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EFFECT OF CEMENTITE PRECIPITATION ON THE EXTEND OF BAINITE TRANSFORMATION IN Fe-Cr-C STEEL

ABSTRACT

Analytical calculations and experimental measurements of volume fraction of bainitic ferrite and volume of the untransformed austenite indicate that there is a necessity of carbides precipitation. A consequence of the precipitation of cementite during austempering is that the growth of bainitic ferrite can continue to larger extent and that the resulting microstructure is not an ausferrite but it is a mixture of bainitic ferrite, retained austenite and carbides.

Key words: *carbon diffusion, decarburization, bainite transformation*

INTRODUCTION

The development of high strength bainitic steels without carbides is a great achievement in steel technology. The attractive properties of bainitic steels without carbides are related to its unique microstructure that consists of ferrite and high carbon austenite. Because of this microstructure, the product of bainitic reaction is often referred to as “ausferrite” rather than bainite [1, 2]. The mixture of bainitic ferrite and untransformed austenite is an ideal combination from many points of view. If the bainitic ferrite-austenite microstructure is held for long time periods, the blocks of high carbon austenite will eventually undergo a transformation to bainite, the two phase ferrite and carbide ($\alpha + \text{Fe}_3\text{C}$). Carbides can be suppressed by alloying with elements such as Si and Al. Once the ausferrite has been produced, the components are cooled to room temperature. The cooling rate will not affect the final microstructure as the carbon content of the austenite is high enough to lower the martensite start temperature to a temperature significantly below room temperature.

The purpose of the present paper is to demonstrate how the precipitation of cementite from ferrite or/and austenite in Fe-Cr-C steel may influence the extent of bainite reaction.

MATERIAL AND EXPERIMENTAL PROCEDURES

The chemical composition of the experimental steel is listed in Table 1.

Table 1. Chemical composition and calculated B_s and M_s temperatures of the steel, wt. %

Steel	C	Si	Mn	P	S	Cr	Ni	B_s , °C	M_s , °C
Fe-0.38C-0.93Cr	0.38	0.29	0.63	0.01	0.025	0.93	0.11	505	320

*The B_s and M_s temperatures are calculated by using methods developed by Bhadeshia [7,8]

Lattice parameter measurements were carried out using a X-ray diffractometer with Fe-filtered CoK_α radiation. The precision ferrite lattice parameter determination included a knowledge of the angular positions of the (110), (200), (211) and (220) peaks. The data were analysed using a Taylor-Sinclair function to extrapolate the values of the ferrite parameter to angular position of $\Theta = 90^\circ$.

A high-speed Adamel Lhomargy LK-02 dilatometer was used to establish change of length ($\Delta L/L$) during isothermal bainitic transformation. In order to ensure rapid cooling ($\sim 300\text{Ks}^{-1}$) from austenitising temperature (1000°C , 10 minutes), the specimens were 13mm in length and 1.1mm in diameter.

The linear expansion coefficient of ferrite (e_α) was determined by annealing a specimen at 650°C for 30 minutes to decompose any retained austenite and then recording the change of length during slow cooling. The linear expansion coefficient of austenite (e_γ) was measured after cooling from temperature of 1100°C while the specimen was in the single γ phase field. Determination of the linear expansion coefficients was carried out in a UBD Leitz-Wetzlar dilatometer.

The dilatometry results show that the relative length change during the formation of bainite increases as the isothermal transformation temperature decreases below the B_s temperature, then the amount of bainite formed is dependent on the transformation temperature.

Lattice parameters, expansion coefficients of ferrite and austenite and parameters for determination of volume fractions of transformation and the carbon concentration of the residual austenite in Fe-Cr-C steel are listed in Tables 2 and 3.

Table 2. Lattice parameters at ambient temperature (25°C) and expansion coefficients of ferrite and austenite in Fe-0.38C-0.93Cr steel

Steel	Lattice parameter of ferrite $a_{0\alpha}$, nm	Lattice parameter of austenite $a_{0\gamma}$, nm	Ferrite e_α , $^\circ\text{C}^{-1} \times 10^{-5}$	Austenite e_γ , $^\circ\text{C}^{-1} \times 10^{-5}$
Fe-0.38C-0.93Cr	0.2868 0.2869 *	0.35919	1.512	2.419

* The ferrite lattice parameters determined using a X-ray diffractometer

The thermal expansion coefficients for ferrite and austenite are taken according to the dilatation curve.

