson et al., 1939; Kolmogorov, 1937) is generally used to model transformations under isothermal conditions, however many authors have applied this equation to the study of austenite formation during continuous heating (Garcia de Andrés et al. 2002; Kop et al., 2001; Caballero et al., 2001; Zhao et al., 2002). The JMAK equation is expressed by:

$$f = 1 - \exp(-k \cdot t^n) \quad (1)$$

where f is the austenite volume fraction, t is the transformation time, K represents the influence of the heating rate on the nucleation and growth rates of austenite, and n is the exponent of the equation. The lever rule has been applied to estimate the volume fraction of austenite from dilatometric data on

continuous heating at a constant rate in low carbon steels. Those results have been compared with metallographic measurements and found to be in very good agreement (Almeida et al., 2010; San Martin et al., 2008; Mohanty et al., 2011).

This work analyzes the influence

of the heating rate on the kinetics austenite formation in the continuous heating of low carbon steel with initial microstructures composed of ferrite and pearlite, ferrite and martensite, and martensite, by using the JMAK equation and by means of dilatometric analysis.

2. Experimental Procedure

The chemical composition of the steel under investigation, expressed in wt.%, was 0.15C, 1.42Mn, 0.37Si, 0.052Al, 0.031Nb, 0.023P, 0.009S, 0.0042N, balanced Fe. Three initial microstructures were used: I) pearlite and ferrite (volume fraction of 0.73) (Figure 1a); II) ferrite and martensite (volume fraction of 0.35) (Figure 1b); III) martensite (Figure 1c). To yield in steel microstructures composed of ferrite and martensite an intercritical heat treatment was performed at 750°C for 30 min, followed by

quenching in an ice-cold water mixture. To produce a fully martensitic structure the austenitization was carried out at 1100°C for 30min, followed by quenching in an ice-cold water mixture. Nital-2% etching solution was used to reveal the microstructure by optical microscopy.

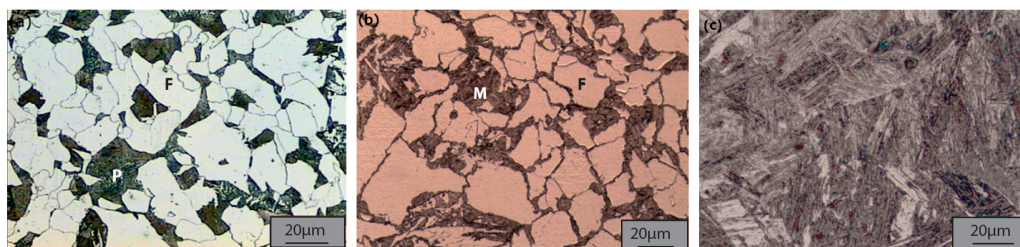
To evaluate the influence of heating rate and initial microstructure on the anisothermal formation of austenite, samples with different initial microstructures were heated at a constant rate ranging from 0.1 to 13°C/s in an Adamel-Lhomargy LK 02

quenching dilatometer. The details of the samples and critical temperatures determination have been presented elsewhere (Almeida et al., 2010).

The lever rule was applied to estimate the volume fraction of austenite from dilatometric data on continuous heating at a constant rate. Figure 2 shows, on a dilatometric curve, the application of the lever rule and the critical temperatures A_{c1} and A_{c3} are indicated in the figure, for the heating rate of 1°C/s and martensitic initial microstructure.

Figure 1.

Images of the initial microstructures obtained by optical microscopy: (a) ferrite (F) and pearlite (P), (b) ferrite (F) and martensite (M), (c) martensite. Nital 2% etchant.



3. Results and Discussion

The dilatometric curve as a function of temperature is presented in Figure 2 for the heating rate of 1°C/s and martensitic initial microstructure. The critical temperatures Ac_1 and Ac_3 are indicated in the figure. The changes in these temperatures with heating rate for the three initial microstructures are shown in Figure 3. One can observe the significant influence of the

heating rate on the critical temperatures, which rise as the heating rate increases. The effect is much more pronounced on the Ac_3 temperature independently of the initial microstructure. The Ac_1 temperature values increase significantly with the heating rate only at lower rates.

