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# BAINITE TRANSFORMATION IN EXPERIMENTAL Fe-Cr-Mo-V-Ti-C STEEL

## ABSTRACT

The mechanism and kinetics of bainite transformation have been studied in Fe-Cr-Mo-V-Ti-C steel using high speed dilatometry and transmission electron microscopy (TEM) backed by thermodynamic analysis. At any temperature investigated did not occur the complete transformation of austenite. Obtained results confirm the incomplete reaction phenomenon with the cessation of the bainite transformation well before paraequilibrium is achieved. These experimental data indicate that bainitic ferrite forms by a displacive transformation mechanism, but soon afterwards, excess of carbon is partitioned into the residual austenite.

Keywords: mechanism of bainite transformation, kinetics, lower, upper bainite

## INTRODUCTION

The mechanism of bainite transformation in steels remains still controversial and involves two general concepts, that bainitic reaction occurs via a diffusional mechanism [1], and that bainitic reaction occurs in a displacive mechanism as far as the substitutional elements are concerned [2]. The present paper attempts to investigate bainite formation in laboratory prepared low alloy Fe-Cr-Mo-V-Ti-C steel (signed as 15HM2VT steel) and to clarify some problems of the formation mechanism of bainite. This type of high strength low alloy (HSLA) steel is supposed to have requisite good combination of strength, toughness and weldability for many industrial applications. Titanium and vanadium are present to refine the austenite grain size resulting in a fine grained ferritic structure and low carbon content promotes good toughness and weldability. In Fe-C-X steels when X is a strong carbide forming alloying element, interphase boundary carbides and fibrous carbides were present after isothermal reaction at temperatures above the bay temperature in the eutectoid range [3-5].

This paper attempts to investigate the mechanism of the bainite transformation in 15HM2VT steel from the thermodynamic point of view.

#### MATERIAL AND EXPERIMENTAL PROCEDURES

The composition of the steel investigated is given in Table 1. Determination of the linear expansion coefficients was carried out in a UBD Leitz-Wetzlar dilatometer. The linear expansion coefficient of ferrite  $(e_{\alpha})$  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  $(e_{\gamma})$  was measured after

Steel		С	Si	Cr	Mn	Mo	V	Ti
15HM2VT	wt.%	0.15	0.24	0.84	0.92	2.60	0.24	0.12
	at.%	0.70	0.48	0.90	0.93	1.51	0.26	0.14

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

cooling from temperature of 1100 °C while the specimen was in the single  $\gamma$  phase field. A high-speed Adamel Lhomargy LK-02 dilatometer was used to establish the  $M_S$  and  $B_S$  temperatures and change of length ( $\Delta L/L$ ) during isothermal bainitic transformation (Fig. 1). In order to ensure rapid cooling (~300Ks<sup>-1</sup>) the specimens were 13mm in length and 1.1mm in diameter. The specimens were austenitised for 10 min. at 1000°C in dilatometry furnace and subsequently gas quenched to the isothermal transformation temperature by an automatically

controlled high-pressure helium jet.



Fig. 1. The relative length change (L/L) observed by dilatometer during isothermal transformation below B<sub>S</sub> temperature

The dilatometry results show that the relative length change during the formation of bainite increases as the isothermal transformation temperature decreases below the *Bs* temperature (Fig. 1), then the amount of bainite formed is dependent on the transformation temperature. Lattice parameter measurements were carried out using a *X*-ray diffractometer with Fe-filtered  $CoK_{\alpha}$  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. 2).



Fig. 2. Extrapolated parameter of ferrite  $a_{o\alpha}$  in Fe-Cr-Mo-V-Ti-C steel using extrapolation function of Taylor-Sinclair

Lattice parameters, values of linear 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-Mo-V-Ti-C steel are listed in Tables 2 and 3.

Steel	Lattice parameter of ferrite $a_{o\alpha}$ nm	Lattice parameter of austenite $a_{o\gamma}$ nm	Ferrite $e_{\alpha} \times 10^{-5}$ $oC^{-1}$	Austenite $e_{\gamma} \times 10^{-5}$ $oC^{-1}$
15HM2VT	0.2873 0.2872 *	0.35928	1.561	2.243

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

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

Transformed	$a_{\gamma}$	$a_{\alpha}$	$\Delta L/L$	$V_{\alpha}$	$x_{\gamma}$ mol
at, <sup>o</sup> C	nm	nm	$\times 10^{-3} *$		mor
460	0.36278	0.28926	3.34	0.74	0.0224
475	0.36290	0.28933	3.03	0.68	0.0185
490	0.36302	0.28939	1.83	0.42	0.0110
508	0.36317	0.28947	1.50	0.35	0.0100
518	0.36325	0.28952	0.92	0.22	0.0085

**Table 3.** Parameters for determination of volume fractions of transformation ( $V_{\alpha}$ ) and the carbon concentration of the residual austenite (x) in Fe-Cr-Mo-V-Ti-C steel

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

 $V_{\alpha}$  - measured volume fraction of bainitic ferrite

#### PHASE DIAGRAM OF AUSTEMPERED Fe-Cr-Mo-V-Ti-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 Fig. 3.

Dhaga	Transformation temperatures, °C								
houndarios	700	600	518	508	490	475	460	400	
Doundaries	Carbon concentration at phase boundaries, mole								
$A_3$ '	0.0194	0.0471	0.0762	0.0795	0.0859	0.0917	0.0978	0.1212	
$T_0(x_{T_0})$	0.0065	0.0139	0.0215	0.0223	0.024	0.0254	0.0274	0.0354	
$T_0'(x_{T_0'})$		0.0016	0.0106	0.0115	0.0135	0.0152	0.0172	0.0241	
$x_{\gamma}$			0.0085	0.0100	0.0110	0.0185	0.0224		

