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RATIONALISATION OF AUSTENITE TRANSFORMATION TO UPPER OR LOWER BAINITE IN STEELS

ABSTRACT

The paper presents an analytical evaluation of transition temperature from upper to lower bainite in Fe-C-Cr steel. The calculations was based on the model constructed by Matas and Hehemann which involves a comparison between the times needed to precipitate cementite within the bainitic ferrite plates (t_θ), with the time required to decarburise supersaturated ferrite plates (t_d). The transition between upper and lower bainite is found to occur over a narrow range of temperatures (350-410°C) and depends on the thickness of bainitic ferrite laths and the volume fraction of precipitated cementite. On comparing the t_d and t_θ times it was found that the transition temperature from upper to lower bainite reaction (L_S) of about 350°C could be predicted if the thickness of bainitic ferrite laths is set as $w_o = 0.1$ μm and volume fraction of cementite is set as $\xi = 0.01$.

Keywords: transition temperature, bainite transformation, lower, upper bainite

INTRODUCTION

Bainite transformation in steels takes place in a broad temperature region, in which thermodynamic and kinetic behaviours vary greatly so that bainite is characterised by miscellaneous morphologies and complicated formation mechanisms.

The classifications of bainite are based on the morphology of ferrite and the morphology and places of cementite particle precipitation during transformation [1,2]. *Upper bainite* in this case consists of parallel ferrite laths with cementite and austenite layers between them. The cementite precipitates from the carbon-enriched austenite films between the ferrite plates; the ferrite itself is free from carbides (Fig.1). *Lower bainite* is of the plate-like morphology and involves fine cementite platelets within bainitic ferrite oriented in a specific direction [3,4] (Fig.1). In any case, the mixture of ferrite laths with retained austenite without carbides is regarded as a special kind of *carbides free bainite* [5,6]. The formation of carbides during bainitic transformation can be detrimental to toughness, especially in mixture of upper bainitic ferrite and particles of cementite, which are responsible for damage initiation.

The shape of bainitic ferrite on a macroscopic scale can be classified as lath-like, plate-like, granular, or even with nodular external morphology [7,8]. In that case in common use are a wide variety of terminology to describe observed morphologies, as "granular bainite",

"nodular bainite", "columnar bainite", "upper and lower bainite", "carbide free bainite", etc. [9,10].

On the assumption that there is no fundamental difference in the mechanism of bainite reaction between upper and lower bainite if bainitic ferrite when it forms is supersaturated with carbon, there could be constructed a useful model for the transition from upper to lower bainite. The model constructed by Matas and Hehemann [11] and by Bhadeshia [12] involves a comparison between the times needed to precipitate cementite within the bainitic ferrite plates with the time required to decarburise supersaturated ferrite plates. When decarburisation dominates upper bainite is obtained. Alternatively, whereas carbides are precipitated within ferrite plates it leads to the formation of lower bainite. The model is illustrated schematically in Figure 1 [12].

CARBON SUPERSATURATED
PLATE OF BAINITIC FERRITE

Carbon diffusion
into austenite

Carbon diffusion into austenite
and carbide precipitation
in ferrite

Carbide precipitation
from austenite

UPPER BAINITE
(High Temperature)

LOWER BAINITE
(Low Temperature)
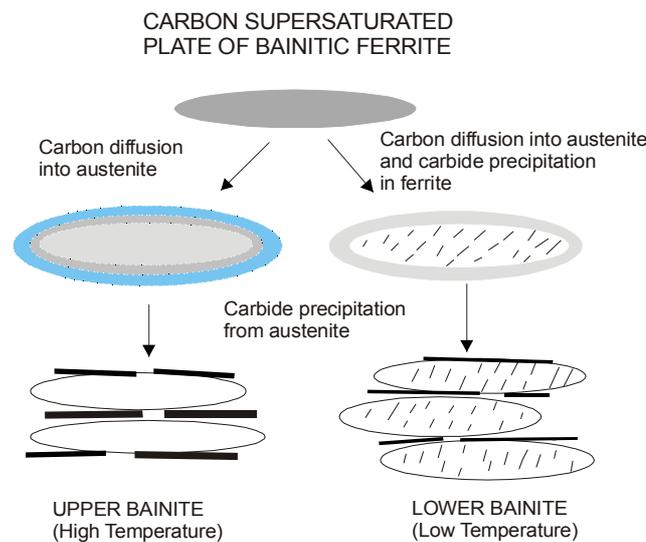
Fig. 1. Schematic illustration of the transition from upper to lower bainite [12]

