JOURNAL OF MATERIALS SCIENCE LETTERS 8 (1989) 477–478

# The interpretation of dilatometric data for transformations in steels

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Dilatometry is one of the most powerful techniques for the study of transformations in steels, because it permits the real-time monitoring of the extent of reaction in terms of dimensional changes due to transformation. In interpreting the experimental data, it is usually assumed that during isothermal reaction the dimensional change observed is proportional to the volume fraction of transformation, and it is sometimes assumed that the point where dimensions cease to change represents 100% of transformation. When reaction ceases before the parent phase has completely transformed, it is useful to be able to calculate the volume fraction of product phase that has been obtained. The purpose of this letter is to examine whether the dimensional change can be assumed to be proportional to the volume fraction of transformation, and to provide a method for quantitatively relating length change to the extent of transformation. To illustrate the results, the equations are applied to a steel of specific composition, Fe–0.3 wt % C–4.08 wt % Cr, which is being used in our current research, but they are of general validity since the chromium can be replaced by other subtitutional elements or combinations of elements. For the transformation of austenite ($\gamma$) into a mixture of bainitic ferrite and carbon-enriched austenite, Bhadeshia [1] has shown that the relative length change $\Delta l/l$, which is the observed length change divided by the length of the specimen, can be related to the volume fraction of ferrite ($V_\alpha$) by

$$\frac{\Delta l}{l} = \frac{2V_\alpha a_\alpha^3 + (1 - V_\alpha)a_\gamma^3 - a_{\gamma 0}^3}{3a_{\gamma 0}^3} \qquad (1a)$$

with

$$a_\alpha = a_{\alpha 0}[1 + l_\alpha(T - 25)]$$

$$a_{\gamma 0} = (c_1 + c_2\bar{X} + c_3 X_{Cr})\,[1 - l_\gamma(T - 25)]$$

$$a_\gamma = (c_1 + c_2 X + c_3 X_{Cr})\,[1 + l_\gamma(T - 25)]$$

where $c_i$ are coefficients which express the lattice parameter as a function of concentration; $\Delta l/l$ = length change due to transformation per unit length; $V_\alpha$ = volume fraction of ferrite transformed; $T$ = reaction temperature (°C); $l_{\alpha,\gamma}$ = linear thermal expansion coefficients of ferrite and austenite, respectively (°C$^{-1}$); $\bar{X}$ = average carbon content in the steel (at %); $X_{Cr}$ = average chromium content in the steel (at %); $X$ = carbon content of residual austenite at any stage of the reaction (at %); $a_{\gamma 0}$ = lattice parameter of austenite at the reaction temperature before the reaction; $a_\gamma$ = lattice parameter of austenite at the reaction temperature at any stage of the reaction; $a_{\alpha 0}$ = lattice parameter of ferrite at ambient temperature (25° C); $a_\alpha$ = lattice parameter of ferrite at reaction temperature.

In Equation 1a it is assumed that $\Delta l/l$ is one-third of the relative volume change $\Delta V/V$; this is a very good approximation since the changes in density during transformations in steels are small. For the same reason the implicit assumption that mass fractions and volume fractions are identical is also justified. If this last assumption is avoided,

$$\frac{\Delta l}{l} = \left[1 + \frac{1}{a_{\gamma 0}^3}\left(\frac{2a_\alpha^3 a_\gamma^3}{V_\alpha a_\gamma^3 + 2(1 - V_\alpha)a_\alpha^3} - a_{\gamma 0}^3\right)\right]^{1/3} - 1 \qquad (1b)$$

However, the difference between the results from Equations 1a and b is found to be negligible. The factor of 2 in the numerator of Equation 1a arises because the unit cell of ferrite contains two iron atoms whereas that of austenite has four.

Note that Equations 1 can be used for all situations where austenite decomposes into a mixture of carbon-enriched residual austenite and ferrite, and, furthermore, the ferrite may or may not be supersaturated with respect to carbon, since the effect of excess carbon is manifested in an alteration of the lattice parameter of the ferrite. Using a similar method, the following equation can be derived for the case where cementite precipitation occurs in conjunction with ferrite formation from austenite:

$$\frac{\Delta l}{l} = \frac{2V_\alpha a_\alpha^3 + V_\theta a_\theta^3/3 + (1 - V_\alpha - V_\theta)a_\gamma^3 - a_{\gamma 0}^3}{3a_{\gamma 0}^3} \qquad (2)$$

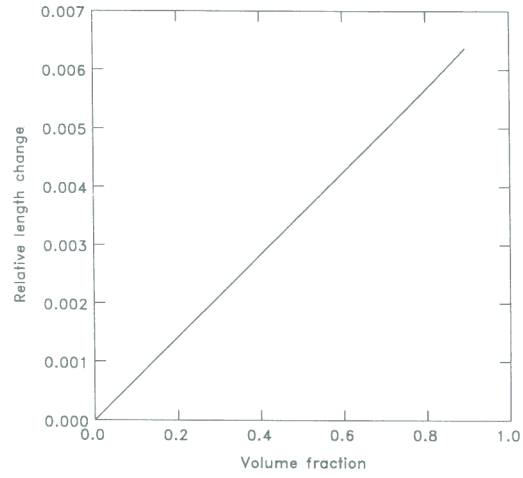


*Figure 1* Length change as a function of volume fraction of ferrite, during isothermal transformation of austenite at 420° C. The ferrite is assumed to contain 0.03 wt % carbon and the composition of the austenite changes during transformation.