**Table 4.** Calculated details for phase diagram of the Fe-Cr-Mo-V-Ti-C steel and the carbon concentrationin austenite,  $x_{\gamma}$  at selected temperatures

 $A_3'$  -  $x^{\gamma\alpha}$  – 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<sub>3</sub>', T<sub>0</sub> and T<sub>0</sub>' for the investigated Fe-Cr-MoV-Ti-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. [6-8] using a model developed by Bhadeshia [6,9] based on the McLellan and Dunn quasi-chemical thermodynamic model [10,11]. The martensite and bainite transformation 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 518, 508, 490°C and also at 475, 460°C is found to stop when measured average carbon concentration of the residual austenite is closer to the  $T_0$  and  $T_0'$  curves than the  $A_3'$  boundary. The  $A_3'$  curve is the calculated paraequilibrium  $(\alpha+\gamma)/\gamma$  phase boundary indicating equilibrium between ferrite and austenite when the ratio of substitutional alloying elements to iron is constant everywhere. 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 bainite at upper temperatures of the bainitic range in Fe-Cr-Mo-V-Ti-C steel does indeed stop close to the  $T_0'$  boundary (Fig. 3).Similar results have previously obtained by Bhadeshia and Christian [2,12] and by Ławrynowicz and Barbacki for other alloys [4,5,7,8,15].

In Figure 3 the reaction to bainite at lower temperatures 475 and 460°C seems to stop when carbon concentration of austenite exceeds the  $T_0$ ' boundary and is close to  $T_0$  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 bainite at 475 and 460°C may indicate on the possibility of cementite precipitation from austenite or ferrite.

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 [20]. 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. The incomplete reaction phenomenon supports the hypothesis that the growth of bainitic ferrite occurs without any diffusion with carbon being partitioned subsequently into the residual austenite.

## CONCLUSIONS

The austenite to bainite transformation was studied in Fe-Cr-Mo-V-Ti-C steel using dilatometry backed by thermodynamic analysis. The results obtained are summarized as follows:

- 1. The formation of bainitic ferrite terminates well before the carbon content of the residual austenite reaches the level given by the extrapolated  $A'_3$  phase boundary, what is called the incomplete reaction phenomenon.
- 2. The carbon concentration of the residual austenite at the end of reaction indicates that the growth of bainitic ferrite is diffusionless.

## REFERENCES

- 1. Aaronson H.I., Reynolds W.T., Shiflet G.J., Spanos G.: Bainite Viewed Three Different Ways. Metallurgical Transactions. 21A (1990), 1343-1380.
- 2. Bhadeshia H.K.D.H., Christian J.W.: Bainite in Steels. Metallurgical Transactions A 21A (1990), 767-797.
- 3. Barbacki A.: Próba uogólnienia mechanizmu wydzielania węglików stopowych podczas przemiany austenitu w ferryt na przykładzie węglików wanadu i molibdenu. Rozprawy nr 73, Politechnika Poznańska, Poznań, 1976.
- Ławrynowicz Z., Barbacki A.: Carbides precipitation in bainite in an experimental Mo-Cr-V-Ti steel, Conference Proceedings of the 6-th International Conference "Carbides, Nitrides, Borides, "Poznań-Kołobrzeg, (1993), 42-47.
- 5. Ławrynowicz Z., Barbacki A.: Features of Bainite Transformation in Steels. Advances in Materials Science 2 (2002), 5-32.

- 6. Bhadeshia H.K.D.H.: Thermodynamic analysis of isothermal transformation diagrams. Metal Science 16 (1982), 159-165.
- 7. Ławrynowicz Z., Barbacki A.: The mechanism of bainite transformation in Fe-Cr-Mn-Si-C steel, Proc. of the Scientific Con. AMTECH'95, Rousse, Bułgaria, pp. 1-8, 19-21 April 1995.
- 8. Ławrynowicz Z., Barbacki A.: Analiza mechanizmu izotermicznej przemiany bainitycznej w stali Cr-Mn-Si. Archiwum Nauki o Materiałach 17, (1996), 127-147.
- 9. Bhadeshia H.K.D.H.: Diffusional and Displacive Transformations. Scripta Metall. 21 (1987), 1017-1022.
- 10. McLellan R.B., Dunn W.W.: J. Phys. Chem. Solids. 30 (1969), 2631.
- 11. Siller, R.H., McLelan, R.B.: The Application of First Order Mixing Statistics to the Variation of the Diffusivity of Carbon in Austenite. Metallurgical Transactions 1 (1970), 985-988.
- 12. Christian J.W.: Theory of transformations in metals and alloys. 778 Oxford, Pergamon Press, 1965.
- 13. Ławrynowicz Z.: Transition from Upper to Lower Bainite in Fe-C-Cr Steel. Materials Science and Technology 20 (2004), 1447-1454.
- 14. Bhadeshia H.K.D.H.: Bainite in Steels, Institute of Materials, 1-458, London, 1992.
- Ławrynowicz, Z., Dymski, S.: Application of the mechanism of bainite transformation to modelling of processing window in ductile iron ADI. Archives of Foundry Engineering 1 (2006), 177-182.