ISOTHERMAL ALLOTRIOMORPHIC FERRITE FORMATION KINETICS IN A MEDIUM CARBON VANADIUM-TITANIUM MICROALLOYED STEEL

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Introduction

A great number of attempts, from purely empirical to semi-empirical models, have been made to predict the kinetics of ferrite transformation [1, 2]. However, models recently developed are becoming less empirical since they rely on thermodynamic and phase transformation theories [3]. Unemoto *et al.* [4] developed a methodology to simulate the allotriomorphic ferrite transformation under isothermal conditions. Reed and Bhadeshia [5] reported a thermodynamic model couple with a simplified kinetic theory. This model can reproduce the C-curve behavior typical of those parts of the time-temperature-transformation diagrams that are due to allotriomorphic ferrite in low-carbon multicomponent steel. In principle, most of these models are able to predict the kinetics of allotriomorphic ferrite for low-carbon low-alloy steels. But, the level of agreement between predicted and calculated allotriomorphic ferrite kinetics is less satisfactory for medium carbon microalloyed steels.

On the other hand, several authors have reported the role of acicular ferrite in the improvement of mechanical properties in medium carbon forging steels [6, 7, 8]. Likewise, recent works have studied the role of the allotriomorphic ferrite to promote the formation of acicular ferrite to the detriment of bainite [9, 10, 11, 12]. Thus, the amount of acicular ferrite increases, as allotriomorphic ferrite is present along the austenite grain boundaries of medium carbon microalloyed steels. Therefore, a deep understanding of the decomposition of austenite in allotriomorphic ferrite is needed in order to control the total amount of acicular ferrite present in the microstructure.

The present paper is concerned with the theoretical and experimental description of the growth kinetics of allotriomorphic ferrite in medium carbon vanadium-titanium microalloyed steel. The theoretical model presented in this work allows to calculate the kinetics of isothermal austenite-to-allotriomorphic ferrite transformation at temperatures at which allotriomorphic ferrite might not be the only austenite decomposition product.

Materials and Experimental Procedure

The chemical composition of the steel studied is presented in Table 1. The material was supplied in the form of 50 mm square bars, obtained by conventional casting as a square ingot (2500 kg) and hot rolling to bar.

The isothermal decomposition of austenite has been analyzed by means of a high resolution dilatometer DT 1000 Adamel-Lhomargy described elsewhere [13]. Cylindrical dilatometric specimens of 2 mm in diameter and 12 mm in length were machined parallel to the rolling direction of the bar, were used for these tests. The change in length of the specimen is transmitted via amorphous silica push-rod. This variation is measured by a linear

variable differential transformer (LVDT) sensor in a gas-tight enclosure enabling testing under vacuum or an inert atmosphere with an accuracy lower than 0.1 μm. The dilatometric curve (relative change in length (dL/L_o) vs. time (t)) is monitored with the help of a computer assisted electronic device. The dilatometer is equipped with a very low thermal inertia radiation furnace for heating. The heat radiated by two tungsten filament lamps is focussed on the specimen by means of a bi-elliptical reflector. The temperature is measured with a 0.1 mm diameter Chromel – Alumel (Type K) thermocouple welded to the specimen. Cooling is carried out by blowing a jet of helium gas directly onto the specimen surface. The helium flow-rate during cooling is controlled by a proportional servovalve. Heating and cooling devices of this dilatometer ensure an excellent efficiency in controlling the temperature and holding time of isothermal treatments, and fast cooling in quenching processes.
With the aim of studying the influence of austenitisation temperature on the austenite-to-allotriomorphic ferrite transformation, specimens were austenitised at two different temperatures (1273 K and 1523 K) for 1 min and subsequently isothermally transformed at 873 K during different times. Finally, specimens were quenched under helium gas flow at a cooling rate of 200 K/s. Specimens were ground and polished using standardized metallographic techniques. 2pct-Nital etching solution was used to reveal the ferrite microstructure by optical microscopy. The prior austenite grain size (*PAGS*) measurements were made on micrographs. The average grain size was calculated by using a linear intercept technique involving at least 50 intercepts, permitting the count of the number of grains intercepted by the grid line. The effects of a moderately non-equiaxial structure may be eliminated by counting the intersections of lines in four or more orientations covering all the observation fields with an approximately equal weight [14]. Table 2 shows the average *PAGS* in microns corresponding to both austenitisation conditions.

