



INFLUENCE OF CEMENTITE PRECIPITATION ON THE EXTENT OF BAINITE REACTION IN Fe-Cr-Si-C STEEL

Zdzisław Ławrynowicz

*University of Technology and Life Sciences in Bydgoszcz, Mechanical Engineering Faculty
Department of Materials Science and Engineering,
av. Kaliskiego 7, 85-789 Bydgoszcz, Poland
e-mail address: lawry@utp.edu.pl*

Abstract

The paper presents an investigation of the extend of bainite reaction in the case of cementite precipitation. Experimental measurements of volume fraction of bainitic ferrite and volume of the untransformed austenite indicate that there is a necessity of carbides precipitation from austenite. Carbon concentration in the residual austenite was calculated using volume fraction data of austenite and a model developed by Bhadeshia based on the McLellan and Dunn quasi-chemical thermodynamic model. The comparison of experimental data with the T_0 , T_0' and A_3' phase boundaries suggests the likely mechanism of bainite reaction in Fe-Cr-Si-C steel is displacive rather than diffusional. A consequence of the precipitation of cementite from austenite 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.

Keywords: *bainite transformation, carbide precipitation, carbon diffusion*

1. Introduction

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 [5,11,12]. 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 a thermodynamic method can be used for determination of the carbon concentration in the retained austenite in Fe-Cr-Si-C steel. The method takes into consideration the precipitation of cementite from ferrite or/and austenite during bainite reaction.

2. Experimental procedures

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. Lattice parameter measurements were carried out using a X-ray diffractometer with Fe-filtered $\text{CoK}\alpha$ 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 $\Theta = 90^\circ$.

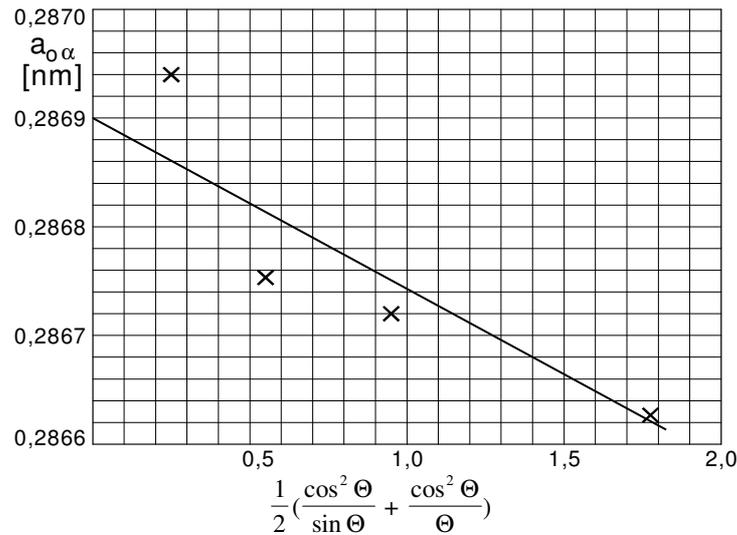


Fig. 1. Extrapolated parameter of ferrite $a_{0\alpha}$ in Fe-Cr-Si-C steel using extrapolation function of Taylor-Sinclair

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

Tab. 1. Chemical composition of the steel used in this study. All concentrations are given in wt.% and at.% ($\times 10^2$)

| Steel | | C | Si | Cr | Mn | Ni | P | S |
|------------|-----------------------|------|------|------|------|------|-------|-------|
| Fe-Cr-Si-C | wt.% | 0.36 | 1.25 | 1.25 | 0.95 | 0.30 | 0.018 | 0.008 |
| | at.% (x_i^α) | 1.63 | 2.42 | 1.31 | 0.94 | 0.28 | - | - |

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-Si-C steel are listed in Tables 2 and 3.

Tab. 2. Lattice parameters and expansion coefficients of ferrite and austenite

| 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-Cr-Si-C | 0.2868 0.2869 * | 0.3591 | 1.589 | 2.475 |

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

Tab. 3. Parameters for determination of volume fractions of transformation a residual austenite in Fe-Cr-Si-C steel

| Transformed at $^{\circ}\text{C}$ | a_{γ} , nm | a_{α} , nm | $\Delta L/L \times 10^{-3}$ * | V_{α} |
|-----------------------------------|-------------------|-------------------|-------------------------------|--------------|
| 352 | 0.3619 | 0.2882 | 2.70 | 0.79 |
| 380 | 0.3622 | 0.2884 | 2.25 | 0.66 |
| 414 | 0.3625 | 0.2885 | 1.70 | 0.50 |
| 442 | 0.3627 | 0.2886 | 1.21 | 0.35 |
| 475 | 0.3630 | 0.2888 | 0.25 | 0.07 |

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

V_{α} - measured volume fraction of bainitic ferrite

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 (Fig. 2), then the amount of bainite formed is dependent on the transformation temperature.