The transition temperature between upper and lower bainite (or the lower bainite start temperature L_S) was defined as the highest temperature at which time required to obtain chosen volume fraction of cementite precipitation is smaller than the time necessary to decarburise ferrite lath [13].

The model requires that the bainitic ferrite when it forms in upper and lower bainite is supersaturated with carbon. The aim of this work presented here was to evaluate the transition temperature between upper and lower bainite and to verify some of the predictions of the model.

EXPERIMENTAL PROCEDURE

The composition of the investigated steel and calculated B_S and M_S temperatures are given in Table 1. In agreement with the previous observations the Fe-C-Cr steel seems to be ideal for testing the change from upper to lower bainite in the transition temperature [7,14,15].

Table 1. *Chemical composition and calculated B_S and M_S temperatures of the steel used in the present study**

Steel	C	Si	Mn	P	S	Cr	Ni	B_S	M_S
	wt. %							^{o}C	
Fe-C-Cr	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 [16,17]

A high-speed Adamel Lhomargy LK-02 dilatometer was used to establish change of length ($\Delta L/L$) during isothermal bainitic transformation. Samples were austenitised at 1000°C for 10 min. when subsequently transformed isothermally below the B_S and above M_S temperatures [16,17]. The dilatometric specimens were held an appropriately long time at the isothermal temperatures until the bainite reaction ceased (when dimensions of dilatometric samples cease to change). Cooling was carried out by blowing a helium gas directly onto the surface of the sample. The volume fraction of bainite (V_B) was determined as in [17,18] by dilatometry. All the details of the determination of the volume fraction of bainite and the carbon concentration of the residual austenite are described elsewhere [17,18].

The morphologies of upper and lower bainite were distinguished by transmission electron microscopy. Thin foils for transmission electron microscopy were prepared from discs slit from heat-treated specimens. The discs were mechanically thinned and electropolished until perforation occurred in a twin jet polishing unit containing an electrolyte of 5% perchloric acid, 25% glycerol and 70% ethyl alcohol mixture solution. The electrolyte temperature was maintained around – 10°C, the polishing potential was 55 V at a current of 30 mA. The foils were examined in a Tesla BS-540 transmission electron microscope operated at 120 kV.

RESULTS AND DISCUSSION

The Matas and Hehemann [11] and Takahashi and Bhadeshia [12] model for evaluation of the transition temperature from upper to lower bainite can only be used when bainite develops by displacive mechanism with a full supersaturation of carbon of bainitic ferrite. Therefore the issue raised is − what is the final carbon content of the untransformed austenite at the cessation of the bainite reaction. The determined carbon concentrations of the residual austenite at the point where the formation of bainite ceases are compared with the T_0, T'_0, $A'e_3$, $A''e_3$ and CCE^1 (constrained carbon equilibrium -CCE) phase boundaries for investigated steel in Figure 2. The diagram was calculated as in Ref. [21,22] using a model developed by Bhadeshia [23,24] based on the McLellan and Dunn quasi-chemical thermodynamic model [25-28]. The T'_0 curve allows for 400 J/mol of stored energy in the bainitic ferrite to take account of the strain energy due to the invariant-plane strain shape change that accompanies the growth of bainitic ferrite [23]. The $A'e_3$ curve is the calculated paraequilibrium ($\alpha+\gamma$)/γ phase boundary indicating equilibrium between ferrite and austenite when the ratio of substitutional alloying elements to iron is constant everywhere and $A''e_3$ curve allows for 50

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[1] Recently, a model has been developed to examine the thermodynamics of carbon partitioning from as-quenched martensite into austenite, under conditions where competing reactions such as bainite, cementite or transition carbide precipitation are suppressed [19,20]. The model predicts the "end point" of partitioning, when martensite (i.e. ferrite) is in metastable equilibrium with austenite, under conditions where (1) the α/γ interface is immobile, and (2) competing reactions (such as carbide precipitation) are precluded. For these conditions, partitioning is complete when the chemical potential of carbon is uniform throughout the system. This final state has been called constrained paraequilibrium (CPE) or constrained carbon equilibrium (CCE).