Figure 4 shows the austenite formation time as a function of the heating

rate for the three initial microstructures. This time decreases as the heating rate increases for the three microstructures. It is observed that the austenite formation time is greater for the martensitic initial microstructure (1390s) than for the initial microstructure composed of ferrite and pearlite (1150s), at the heating rate of 0.1°C/s. The value of austenite formation

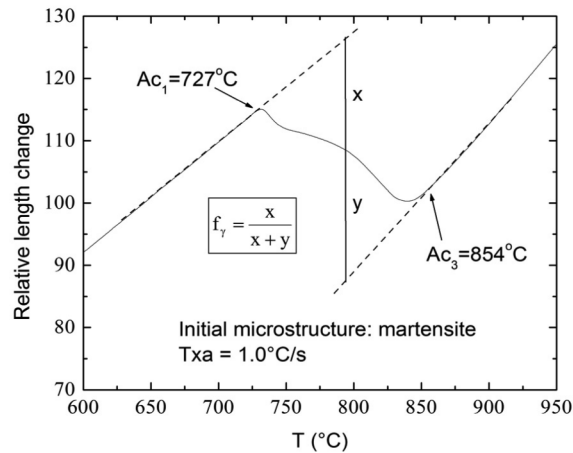


Figure 2.

Dilatometric curve for the heating rate of 1°C/s and martensitic initial microstructure. f_y is the volume fraction of austenite determined by lever rule, Ac_1 is the starting temperature of austenite formation and Ac_3 is the finishing temperature of austenite formation.

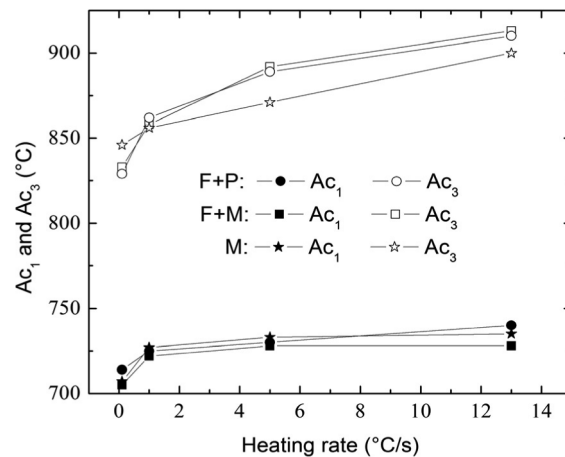


Figure 3.

Effect of heating rate on the Ac_1 and Ac_3 critical temperatures of the steel with different initial microstructures: M – martensite, F+M – ferrite and martensite, F+P – ferrite and pearlite.

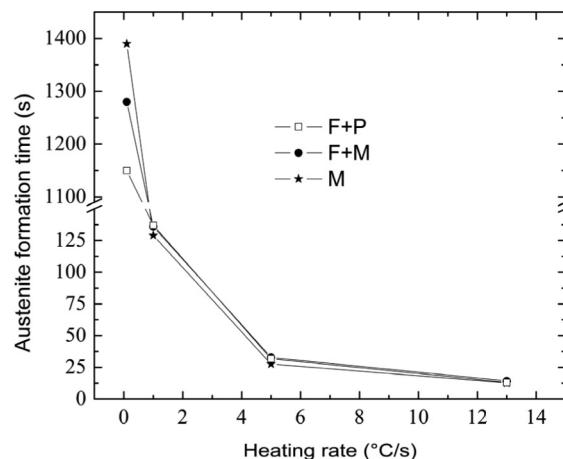


Figure 4.

Effect of heating rate on the transformation time of the steel with different initial microstructures: M – martensite, F+M – ferrite and martensite, F+P – ferrite and pearlite.

time is 1280s for an initial microstructure composed of ferrite and martensite at the same heating rate.

For martensitic initial microstructure, the heating that is necessary to induce the austenite formation may first lead to a tempering of the martensite and eventually to its decomposition into virtually carbon free ferrite and cementite or other carbide phases. It should be noted that when austenite forms from martensite in steels, tempering during continuous heating can make the reaustenitisation process identical to that for the ferrite and cementite starting microstructure (Krauss, 1990).

When martensitic initial microstructure is heated slowly, at a heating rate of 0.1°C/s , the tempering occurs on heating and this prolonged heating may also lead to the coarsening of cementite precipitates (Mohanty et al., 2011). It has been observed that austenite preferentially nucleates at the ferrite/cementite particle interface located on a ferrite grain boundary in the tempered martensite structure. Austenite soon envelops the cementite particle, and further growth is controlled by carbon diffusion in austenite. As time increases, the amount of austenite increases due to the ferrite to austenite transformation and cementite significantly decreases in size and density, indicating that austenite growth is accompanied by the dissolution of cementite particles

(Krauss, 1990; Miyamoto et al., 2007; Hillert et al., 1971; Speich et al., 1969; Miyamoto et al., 2010).