Finally, the formed volume fraction of allotriomorphic ferrite (V_α) was estimated statistically by a systematic manual point counting procedure [14]. A grid superimposed on recorded micrographs provides, after a suitable number of placements, an unbiased statistical estimation of the V_α.

Table 1
Chemical composition (wt - %)

C	Si	Mn	Cr	Al	Ti	V	Cu	Mo
0.37	0.56	1.45	0.04	0.024	0.015	0.11	0.14	0.025

Table 2
Prior austenite grain size

T_γ (K)	*PAGS* (μm)
1523	76
1273	11

T_γ= Austenitising temperature

Results and Discussion

Ferrite which grows by diffusional mechanism can be classified into two main forms: allotriomorphic ferrite and idiomorphic ferrite [15]. Allotriomorphic ferrite which nucleates at prior austenite grain boundaries tends to grow faster along austenite boundaries than in a direction normal to the boundary plane. By contrast, idiomorphic ferrite usually forms intragranularly presumably at inclusions [15]. The maximum amount of ferrite (allotriomorphic + idiomorphic) that could be obtained by isothermal decomposition of austenite only depends on temperature and chemical composition of the steel [16.

The equilibrium volume fraction of allotriomorphic ferrite (V_e) formed during the isothermal decomposition of austenite at a given temperature tested was determined by a combination of dilatometric and metallographic analysis. When the relative change in length vs. time curve reaches saturation (no further dilatation due to transformation is observed), the isothermal decomposition of austenite is completed and that time represents approximately the minimum holding time needed to reach the equilibrium volume fraction of allotriomorphic ferrite V_e. Since dilatometric examination do not discriminate between allotriomorphic and idiomorphic ferrite transformation, subsequent metallographic examination of microstructures obtained by quenching of specimens isothermally treated at different holding times, allows to perform an accurate determination of V_e. The experimental V_e value obtained after isothermal decomposition of austenite at 873 K was 24% for a *PAGS* of 11 μm and 18% for a *PAGS* of 76 μm. This result is consistent with the fact that as *PAGS* increases, intragranular nucleation of ferrite becomes more favorable than grain boundary nucleation.

The experimental determination of allotriomorphic ferrite incubation time (τ) has been also carried out by dilatometric and metallographic analysis. The incubation time of allotriomorphic ferrite is defined as the minimum time at which it is possible to find some allotriomorphs nucleated on the austenite grain boundary. A detailed analysis of the dilatometric curve associated to the isothermal decomposition of austenite (Fig. 1) allows to determine an interval of time, Δt, in which it is more likely to find the incubation time value. With the aim of carrying out an accurate determination of τ, samples were isothermally treated at different holding times within the Δt interval and immediately quenched. Metallographic analysis of those samples led to find a τ determined the incubation time at which some allotriomorphs appear in the microstructure. The value of τ = 5 s at 873 K. The *PAGS* parameter directly affects the growth kinetics of allotriomorphic ferrite obtained by isothermal decomposition of the austenite. But, there is no influence on the nucleation time of this phase [17 18].

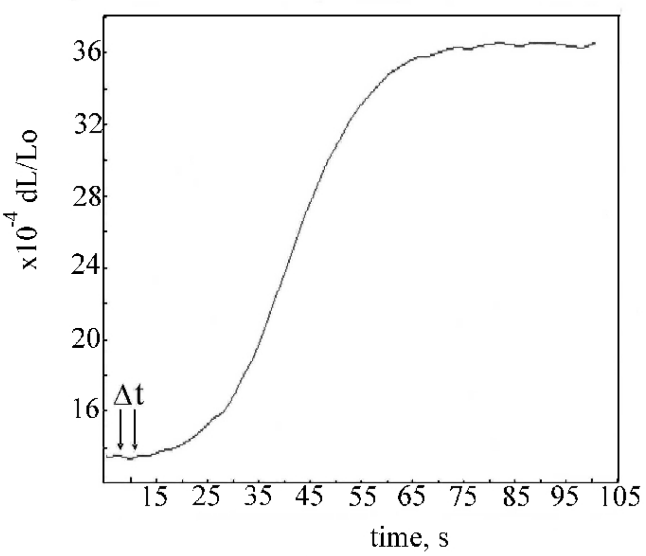


Figure 1. Dilatometric curve obtained during isothermal decomposition of austenite at 873 K for 100 s for the studied steel (PAGS=76 μm).