J/mol of stored energy in the ferrite. The bainite and martensite reactions start temperatures B_S and M_S are also marked on these diagram. The paraequilibrium phase boundary is chosen because no substitutional alloying element partitioning occurs during bainite formation. In presented diagram the reaction is found to stop when the average carbon concentration of the residual austenite is close to the T'_0 curve than the $A'e_3$ boundary (black circles in Fig. 2). The presented above results can be explained when it is assumed that bainitic ferrite grows without diffusion, but any excess of carbon is soon afterwards rejected into the residual austenite by diffusion [24]. This makes more difficult for subsequent bainitic ferrite to grow, when the austenite becomes stabilised by increased carbon concentration. The maximum extent to which the bainite reaction can proceed is therefore determined by the composition of the residual austenite. A stage where diffusionless growth becomes thermodynamically impossible and the formation of bainitic ferrite terminates is where the carbon concentration of the austenite reaches the T'_0 curve.
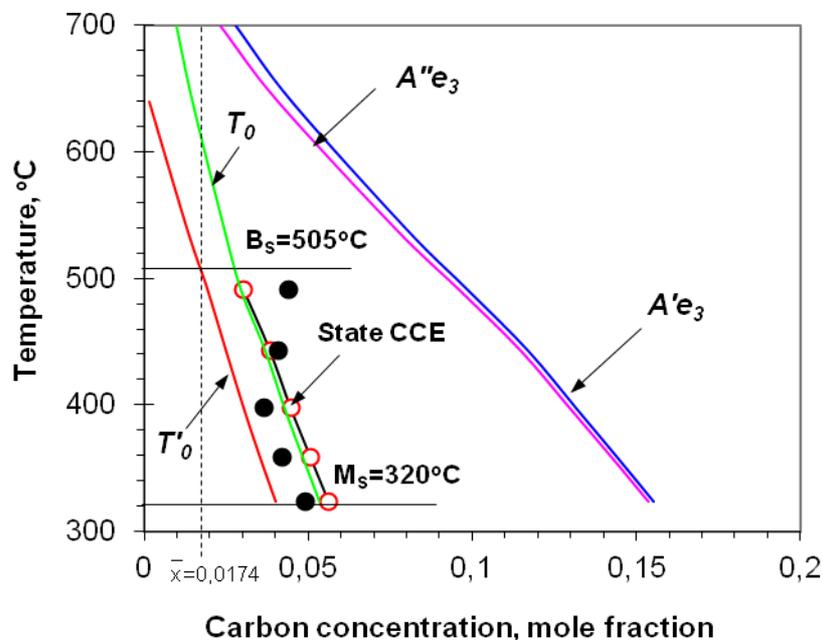
Fig. 2. Calculated phase diagram with experimental data of carbon concentration of residual austenite at the termination of isothermal bainite formation for Fe-C-Cr steel (black circles represent experimental data)

Since diffusionless transformation is not possible beyond the T_0 curve, the obtained results need explanation. 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. Secondly, when carbide precipitation accompanies the development of bainitic ferrite laths as a secondary process, it reduces the carbon content in the austenite and allows the bainitic reaction to proceed to a larger extend. This fact is illustrated on Fig. 3. Isothermal transformation at 350°C for the prolonged period of 3600 seconds gave a typical lower bainitic microstructure of ferrite laths containing cementite particles inside ferrite laths of thickness beyond 0.2μm (Fig. 3a,b). Retained austenite was present between the ferrite laths