The characteristic of austenite formation of an initial microstructure consisting of ferrite and pearlite has been described in recent papers (Oliveira et al., 2007; Garcia de Andrés et al., 2002; Caballero et al., 2001; Garcia de Andrés et al., 1998). Those authors proposed that the nucleation of austenite inside pearlite takes place preferentially at the points of intersection of cementite with the edges of the pearlite colony. Austenite nuclei in pearlite grow when carbon atoms are transported through austenite by diffusion from the austenite/cementite boundary to the ferrite/austenite boundary and from the ferrite/cementite boundary through ferrite, resulting in a transformation of ferrite to austenite. The pearlite to austenite transformation is a rather rapid process and proceeds within a narrow temperature range. The ferrite to austenite transformation is a much slower process compared to the pearlite to austenite transformation. Recently, Li et al. (2009) have adopted a new approach to explain the austenite formation on pearlite by means of electron backscatter diffraction (EBSD). It was found that austenite preferentially nucleates at high-angle boundaries of pearlitic ferrite but not the colony boundary as considered previously.

The austenite growth rate along cementite lamellae is increased with the decreasing of interlamellar spacing because the effective diffusion distance decreases, as proved by Caballero et al. (2000).

The austenite formation from pearlite and ferrite in this steel is controlled by carbon diffusion, which is similar to the austenite formation from martensitic initial microstructure. The austenite formation time is greater for the martensitic initial microstructure than for the initial microstructure composed of ferrite and pearlite, at the heating rate of 0.1°C/s , due to the fact that the effective diffusion distance corresponding to the interspacing of cementite is greater in the tempered martensite than in the pearlite case (microstructure composed of pearlite and cementite).

On the other hand, in the case of heating rates higher than 0.1°C/s the tempering of martensite seems to occur, and it is observed in Figure 4 that kinetics of austenitization of a martensite structure is faster than that of pearlite+ferrite one. The austenite formation times from martensite are 129, 27.6 and 12.7s and from ferrite+perlite are 137, 31.8 and 13.1s at the heating rates of 1.0, 5.0 and 13°C/s , respectively.

Fig. 5 describes the evolution of the volume fraction of austenite as a function of the time for the heating rate of 0.1, 1.0,

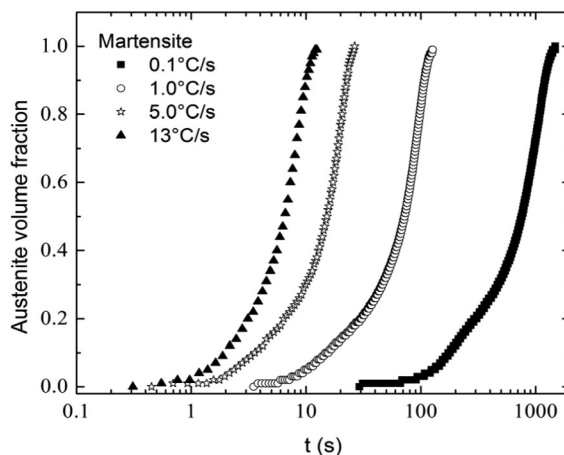


Figure 5.

Austenite volume fraction as function of the time for initial martensitic microstructure, for the four heating rates.

5.0 and 13°C/s for the initial martensitic microstructure.

Thus, during the austenite formation on isochronal heating, both the driving force and diffusion rate increase with temperature above the equilibrium transformation temperature, so that the rate of austenite formation continuously increases with temperature.

The austenite volume fraction as a function of time was fitted to the JMAK

equation (Equation 1) and the values of n and K determined are showed in Figure 6 and 7 for the three initial microstructures, respectively.

Figure 6 shows that values of n parameter are practically independent of the heating rate but are dependent on the initial microstructure. The values of n for an initial microstructure composed of ferrite and pearlite vary from 1.3 to 1.44 and these values are similar to the values

predicted by Oliveira et al. (2007) that determined the austenite volume fraction by means of metallographic analysis for the heating rates of 0.1 and 1.0°C/s and for the same steel. The values of n for an initial microstructure composed of martensite and ferrite+martensite vary from 1.65 to 1.87 and from 1.5 to 1.67, respectively.

