MECHANISM OF BAINITE TRANSFORMATION
IN Fe-Cr-Mo-V-Ti-C STEEL

Z. Lawrynowicz

Materials Science and Metals Technology
Mechanical Engineering Faculty
ATR, ul. Kordeckiego 20, 85-225 Bydgoszcz, Poland

Abstract The kinetics and mechanism of bainite transformation have been studied in Fe-Cr-Mo-V-Ti-C steel using high speed dilatometry backed by thermodynamic analysis. The complete transformation of austenite, however, has not occured at any reported temperature. Obtained results confirm the incomplete reaction phenomenon with the cessation of the bainite transformation well before the paraequilibrium is achieved. These experimental data indicate that bainitic ferrite is formed by a displacive transformation mechanism, but soon afterwards, excess of carbon is partitioned into the residual austenite. The results are discussed in terms of the mechanism of bainite transformation.

Key Words Bainite Transformation, Steel, Thermodynamic Analysis

چکیده   سینتیک و مکانیزم استحاله بینایت در فولاد Fe-Cr-Mo-V-Ti-C از طریق دیلاتومتری سریع و تحلیل ترمودینامیکی بررسی شده در حالیکه تغییر حالت کامل آستنیت در هیچ دمایی گزارش نشده است. نتایج بدست آمده، پدیدهٔ واکنش ناقص همراه با توقف استحاله بینایتی را قبل از حصول تعادل کامل تأیید می کند. این اطلاعات نشاندهندهٔ تشکیل فریت بینایتی از طریق مکانیزم جابجایی و متعاقب آن توزیع کربن اضافی در فاز آستنیت باقیمانده است. نتایج براساس مکانیزم استحالهٔ بینایت بحث شده است.

INTRODUCTION

The mechanism of bainite transformation in steels remains still controversial and involves two general concepts, the 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]. In 1962 Aaronson developed microstructural definition of bainite. According to this definition, the idea that kinetic bainite start temperature has any fundamental significance was rejected[3,4]. On microstructural definition, bainite is the product of a non-lamellar, non-cooperative mode of eutectoid decomposition. Both product phases are formed by diffusional nucleation and growth, and from this the upper limiting temperature of bainite formation is that of the eutectoidal reaction [5]. Aaronson and co-workers also introduced the hypothesis that occurrence of bainitic "bay" on TTT diagrams in many commercial steels and incomplete reaction phenomenon (transformation stasis) are attributed to a special effect of alloing elements on the growth kinetics, which was termed as a solute drag-like effect (SDLE) [4,6-11]. Problems concerning the kinetic B_s temperature and incomplete reaction phenomenon are important because they are strictly relevant to the mechanism of bainite reaction. The role of carbon in the growth of bainite, is difficult to resolve directly. The relatively high temperatures that bainite typically forms provide an opportunity for the excess of carbon to diffuse rapidly into residual austenite before any experimental measurements can be made [12]. There are however indirect methods of determining the carbon concentration of bainitic ferrite during growth, e.g. the dilatometry method.

It is usually assumed that the point where dimentions cease to change represents the full transformation. But in case of bainitic transformation, reaction ceases before the parent phase has completely transformed to what is known as an incomplete reaction phenomenon. 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 is formed before the reaction terminates. This paper attempts to investigate the mechanism of the bainite transformation in 15HM2VT steel from the thermodynamic point of view.

EXPERIMENTAL PROCEDURES

The composition of the steel investigated is given in Table 1. It was established that 15HM2VT steel exhibits a bainitic microstructure in the range of upper bainite formation without carbides precipitation, consisting of a mixture of bainitic ferrite, retained austenite and martensite after isothermal transformation at temperatures below the bainite start temperature B_s and on subsequent cooling to room temperature [13]. 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$300Ks^{-1}) from austenitizing temperature (1000°C. 10 minutes), the specimens were 13 mm in length and 1.1mm in diameter. Lattice parameter measurements were carried out using an X-ray diffractometer with Fe-filtered CoK$_\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 $\theta = 90°$. 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 tempeature of 1100°C while the specimen was in the single γ phase field. Determination of the linear expantion coefficients was carried out in a UBD Leitz-Wetzlar dilatometer.