At temperature of 873 K, lower than the critical temperature Ae_1 of this steel, pearlite is formed after allotriomorphic ferrite transformation is completed. Since pearlite formation, the carbon enrichment of austenite, due to previous ferrite formation,, is avoided and carbon concentration in austenite far from the α/γ interface remains the same as the overall carbon content of the steel. Hence, soft-impingement effect caused by allotriomorphs growing from opposite sites of austenite grains should be neglected [19]. Therefore, allotriomorphic ferrite can be considered to grow under a parabolic law, and the assumption of a semi-infinite extent austenite with constant boundary conditions is suitable for the kinetics of the isothermal decomposition of austenite at temperatures below eutectoid temperature (Ae_1).

Bhadeshia et al. [20] describe a theory which is able to model the nucleation and growth of allotriomorphic ferrite. The allotriomorphs, before site saturation, are considered as discs having their faces parallel to the austenite grain boundary plane. The discs are assumed to grow radially, and the half thickness Z and radius ηZ, being η the aspect ratio of the allotriomorphs, varies parabolically with time, through the equation

$$Z = \alpha_1 t^{1/2} \tag{1}$$

where α_1 is the one – dimensional parabolic growth rate constant and t represents the growth time. The aspect ratio η of the allotriomorphs is considered constant, because the lengthening and thickening processes are actually coupled. Consistent with experimental evidences [21], η is assume to have a value of 3. The value of α_1 can be obtained by numerical solution from the equation [22],

$$\alpha_1 exp\left(\frac{\alpha_1^2}{4D_C^\gamma}\right)\mathrm{erfc}\left(\frac{\alpha_1}{2\sqrt{D_C^\gamma}}\right) = 2\left(\frac{D_C^\gamma}{\pi}\right)^{1/2}\frac{\overline{C} - C^{\gamma\alpha}}{C^{\gamma\alpha} - C^{\alpha\gamma}} \tag{2}$$

where D_C^{γ} is the diffusivity of carbon in austenite, $\overline{C}$ is the overall carbon content, $C^{\gamma\alpha}$ is the austenite solute content at the interface, and $C^{\alpha\gamma}$ is the ferrite solute content at the interface. According to Bhadeshia [23], the consideration of *paraequilibrium* is a good approach to the modeling of the kinetics of this transformation. In that case, partitioning of substitutional solute atoms is not able to occur and the adjoining phases have identical X/Fe atom ratios, where X represents the substitutional solute elements. The substitutional atoms remain configurationally frozen, but interstitial solutes such as carbon are able to partition and attain equilibration of chemical potential in both phases. Hence, the values of $C^{\gamma\alpha}$ and $C^{\alpha\gamma}$ in Eqn. (2) refer to carbon concentrations, and they were calculated according to the procedure reported by Shiflet *et al.* [24]. $C^{\gamma\alpha}$ and $C^{\alpha\gamma}$ values as well as α_1 values are listed in Table 3.

Table 3
Calculated values of $C^{\alpha\gamma}$, $C^{\gamma\alpha}$ and α_1

T, K	$C^{\alpha\gamma}$, wt. %	$C^{\gamma\alpha}$, wt. %	$\alpha_1 \times 10^{-7}$, m s$^{-1/2}$
873	0.016	1.195	4.76

On the other hand, Reed and Bhadeshia [5] presented a theory that closely follows Cahn's analysis [25] for grain boundary nucleation and growth kinetics. To determine the formed volume fraction of allotriomorphic ferrite (V_α), they considered a series of arbitrary planes parallel to the boundary and spaced a distance y apart. If the half thickness of the particle (Z) exceeds the distance y then the area of intersection with the plane can be obtained. Thus, V_α is determined evaluating the total of such areas of intersection for all the particles growing from the boundary. Moreover, no allowance have been made for the overlap of regions emanating from different regions of the boundary. They proposed the following equation to describe the evolution of V_α with time ($t>\tau$) during the isothermal decomposition of austenite