as thin films (Fig. 3c). The ability to retain such films of austenite is due to partitioning of carbon into residual austenite following the formation of supersaturated bainitic ferrite.
 It is seen in Fig. 3a,b 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.
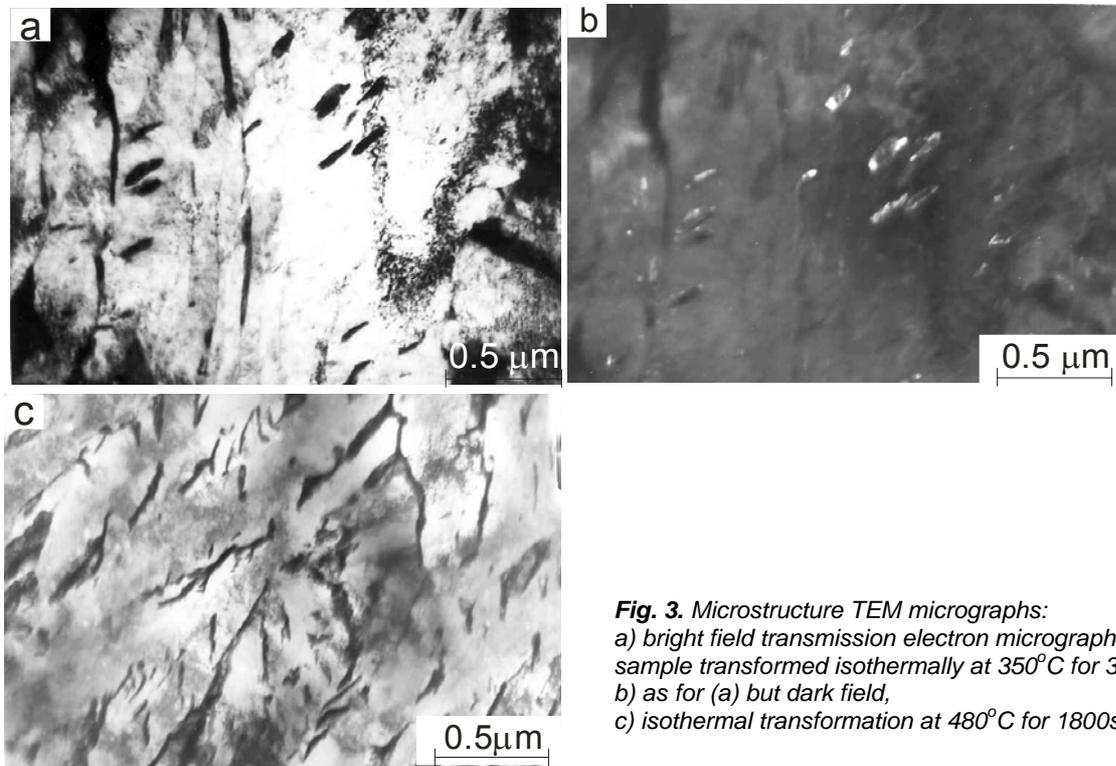
Fig. 3. *Microstructure TEM micrographs:*
a) bright field transmission electron micrograph of sample transformed isothermally at 350°C for 3600s,
b) as for (a) but dark field,
c) isothermal transformation at 480°C for 1800s

However, since the carbon concentration of the residual austenite when the reaction is found to stop is close to the T'_0 curve than the $A'e_3$ boundary, the analysis suggest that bainite grows by displacive transformation, but carbon atoms partition into the residual austenite or precipitate as carbides shortly after growth is arrested. Similar results have previously obtained by Bhadeshia, Edmonds and Ławrynowicz for other alloys [17,24]. In this case the model constructed by Matas and Hehemann can be used for evaluation the transition temperature from upper to lower bainite.