THEORY FOR THE CONVERSION OF DILATOMETRY DATA

Assuming isotropic strain, and for the transformation of austenite into a mixture of bainitic ferrite and carbon enriched residual austenite involving no precipitation of carbides the relationship between dimentional changes ΔL and volume changes ΔV is given by the equation [14]:

$$\frac{\Delta V}{V} \approx 3\frac{\Delta L}{L} = 1 - \frac{a_\gamma^3}{\beta + a_{e\gamma}^3} \tag{1}$$

where

$$\beta = \frac{2a_\alpha^3 - a_{e\gamma}^3}{1 + [(2 V_\gamma a_\alpha^3)/(V_\gamma a_{e\gamma}^3)]} \tag{2}$$

TABLE 1. Chemical Composition of the Steel Used in This Study. All Concentrations Are Given in wt. % and at. %.

Steel		C	Si	Cr	Mn	Mo	V	Ti
15 HM2VT	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

L is the specimen length at the transformation temperature, V_γ and V_α are the volume fraction of residual austenite and bainitic ferrite, respectively and $a_{e\gamma}$ is the calculated lattice parameter of austenite after trasnformation, taking account of the carbon enrichment in austenite when $V_\alpha \neq 0$. The lattice parameters of bainitic ferrite and untransformed austenite at the reaction temperature, a_α and a_γ, can be calculated from the values of lattice parameters at ambient temperature (25°C, 298K) using the linear thermal expansion coefficients e_α and e_γ:

$$a_\alpha = a_{o\alpha} [1 + e_\alpha (T - 298)] \qquad (3)$$

$$a_\gamma = a_{o\gamma} [1 + e_\gamma (T - 298)] \qquad (4)$$

where T is the absolute temperature. The room temperature lattice parameter of austenite ($a_{o\gamma}$ in nm) at the mean steel composition (i.e. when $V_\alpha = 0$) can be calculated using the equation determined by Dyson and Holmes [15]:

$$a_{o\gamma} [nm] = 0.3578 + \sum_{i=1}^{n} C_i x_i \qquad (5)$$

where C_i are coefficients and x_i is the weight fraction of alloying element in phase γ, where $i = 1, 2, ..., n$ represents alloying elements ($i=1$ for carbon, $i>1$ for substitutional solutes). The ferrite lattice parameter $a_{o\alpha}$ was determined by X-ray analysis and for assurance it was calculated using following equation [14]:

$$a_{o\alpha} [nm] = 0.28664 + (3 a_{Fe}^2)^{-1} [(a_{Fe} - 0.0279 x^\alpha_c)^2 \times (a_{Fe} + 0.2496 x^\alpha_c) - a_{Fe}^3] - 0.003 x^\alpha_{Si} + 0.006 \ x^\alpha_{Mn} + 0.007 x^\alpha_{Ni} + 0.031 x^\alpha_{Mo} + 0.005 \ x^\alpha_{cr} + 0.0096 x^\alpha_V \qquad (6)$$

The lattice parameter of pure ferrite was taken as $a_{Fe} = 0.28664 nm$ [16]. The terms x^α_i represent the mole fraction of the species i in phase α. The carbon concentration of the residual austenite x_i^γ increases during bainitic transformations as a consequence of the increasing volume fraction of bainitic ferrite. Given that the excess carbon in the bainite ferrite partitions into the residual austenite and assuming that the final microstructure consists of only bainitic ferrite and residual austenite it is possible to estimate the carbon concentration according to the following relationship derived from mass balance considerations [14]:

$$X_1^\gamma = \frac{2 a_\alpha^3 \bar{x} (1 - x_1^\alpha)(1 - V_\alpha) + a_{e\gamma}^3 (\bar{x} - x_1^\alpha) V_\alpha}{2 a_\alpha^3 (1 - x_1^\alpha)(1 - V_\alpha) + a_{e\gamma}^3 (\bar{x} - x_1^\alpha) V_\alpha} \qquad (7)$$

The carbon content of the ferrite x_1^α, is very small and is approximated by the $A_{e1} \alpha/(\alpha+\gamma)$ phase boundary of the Fe-C phase diagram (because of its smallness the effect of substitutional elements is ignored). The value of carbon in bainitic ferrite was taken to be $x_1^\alpha = 0.00139 (0.03$ wt.%) [17]. The calculated carbon concentrations of residual austenite at the point where the formation of bainite terminates will be then compared against the extrapolated T_o, T'_o and A'_{e3} phase boundaries.