$$V_\alpha = V_e\left[1 - \exp\left(-\frac{2S_V\alpha_1(t-\tau)^{1/2} f(\eta\alpha_1,I,t)}{\Phi}\right)\right] \tag{3}$$

where t is the isothermal holding time; τ is the incubation time; S_V is the austenite grain surface per unit volume; I is the classical nucleation rate on grain boundary per unit area, and Φ is the supersaturation in carbon which can be estimated from the phase diagram as follows

$$\Phi = \frac{\overline{C} - C^{\gamma\alpha}}{C^{\alpha\gamma} - C^{\alpha\gamma}} \tag{4}$$

The process of nucleation is taking into account in Eqn. (3) by means of the expression $f(\eta\alpha_1,I,t)$, which takes values between 0 and 1. A value of $f(\eta\alpha_1,I,t) = 0$ means that nucleation has not started. By contrast, a value of $f(\eta\alpha_1,I,t) = 1$ means that saturation of nucleation sites has been reached. The expression for $f(\eta\alpha_1,I,t)$ is [5]

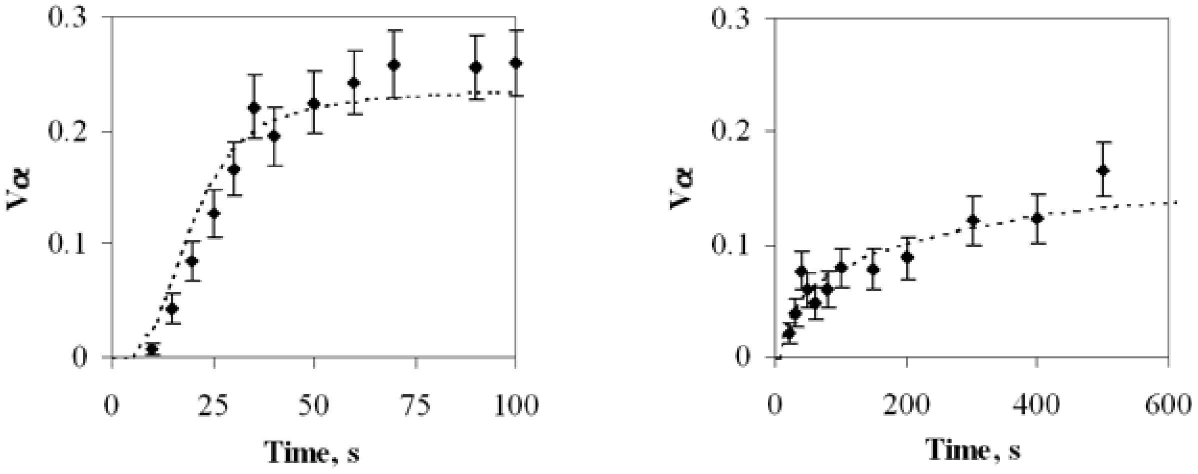
$$f(\eta\alpha_1,I,t) = \int_0^1 1 - \exp\left\{-0.5\pi I(\eta\alpha_1)^2 t^2\left[1-\theta^4\right]\right\} d\theta \tag{5}$$

where $\theta = y/(\alpha_1 t^{1/2})$ corresponding to the ratio between the distance to the arbitrary plane and the half thickness of the allotriomorph at time t. The nucleation rate (I) has been calculated according to Reed and Bhadeshia [5] taking into account the chemical composition of the studied steel, and its values for a temperature of 873 K is 6.3×10^{8} (m^{-2} s^{-1}). The value of the expression $f(\eta\alpha_1,I,t)$ tends to unity when the saturation of the nucleation sites in the austenite grain boundary is reached. Assuming that austenite grains have a tetrakaidecahedra geometry, S_V in Eqn. (3) can be expressed in terms of the average austenite grain diameter d_γ by [5],

$$S_V = \frac{3.35}{d_\gamma} \tag{6}$$

with d$_g$in microns. Figure 2 shows the experimental and predicted evolution of V_a during the isothermal decomposition of austenite at 873 K for both *PAGS* studied. This figure suggests that the time required to reach V_e increases as PAGS increases. Likewise, the total amount of allotriomorphic ferrite decrease as PAGS increase. A comparison between those V_a values is shown in Fig. 3. One can concluded from this figure that a good agreement (94% in R^2) between experiment and theory exists in the calculations. Therefore, allotriomorphic ferrite growth under a parabolic law and a semi-infinite extent austenite with constant boundary conditions are reasonable assumptions.