The schematic stages of development of bainitic sheaf are shown in Figure 4. As it is seen in Fig. 4 the bainite sheaves usually take the wedge shape. As indicated by many prior studies [7,13] new ferrite laths are mostly nucleated near the tips of laths on the sheaf, rather than at the broad sides. Thus, the different sides of the bainite sheaf may have different carbon concentration and different nucleation rates.
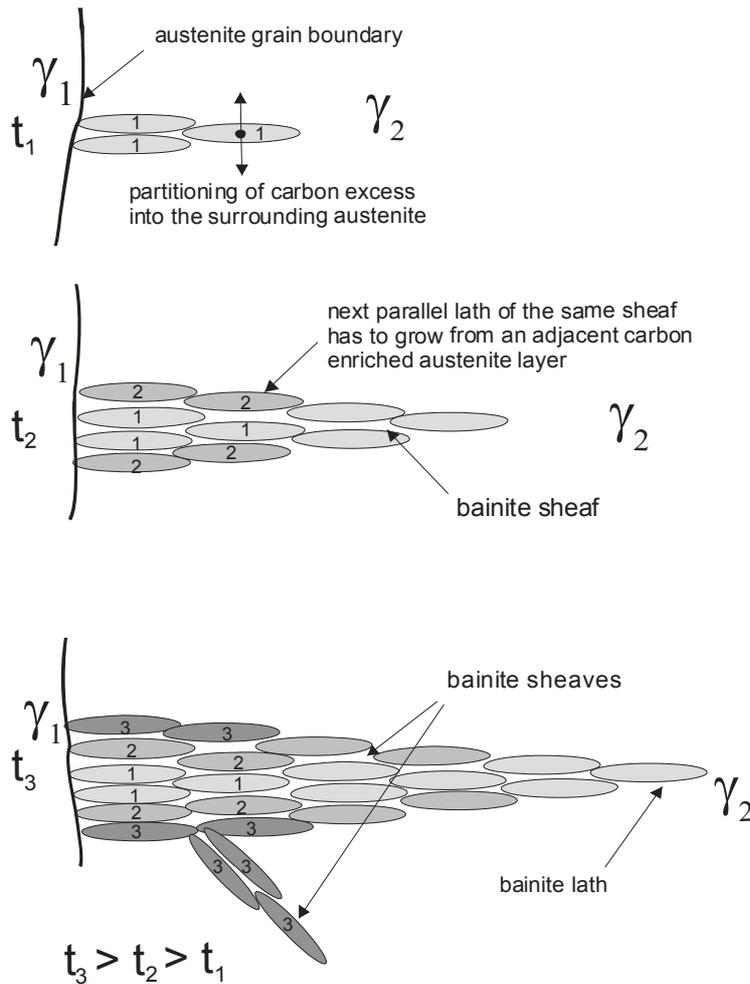
Fig. 4. Scheme of stages of development of bainitic sheaf (t_1, t_2 and t_3 - time of transformation, γ_1, γ_2 - adjacent austenite grains)

Suppose that the lath denoted 1 of bainitic ferrite forms without diffusion, but any excess carbon is soon rejected into the residual austenite. Consequently, all the laths denoted 1 were formed at the early stage of transformation from austenite whose carbon concentration is initially identical to that of bulk alloy (region of upper bainite). The laths denoted 2 and 3 were formed from enriched austenite as a consequence of carbon redistribution occurring after the growth event (region of lower bainite). The transition between these two regions is not sharply defined. There is then the possibility of the reaction beginning with the growth of upper bainite but decomposing to lower bainite from the enriched austenite at the later stages of reaction. This explains why both upper and lower bainite sometimes can be found in the same temperature.

Furthermore, because ferrite laths have a different thickness, then intralath carbides can be expected in thicker laths when at the same time inside the thin laths carbide precipitation has not observed.

The method to estimate the transition temperature between upper and lower bainite is based on comparison of the time required to decarburise ferrite lath (t_d) with the time interval necessary to obtain chosen volume fraction of cementite precipitation (t_θ) for the temperatures below the calculated B_S and above M_S.

The time required to decarburise a supersaturated bainitic ferrite lath of thickness w_o is given by [12]:

$$t_d = \frac{w_o^2 \pi (\overline{x} - x^{\alpha\gamma})^2}{16\overline{D}(x^{\gamma\alpha} - \overline{x})} \tag{1}$$

where: $\overline{x}$ is the average carbon concentration in the steel, $x^{\alpha\gamma}$ and $x^{\gamma\alpha}$ are the carbon concentrations in ferrite and austenite respectively, when the two phases are in paraequilibrium. The concentration dependence of the diffusivity D of carbon in austenite makes it imperative to account for the variation of D with the fraction of carbon. Taking into account carbon concentration gradients it has been demonstrated [29] that for most purposes a weighted average diffusivity $\overline{D}$ can adequately represent the effective diffusivity of carbon given by [29]:

$$\overline{D} = \int_{\overline{x}}^{x^{\gamma\alpha}} \frac{D dx}{(x^{\gamma\alpha} - \overline{x})} \tag{2}$$