RESULTS AND DISCUSSION

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 (Figure 1), then the amount of bainite formed is dependent on the transformation temperature. The lattice parameters of ferrite and austenite and values of linear expansion coefficients are given in Table 2. The details for calcualtion of volume fraction of transformation and determined carbon concentration of the residual austenite are given in Table 3.
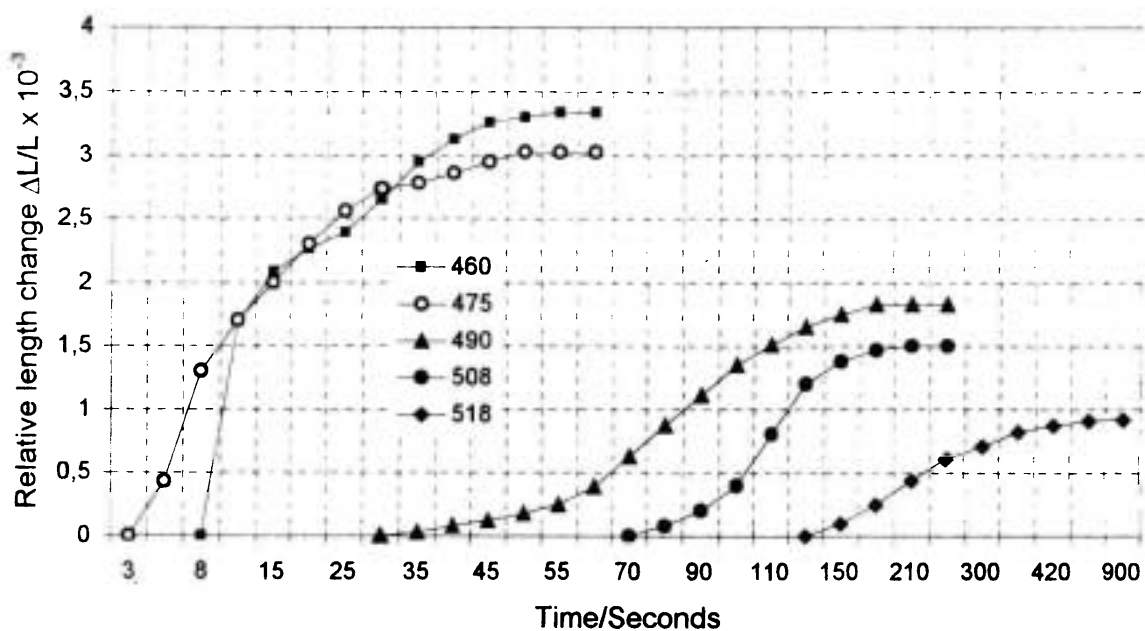
Relative length change $\Delta L/L \times 10^{-3}$

4
3,5
3
2,5
2
1,5
1
0,5
0

—■— 460
—○— 475
—▲— 490
—●— 508
—◆— 518

3 8 15 25 35 45 55 70 90 110 150 210 300 420 900

Time/Seconds

Figure. 1. The relative length change ($\Delta L/L$) observed by dilatometry during isothermal transformation below B_s temperature in 15HM2VT steel.

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 and A'_{e3} phase boundaries for examined 15HM2VT steel in Figure 2. The diagram was calculated as in Reference [17] using a model developed by Bhadeshia [18] based on the McLellan and Dunn quasi-chemical thermodynamic model [19]. The T'_0 curve allows for 400J/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 [20, 21]. The A'_{e3} curve is the

calculated paraequilibrium ($\alpha+\gamma$)/γphase boundary indicating equilibrium between ferrite and austenite when the ratio of substitutional alloying elements to iron is constant everywhere. The bainite and martensite reactions start temperatures B_s and M_s are also marked on that diagram. The paraequilibrium phase boundary is chosen because no substitutional alloying element partitioning occurs during bainite formation. In presented experiment 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'_{e3} boundary (black circles in Figure 2). The above presented

TABLE 2. Lattice Parameters and Linear Expansion Coefficients of Ferrite and Austenite.