Table 3. Parameters for determination of volume fractions of bainite (V_B) and the carbon concentration of the residual austenite (x^γ) in Fe-0.38C-0.93Cr steel

Transformed at, °C	a_γ nm	a_α nm	$\Delta L/L$ $\times 10^{-3}$ *	V_B	$V_{BT_o'}$	x^γ , mole
491	0.36324	0.28882	1.154	0.64	0.15	0.04421
443	0.36282	0.28861	1.346	0.61	0.31	0.04104
398	0.36243	0.28842	1.461	0.56	0.44	0.03668
359	0.36209	0.28825	1.846	0.62	0.53	0.04198
324	0.36178	0.28809	2.115	0.68	0.59	0.04919

* Values of the dimensional changes accompanying the transformation of austenite to bainitic ferrite measured at transformation temperature,

V_B Measured volume fraction of transformation,

$V_{BT_o'}$ Analytical evaluation of volume fraction of transformation for $x_{T_o'}$ carbon concentration

PHASE DIAGRAM OF AUSTEMPERED Fe-Cr-C STEEL

The determined carbon concentrations of the residual austenite at the different temperatures of transformation of bainite (Table 4) are compared with the T_0 , T_0' and A'_3 phase boundaries for investigated steel in Fig. 1.

Table 4. Calculated details for phase diagram of Fe-0.38C-0.93Cr steel at selected temperatures of isothermal transformation

Temperature, °C	A'_3 mole	x_{T_0} mole	$x_{T_0'}$ mole
491	0.1004	0.0302	0.0201
443	0.1170	0.0365	0.0247
398	0.1312	0.0421	0.0299
359	0.1442	0.0479	0.0352
324	0.1561	0.0540	0.0406

A'_3 - the paraequilibrium carbon concentration of austenite in mole fraction ($A'_3 - x^{\gamma\alpha}$),

x_{T_0} - the T-zero carbon concentration in mole fraction,

$x_{T_0'}$ - the same but allowing for 400J/mol of stored energy in the ferrite

The diagram was calculated as in Ref. [3-6] using a model developed by Bhadeshia [7, 8] based on the McLellan and Dunn quasi-chemical thermodynamic model [9, 10]. The martensite and bainite reaction starts temperatures, M_S and B_S are also marked on this diagram. The paraequilibrium phase boundary is chosen because no substitutional alloying element partitioning occurs during bainite formation.

It is usually assumed that the point where the microstructure of austempered steel ceases to change represents full transformation. But in case of bainitic transformation, reaction ceases before the parent phase (austenite) has completely transformed. It means that at any

temperature below B_s and in the absence of any interfering secondary reactions only a limited quantity of bainitic ferrite forms before the reaction terminates.

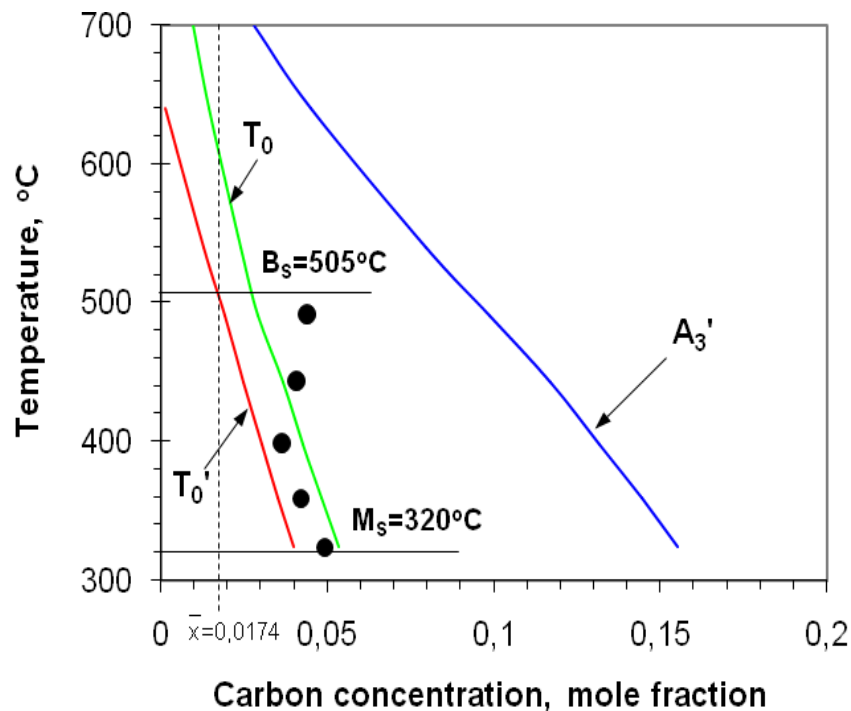


Fig. 1. The calculated phase boundaries A_3' , T_0 and T_0' for the investigated Fe-0.38C-0.93Cr steel together with all the experimental data of the measured carbon contents of the untransformed austenite (black circles)