The value of D was calculated as discussed in Ref. [22]. The calculated kinetics of partitioning are shown in Fig. 5 for different thickness of bainitic ferrite laths. The decarburisation time t_d (for w_o=0.1, 0.2 and 0.4 μm) is a function of lath width and increases with decreasing temperature because the diffusion coefficient of carbon also decreases with temperature. The decarburisation time also increases as the thickness of the ferrite laths increases.

Calculation of the volume fraction of cementite precipitation from supersaturated ferrite as a function of time, temperature, and chemical composition enables of using the Avrami type equation, evaluated previously by Takahashi and Bhadeshia in the form [12]:

$$\xi\{t\} = 1 - \exp\{-4.07 \times 10^4 \overline{x}^{0.635} t^{0.62}\} \tag{3}$$

where $\xi\{t\}$ is the volume fraction of cementite normalised by its equilibrium volume at the reaction temperature, and t is the time and $\overline{x}$ is the overage carbon concentration in the alloy. This equation was used to estimate the time necessary to obtain a specified degree of cementite precipitation (1, 2 and 5% of Fe_3C) as a function of temperature and the carbon concentration of the Fe-C-Cr steel.

Calculated values of t_d and t_θ (for ξ=0.01, 0.02, 0.05) are plotted in Fig. 5. For temperature below the calculated B_S any intersection between the t_d and t_θ lines points to the location of the transition temperature that is defined as the highest temperature at which $t_\theta < t_d$ [12].
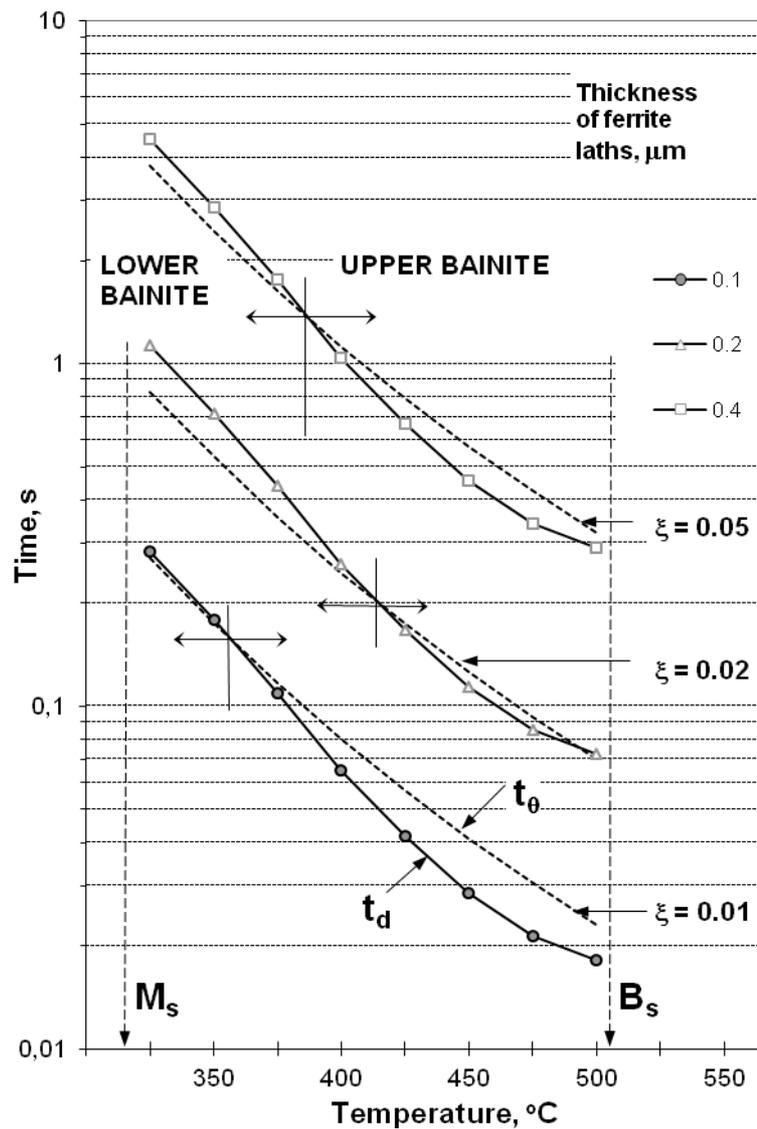
Fig. 5. Comparison between decarburisation time (t_d) and time required for cementite precipitation (t_θ) for Fe-C-Cr steel (ξ - volume fraction of cementite precipitation). Time (t_θ) was calculated for 0.01, 0.02 and 0.05 volume fraction of cementite precipitation and time (t_d) was calculated for different thickness of ferrite laths 0.1, 0.2 and 0.4 μm