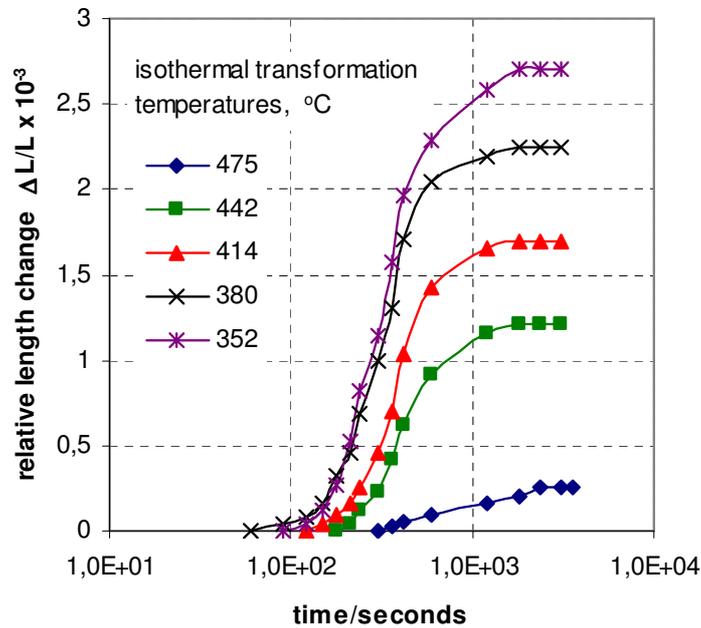


Fig. 2. The relative length change ($\Delta L/L$) observed by dilatometer during isothermal transformation below B_s temperature

3. Phase diagram of austempered Fe-Cr-Si-C steel

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.

The determined carbon concentrations of the residual austenite at the different temperatures of transformation of bainite are compared with the T_0 , T_0' and A_3' phase boundaries (Table 4) for investigated steel in Figure 3.

Tab. 4. Calculated details for phase diagram of the Fe-Cr-Si-C steel and the carbon concentration in austenite, x_γ at selected temperatures

| Reaction temperature, °C | A_3' , mol | x_{T_0} , mol | $x_{T_0'}$, mol | x_γ , mol |
|--------------------------|--------------|-----------------|------------------|------------------|
| 475 | 0.0990 | 0.0282 | 0.0184 | 0.068 |
| 442 | 0.1104 | 0.0324 | 0.0221 | 0.054 |
| 414 | 0.1198 | 0.0359 | 0.0246 | 0.036 |
| 380 | 0.1308 | 0.0400 | 0.0283 | 0.028 |
| 352 | 0.1397 | 0.0436 | 0.0317 | 0.018 |

A_3' - $x^{\gamma\alpha}$ □ - paraequilibrium carbon concentration of austenite in mole fraction,

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

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

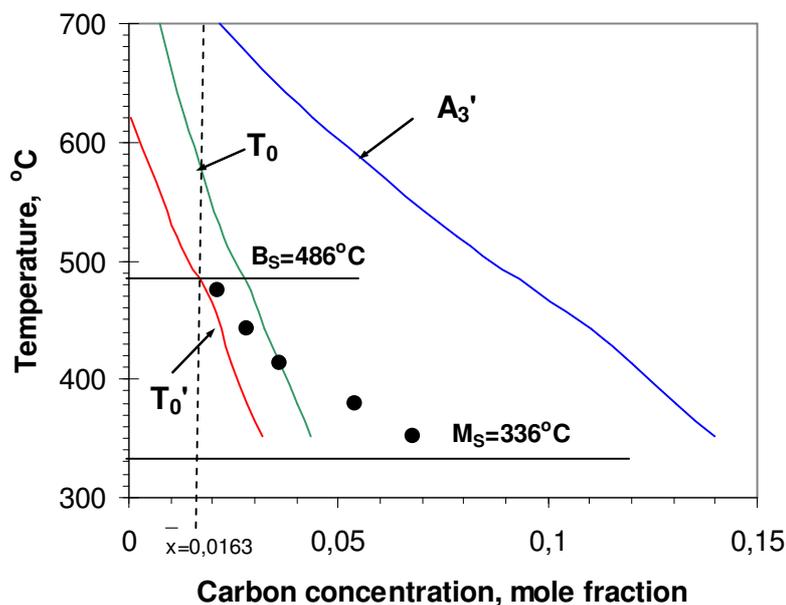


Fig. 3. The calculated phase boundaries A_3' , T_0 and T_0' for the investigated Fe-Cr-Si-C steel together with all the experimental data of the measured carbon contents of the untransformed austenite (black circles)

The diagram was calculated as in Ref. [1-3,8] using a model developed by Bhadeshia [3] based on the McLellan and Dunn quasi-chemical thermodynamic model [13,14]. 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.