Fig.7 shows that values of K increase as the heating rate increases for the three previous microstructures. The parameter

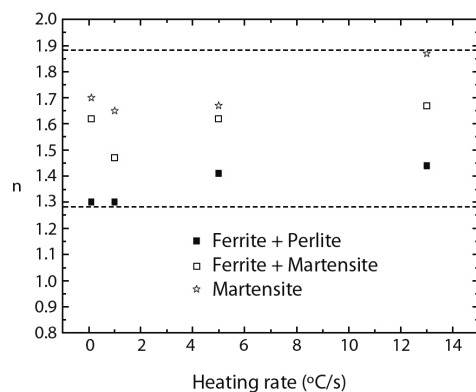


Figure 6.
Values of n (parameter of the JMAK equation) as a function of the heating rate for the three initial microstructures.

K represents the influence of the heating rate on the nucleation and growth rates of austenite, i.e. on the formation rate of austenite. A closer look into the parameters adjusted for the JMAK equation reveals that the K parameters associated with the austenitization kinetics are greater for the initial microstructure composed of ferrite and pearlite than for the martensitic initial microstructure, independent of the heating rate. For the heating rate of 0.1°C/s the values of K are: 1.2×10^{-5} (martensite), 2.23×10^{-5} (ferrite + martensite) and 25.1×10^{-5} (ferrite + pearlite).

Recently, Schmidt et al. (2006, 2007) studied the austenite formation from a ferrite-pearlite microstructure during continuous heating using hot-stage confocal microscopy and observed that at low heating rates the formation of austenite is controlled by the long-range diffusion of carbon. However, at higher

heating rates under certain conditions (above the T_0 temperature: the temperature at which two phases, with identical compositions, have the same free energy and can exist at metastable equilibrium at an interface) the growth rate increased drastically and the interface-controlled reaction growth mechanism was claimed to be responsible for the transformation. Thus, results appear to suggest that assuming long-range diffusion of carbon to be determining for different heating conditions might not be accurate and a change from diffusion-controlled to interface-controlled transformation can be expected during austenitization of steels with a pearlite-ferrite microstructure. The conservative motion of the interface under partitionless conditions (the interface reaction-controlled growth) will result in a formation of austenite with lower (than equilibrium) carbon content.

It can be supposed for initial microstructure composed of ferrite and pearlite that the growth rate of austenite is primarily an interface-controlled transformation for the heating rates greater than 5.0°C/s , due to higher K parameter (smaller transformation time). Conversely, at heating rates of 0.1 and 1.0°C/s the growth rate of austenite may be assumed to be controlled by volume diffusion of carbon in austenite.

In relation to the martensite to austenite transformation in low carbon steels at high heating rates, the authors believe that the martensite structure is slightly tempered and the mechanism of austenite formation should be diffusion-controlled and its nucleation occurs between the laths of martensite. The growth rate of austenite is greater at the higher heating rates, due to higher K parameter (smaller transformation time).

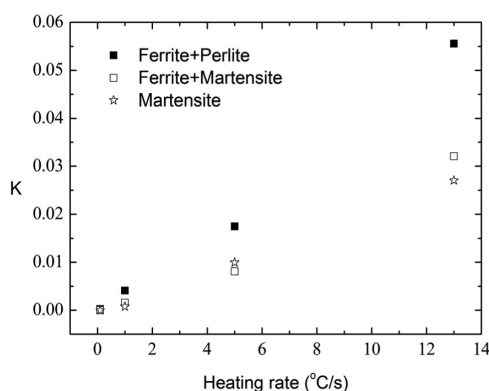


Figure 7.
Values of K (parameter of the JMAK equation) as a function of the heating rate for the three initial microstructures.

4. Conclusions

1. The kinetics of austenitization from pearlite+ferrite is faster than that from martensite (tempered martensite) at a heating rate of 0.1°C/s . For heating rates higher than 0.1°C/s , the kinetics of austenitization of a martensite (tempered martensite) structure is faster than of pearlite+ferrite one.

2. The values of n of the JMAK

equation for an initial microstructure composed of pearlite+ferrite, martensite and ferrite+martensite vary from 1.3 to 1.44, from 1.65 to 1.87 and from 1.5 to 1.67, respectively.

3. The parameter K of the JMAK equation increases as the heating rate increases for the three previous microstructures and is greater for the initial mi-

crostructure composed of ferrite+pearlite than for the martensitic initial microstructure, independent of the heating rate.

4. At lower heating rates, the formation of austenite in this steel is controlled by carbon diffusion, from initial microstructures composed by pearlite+ferrite, ferrite+martensite and martensite. In particular, at higher heating

rates, the formation of austenite from an initial microstructure composed of pearlite+ferrite must be an interface-controlled transformation.

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