For bainitic ferrite laths thickness beyond 0.1 μm ($w_o > 0.1$ μm) no upper bainite is predicted because for all temperatures $t_{\theta (0.01)} \ll t_d$. Furthermore, on comparing the calculated values of t_d and t_θ for lath thickness $w_o = 0.2$ μm and $\xi = 0.02$, it was found that L_S temperature is about 410°C. In this case only upper bainite should be found for $w_o < 0.2$ μm (no lower bainite can be expected) and for $w_o > 0.2$ μm only lower bainite is predicted to exist. Furthermore, it is generally observed (Fig. 6) that the width of ferrite laths is highly diverse. This reflect the possibility that cementite can precipitate in thicker bainite laths (when $t_\theta \ll t_d$) and in thinner laths has not during isothermal transformation. It is also consistent with the fact that upper and lower bainite often form at the same temperature in a given steel. The calculated differences in relative behaviour of t_d and t_θ lines can lead to different types of bainitic reaction in Fe-C-Cr steel and enable investigation of the transition from upper to lower bainite. As a result the following conclusions are reached:

1. A comparison between calculated time required to precipitate cementite within the ferrite plates with the time required to decarburise supersaturated plates can be used to rationalise the transition from upper to lower bainite. When relatively rapid cementite precipitation within the ferrite dominates, lower bainite is predicted. Alternatively, if the decarburisation process dominates it leads to the formation of upper bainite.

2. Generally the transition between upper and lower bainite is found to occur over a narrow range of temperatures (350-410°C) and depends on the thickness of bainitic ferrite laths and the volume fraction of precipitated cementite. On comparing the t_d and t_θ times for the investigated steel it was found that the transition temperature (L_S) of about 350°C could be predicted if the thickness of bainitic ferrite laths is set as $w_o = 0.1$ μm and volume fraction of cementite is set as $\xi = 0.01$.

REFERENCES

1. Aaronson H.I., Reynolds W.T., Shiflet G.J.,Spanos G.: Bainite Viewed Three Different Ways. Metall. Trans. A 21A (1990), 1343-1380.

2. Bhadeshia H.K.D.H.: Bainite in Steels, The Institute of Materials, London, 1992.

3. Bradley J.R., Aaronson H.I.: Growth Kinetics of Grain Boundary Ferrite Allotriomorphs in Fe-C-X Alloys. Metall. Trans. A 12A (1981), 729-1741.

4. Spanos G et al.: Influence of Carbon Concentration and Reaction Temperature upon Bainite Morphology in Fe-C-2Pct Mn Alloys. Metall. Trans. A 21A (1990), 1391-1411.

5. Goldstein H., Aaronson H.I.: Overall Reaction Kinetics and Morphology of Austenite Decomposition between the Upper Nose and the M_S of a Hypoeutectoid Fe-C-Cr Alloy. Met. Trans. A 21A (1990), 1465-1478.

6. Shiflet G.J., Aaronson H.I.: Growth and Overall Transformation Kinetics above the Bay Temperature in Fe-C-Mo Alloys. Metall. Trans. A 21A (1990), 1413-1432.