Figure 4 illustrate the evolution of the nucleation function (the expression $f(ha_1,I,t)$ in Eqn. (5)) with the homologous time (a ratio between time and the total time need to reach the equilibrium volume fraction of allotriomorphic ferrite). This figure shows that the time required to saturate the total number of sites available for allotriomorphic ferrite nucleation ($f(ha_1,I,t) = 1$) is almost the 75 % of the transformation time for a *PAGS* of 11 mm. By contrast, for a *PAGS* of 76 mm this time is almost negligible. Therefore, for a coarse austenite grain size, the time necessary to saturate the austenite boundaries is so small that the formation of the majority of ferrite essentially involves the diffusional thickening of layers of grain boundary ferrite. Hence, it is a reasonable approach to consider this transformation mainly in terms of growth for modeling of isothermal austenite decomposition of austenite in allotriomorphic ferrite.



(a) (b)

Figure 2. Comparison between measured and calculated V_a values during the isothermal decomposition of austenite at 873 K for both studied *PAGS* (a) 11 mm, and (b) 76 mm.

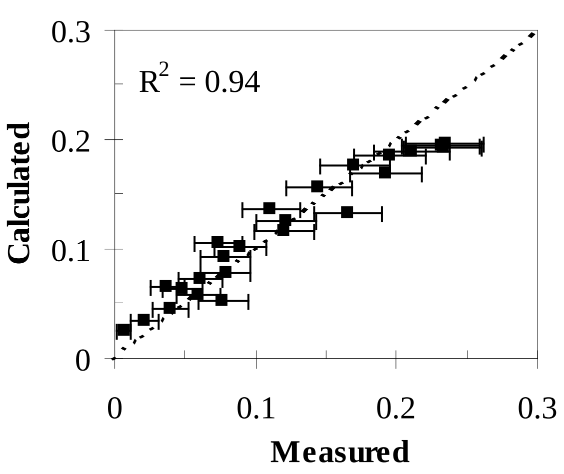


Figure 3. A comparison of the experimental and predicted ferrite volume fraction formed at a temperature of 873 K.

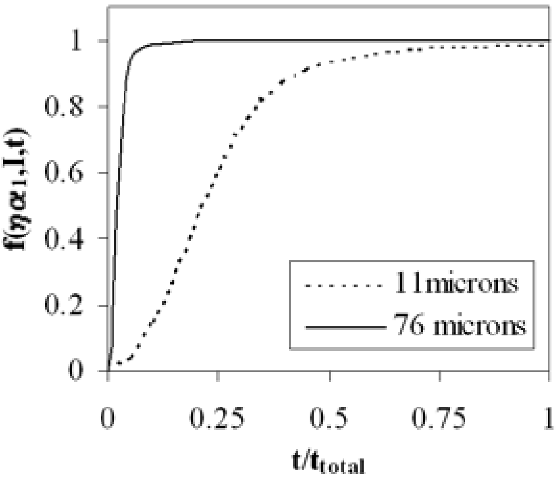


Figure 4. Fraction of the total transformation time needed for site saturation for both PAGS studied.

Conclusions

1. A mathematical model proposed by Reed and Bhadeshia has been used to calculate the evolution of V_a during the isothermal decomposition of austenite in allotriomorphic ferrite at temperatures below eutectoid temperature Ae_1 for a 0.37C–1.45Mn–0.11V (in wt-%) microalloyed steel with two very different *PAGSs*.
2. Due to the excellent agreement between experimental and calculated results, the consideration of the soft-impingement effect as negligible is a reasonable assumption for modeling the isothermal decomposition of austenite in allotriomorphic ferrite at temperatures below Ae_1.
3. Since for a coarse *PAGS* the time required to complete the transformation is much longer than that needed for the saturation of nucleation sites in the austenite grain boundary, it is a sensible approach to consider the formation of allotriomorphic ferrite during the isothermal decomposition of austenite essentially in terms of growth.

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