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

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

Transformed at [°C]	a_γ [nm]	a_α [nm]	$\Delta L/L$ $\times 10^{-3}$*	$\Delta L/L$ $\times 10^{-3}$**	V_{BT}	x_1^γ [mol]
460	0.36278	0.28926	4.53	3.34	0.74	0.0224
475	0.36290	0.28933	4.43	3.03	0.68	0.0185
490	0.36302	0.28939	4.33	1.83	0.42	0.0110
508	0.36317	0.28947	4.22	1.50	0.35	0.0100
518	0.36325	0.28952	4.15	0.92	0.22	0.0085

* Values of the dimentional changes accompanying the complete transformation of austenite to bainitic ferrite at transformation temperature,
** Measured data at transformation temperature,
V_{BT} Volume fraction of transformation

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
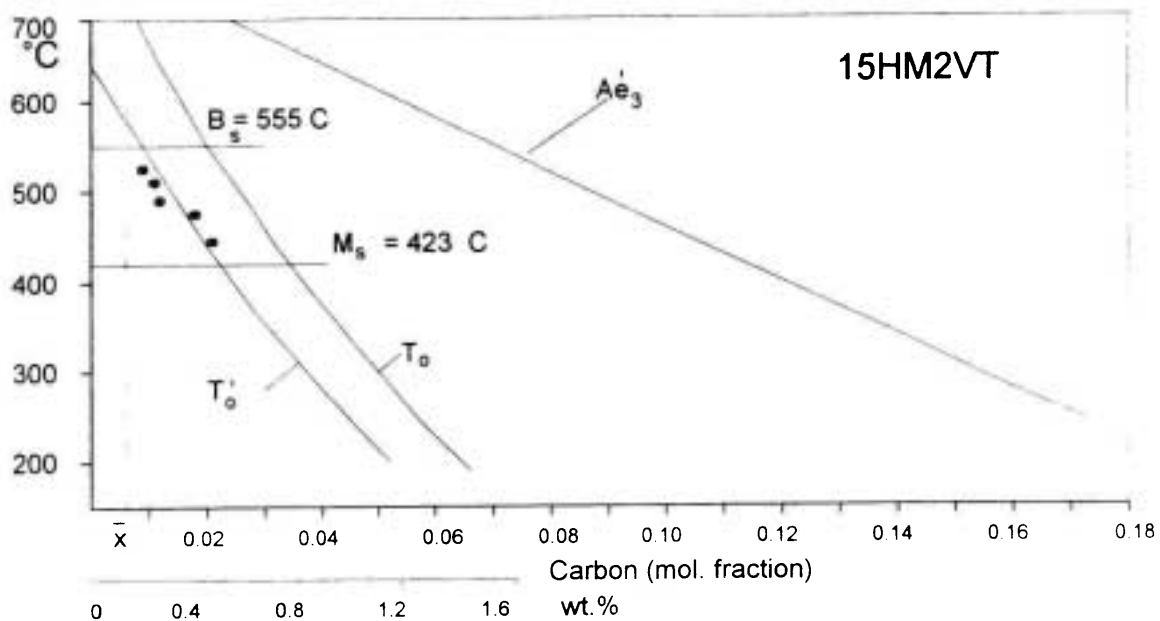

Figure 2. Calculated phase diagram with experimental data of carbon concentration of residual austenite at the termination of isothermal bainite formation for 15HM2VT steel (black circles represent experimental data).

hypothesis that the growth of bainitic ferrite occurs without any diffusion with carbon being partitioned subsequently into the residual austenite.

CONCLUSION

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 degree of transformation to bainite strongly decreases with approaching the bainite start temperature. At any temperature investigated did not occur the complete transformation of austenite.

2. The formation of bainitic ferrite terminates well before the carbon content of the residual austenite reaches the level given by the extrapolated A'_{e3} phase boundary, what is called the incomplete reaction phenomenon.

3. The bainite reaction in 15HM2VT steel follows an incomplete reaction phenomenon which indicates that the growth of bainitic ferrite is diffusionless.

ACKNOWLEDGEMENTS

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