In presented diagram the reaction at temperatures 475, 442 and 414°C is found to stop when the average carbon concentration of the residual austenite is closer to the T_0 and 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 upper bainite in Fe-Cr-Si-C steel does indeed stop close to the T_0 boundary (Fig. 3). Similar results have previously obtained by Bhadeshia and Christian [2,4] and by Ławrynowicz and Barbacki for other alloys [6-10].

In Figure 3 the reaction to lower bainite at 352 and 380°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 400J/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 lower bainite at 352 and 380°C may indicate on the possibility of cementite precipitation from austenite or ferrite.

When the microstructure of Fe-Cr-Si-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, Figure 4. The maximum volume fraction of retained austenite (V_γ) will then equal $1 - V_\alpha$.

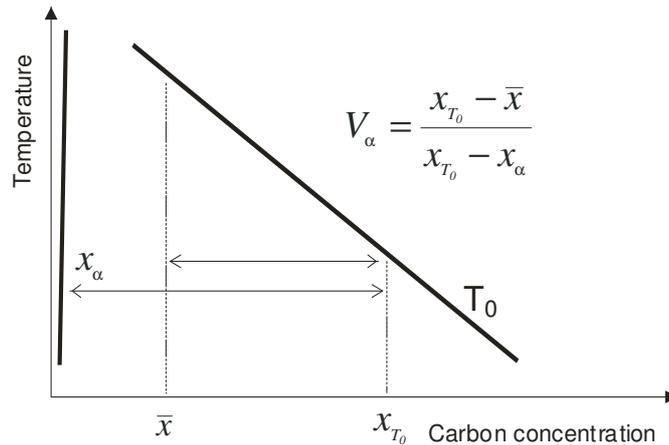


Fig. 4. Application of the Lever-rule to the T_0 curve allows the estimation of the permitted fraction of bainite V_α at any temperature

In case of carbides precipitation the maximum volume fraction of bainitic ferrite (V_α) can be calculated using the following equation [6,15]:

$$V_\alpha = \frac{x_{T_0} - \bar{x}}{x_{T_0} - x_\alpha - x_c} \quad (2)$$

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. 5.

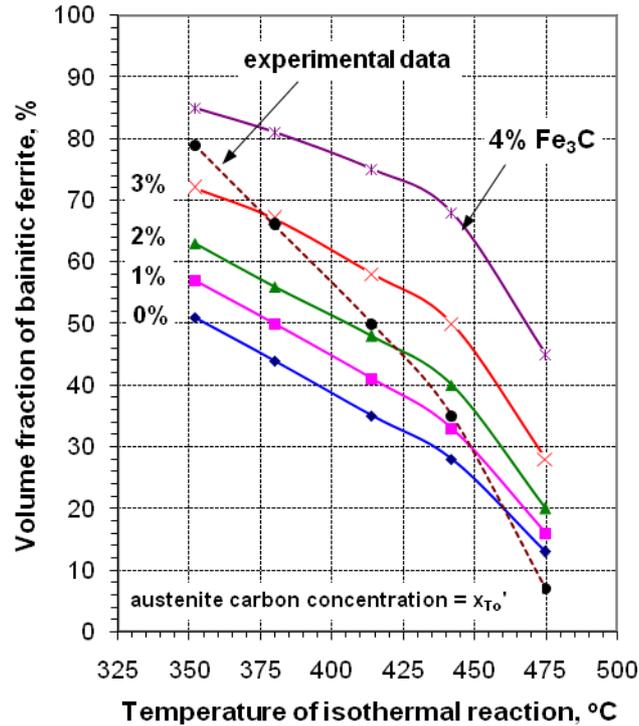


Fig. 5. Experimentally determined and calculated the maximum volume fraction of bainite in investigated Fe-Cr-Si-C steel taking into account cementite precipitation in the range from 0% to 4 wt % Fe_3C . Assumed austenite carbon concentration at the cessation of bainite transformation $x_\gamma = x_{T_0}$

It is seen in Figure 5 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.

4. Conclusions

The paper presents an investigation of the extend of bainite reaction in the case of cementite precipitation.

The following conclusions were reached:

1. Experimental measurements of volume fraction of bainitic ferrite and volume of the untransformed austenite indicate that there is a necessity of carbides precipitation during transformation.
2. 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.
3. The extent of transformation to bainite decreases when increasing the isothermal transformation temperature towards the bainite start temperature (B_S). 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.
4. The carbon concentration of the residual austenite increases during bainitic transformation as a consequence of the increasing volume fraction of bainitic ferrite.

5. 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.
6. 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.

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