7. Aaronson H.I., Furuhara T., Hall M.G., Hirth J.P., Nie J.F., Purdy G.R., Reynolds Jr. W.T., On the mechanism of formation of diffusional plate-shaped transformation products. Acta Materialia 54 (2006), 1227-1232.

8. Spanos G.: The Fine Structure and Formation Mechanism of Lower Bainite. Metall. mater. Trans. A 25A (1994), 1967-1980.

9. Vetters H.: Transformation of austenite into bainitic ferrite and martensite. Materials technology. 67 (1996), 408-411.

10. Honeycombe R.W.K.: Ferrite. Metal Sci. 6 (1980), 201-214.

11. Matas S.J., Hehemann R.F.: The Structure of Bainite in Hypoeutectoid Steels. Trans. TMS-AIME 221 (1961), 179-185.

12. Takahashi M., Bhadeshia H.K.D.H.: Model for transition from upper to lower bainite. Mater. Sci. Technol. 6 (1990), 592-603.

13. Christian J.W.: Theory of Transformations in Metals and Alloys, 2nd edition, Pt.1, Pergamon Press, Oxford, 1975.

14. Ławrynowicz Z.: Carbon Partitioning During Bainite Transformation in Low Alloy Steels. Materials Science and Technology 18 (2002), 1322-1324.

15. Ławrynowicz Z.: Bainite Morphology in Two Experimental Mn-V and Mo-Cr Steels, 13th International Symposium on Advanced Materials (ISAM-2013), Institute of Space Technology, Islamabad, Pakistan, 23 – 27 September, 2013, 13-75.

16. Bhadeshia H.K.D.H.: Thermodynamic analysis of isothermal transformation diagrams. Metal Science 16 (1982), 159-165.

17. Ławrynowicz Z.: Mechanism of bainite transformation in Fe-Cr-Mo-V-Ti-C steel. International Journal of Engineering 12 (1999), 81-86.

18. Bhadeshia H.K.D.H., David S.A., Vitek J.M., Reed R.W.: Stress induced transformation to bainite in Fe-Cr-Mo-C pressure vessel steel. Materials Science and Technology 7 (1991), 686-698.

19. Speer J.G., Streicher A.M., Matlock D.K., Rizzo F., Krauss G.: Quenching and partitioning: a fundamentally new process to create high strength TRIP sheet microstructures. [In:] Austenite formation and decomposition, E.B. Damm, M. Merwin (eds). Warrendale, PA: TMS/ISS (2003), 505-522.

20. Speer J.G., Edmonds D.V., Rizzo F.C., Matlock D.K.: Partitioning of carbon from supersaturated plates of ferrite, with application to steel processing and fundamentals of the bainite transformation. Current Opinion in Solid State & Materials Science 8 (2004), 219-237.

21. Bhadeshia H.K.D.H.: Application of first-order quasichemical theory to transformations in steels. Met. Sci. 16 (1982), 167-169.

22. Bhadeshia H.K.D.H.: Diffusion of carbon in austenite. Met. Sci. 15 (1981), 477-479.

23. Bhadeshia H.K.D.H., Christian J.W.: Bainite in Steels, Metall. Trans. A 21A (1990), 767-797.

24. Bhadeshia H.K.D.H., Edmonds D.V.: The Mechanism of Bainite Formation in Steels. Acta Metall. 28 (1980), 1265-1273.

25. McLellan R.B., Dunn W.W.: J. Phys. Chem. Solids. 30 (1969), 2631.

26. Siller R.H., McLelan R.B.: The Variation with Composition of the Diffusivity of Carbon in Austenite. Trans. of TMS of AIME 245 (1969), 697-700.

27. Siller R.H., McLelan R.B.: The Application of First Order Mixing Statistics to the Variation of the Diffusivity of Carbon in Austenite. Metall. Trans. 1 (1970), 985-988.

28. Dunn W.W., McLellan R.B.: The Application of a Quasichemical Solid Solution Model to Carbon Austenite. Metall. Trans. 1 (1970), 1263-1265.

29. Trivedi R., Pound G.M.: The Effect of Concentration-Dependent Diffusion Coefficient on the Migration of Interphase Boundaries. J. Applied Physics 38 (1967), 3569-3576.