In presented diagram the reaction at temperatures 324, 359 and 398 °C is found to stop when the average carbon concentration of the residual austenite is closer to the T_0 , T_0' curves than the A_3' boundary. The maximum extent to which the bainite reaction can proceed is therefore determined by the composition of the residual austenite.

Thus, it is found experimentally that the transformation to lower bainite in Fe-Cr-C steel does indeed stop close to the T_0' boundary (Fig. 1). Similar results have previously obtained by Bhadeshia and Christian for other alloys [11, 12].

In Fig. 1 the reaction to upper bainite at 443 and 491 °C seems to stop when carbon concentration of austenite exceeds the T_0' boundary. This might be explained by the fact that the T_0' line accounts for 400 J/mol of stored energy in the bainite. If this energy is reduced by plastic deformation of the surrounding austenite then a higher volume fraction of bainite should be able to form. Furthermore, the measured carbon contents of the austenite after reaction to upper bainite at 443 and 491 °C may indicate on the possibility of cementite precipitation from austenite or ferrite.

When the microstructure of Fe-Cr-C steel consists of ausferrite, thus:

$$V_\gamma + V_\alpha = 1 \quad (1)$$

and the permitted fraction of bainite (V_α) can be determined from Lever rule applied to the T_0 curve, Fig. 2. The maximum volume fraction of retained austenite (V_γ) will then equal $1 - V_\alpha$.

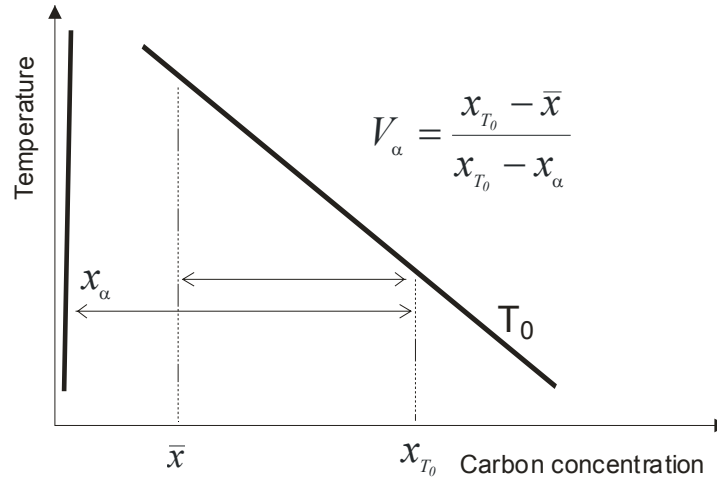


Fig. 2. Application of the Lever-rule to the T_0 curve allows the estimation of the permitted fraction of bainite V_α at any temperature

In case of carbides precipitation the maximum volume fraction of bainitic ferrite (V_α) can be calculated using the following equation [12]:

$$V_\alpha = \frac{x_{T'_0} - \bar{x}}{x_{T'_0} - x_\alpha - x_C} \quad (2)$$

where V_α is volume fraction of bainitic ferrite, \bar{x} is the average carbon concentration in the matrix of the alloy, x_α is the paraequilibrium carbon concentration in the bainitic ferrite (0.03 wt. %), $x_{T'_0}$ is the carbon concentration of the austenite corresponding to the T'_0 curve, x_C is the amount of carbon, which is tied up as carbides (cementite).

Thus, the maximum volume fraction of bainite taking into account cementite precipitation can be calculated using the relationship (2), see Fig. 3.

Austenite is supersaturated with respect to cementite precipitation when $x_\gamma > x^{\gamma\theta}$, where $x^{\gamma\theta}$ denotes carbon concentration at the extrapolated A_{cm} boundary. This means for the bainite reaction, that $x_{T_0} > x^{\gamma\theta}$ since the growth of bainitic ferrite stops when x_γ reaches the value x_{T_0} given by the T_0 curve of the phase diagram. A consequence of the precipitation of cementite from austenite is that its carbon concentration drops below x_{T_0} , so that the growth of bainitic ferrite can continue to an extent larger than would be otherwise possible (see Fig. 1).

It is seen in Fig. 3 that precipitation of cementite leads to an increase of volume fraction of bainitic ferrite. Carbides locally reduce the carbon content of the parent austenite and increase the driving force for further ferrite growth. A consequence of the precipitation of cementite from austenite is that its carbon concentration drops below x_{T_0} , so that the growth of bainitic ferrite can continue to an extent larger than would be otherwise possible.

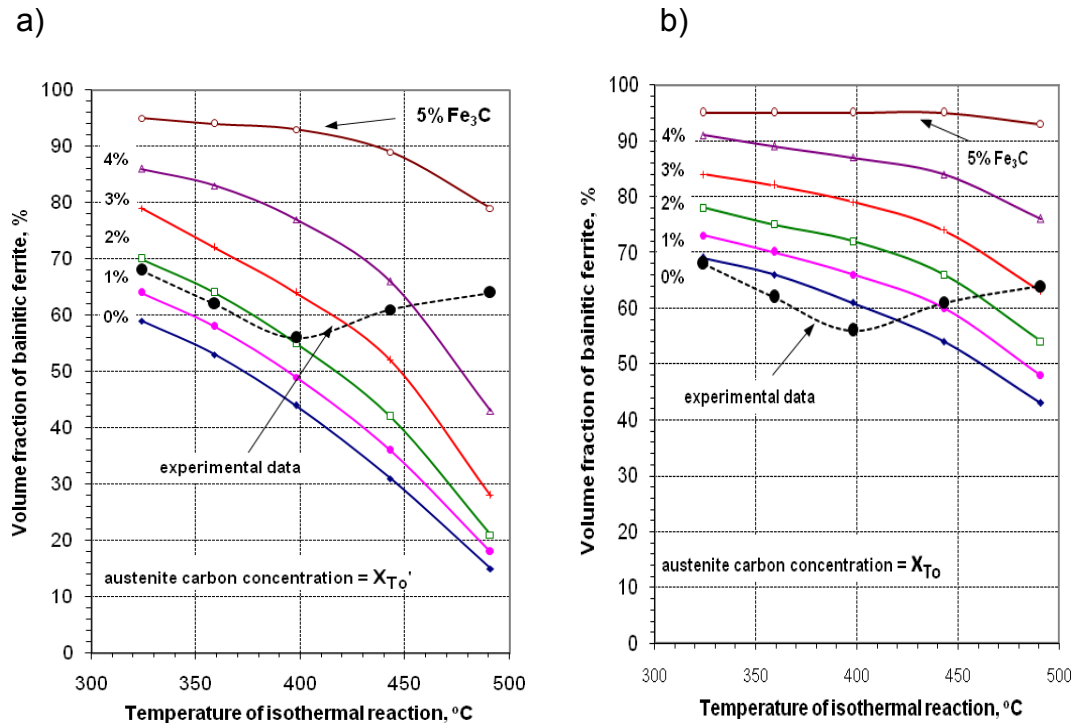


Fig. 3. Experimentally determined and calculated the maximum volume fraction of bainite in investigated Fe-0.38C-0.93Cr steel taking into account cementite precipitation in the range from 0% to 5 wt. % Fe_3C . Austenite carbon concentration at the cessation of bainite reaction,

a) $x_T = X_{T_0}'$, b) $x_T = X_{T_0}$

CONCLUSIONS

The paper presents an investigation of the cementite precipitation on the extend of bainite transformation in Fe-0.38C-0.93Cr steel. The following conclusions were reached:

1. Precipitation of cementite leads to an increase of volume fraction of bainitic ferrite. Carbides locally reduce the carbon content of the parent austenite and increase the driving force for further ferrite growth.
2. A consequence of the precipitation of cementite from ferrite or/and austenite during bainite reaction is that the resulting microstructure is not a pure ausferrite but is a mixture of bainitic ferrite, retained austenite and carbides.
3. The carbon concentration of the residual austenite reaches the critical value represented by the T_0 curve and renders the displacive bainite reaction to cease. This is because the austenite can only transform to bainite if its carbon concentration is less than a value x_{T_0} given by the T_0 curve.

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