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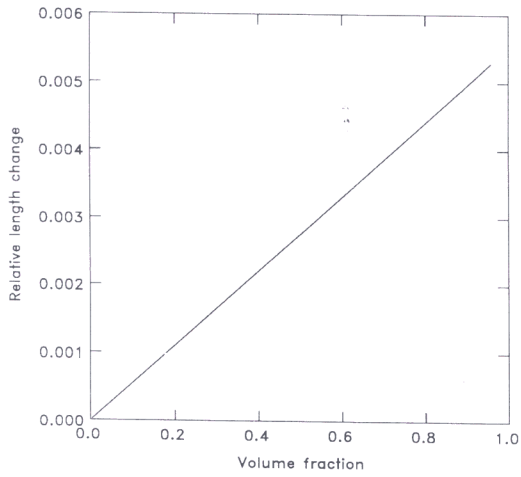


*Figure 2* Length change as a function of volume fraction of ferrite, during isothermal transformation of austenite at 420° C. The ferrite is assumed to be supersaturated with 0.2 wt % carbon and the composition of the austenite changes during transformation.

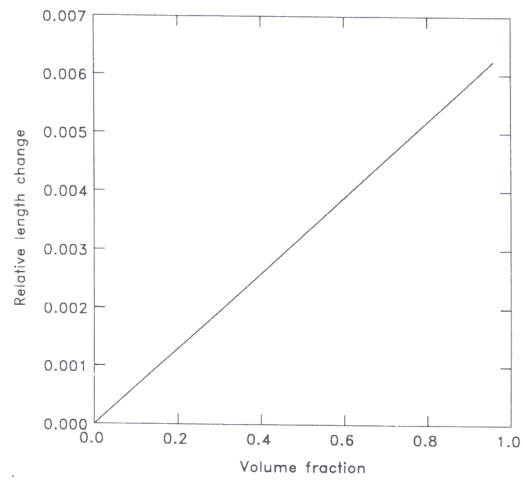


*Figure 3* Length change as a function of the combined volume fractions of ferrite and cementite, obtained by isothermal transformation of austenite at 420° C. The ferrite is assumed to be carbon-free, and the carbon used up in forming cementite is represented by $S = 0.2$ wt %. The composition of the austenite changes during transformation.

where $V_\theta$ = volume fraction of cementite, $a_\theta^3 = a_\theta b_\theta c_\theta$, and $a_\theta$, $b_\theta$ and $c_\theta$ = lattice parameters of cementite, which are 0.451, 0.508 and 0.673 nm, respectively, at room temperature. The volume fraction of cementite, where the total carbon content in ferrite including any cementite particles is $S$, can be obtained as follows, assuming all carbon atoms in the ferrite to be locked in cementite,

$$V_\theta = 1/(1 + k)$$

with

$$k = \frac{a_\alpha^3(1 - 3\,S/X_{Fe})}{a_\theta^3\,\frac{1}{2}\,S/X_{Fe}}$$

where $X_{Fe}$ = iron content in ferrite (at %) and $S$ = total carbon content in ferrite including any cementite (at %). The dependences of the lattice parameter on alloying elements have been calculated using $c_1 = 0.3573$, $c_2 = 0.000\,63$ and $c_3 = 0.000\,06$ nm [2] when the chemical contents of carbon and chromium are measured in at %. The carbon content of residual austenite $X$ is related to the volume fraction $V$ of ferrite or ferrite and cementite transformed:

$$X = \frac{\bar{X} - VS}{1 - V}$$

Therefore the lattice parameter of austenite in the equations changes with the volume fraction of ferrite or ferrite and cementite.

Figs1–3 represent the relationships between volume fractions transformed and corresponding relative length changes during isothermal transformation at 420° C to ferrite with 0.03 wt % carbon, to supersaturated ferrite with 0.2 wt % carbon and to a mixture of carbon-free ferrite and cementite with 0.2 wt % of carbon locked in the transformed phases altogether, respectively. In these calculations the expansion coefficients of ferrite and austenite are taken to be $1.1826 \times 10^{-5}$ and $1.8431 \times 10^{-5}\,°C^{-1}$ [1] and, in the absence of experimental data, the linear expansivity of cementite is assumed to be the same as that of ferrite. It is evident that the linearity between the volume fraction of transformation products and the corresponding relative length change is preserved, at least, up to 0.7 of the volume fraction. It is emphasized, however, that in Equations 1 and 2 it is never justified to assume that the maximum length change observed during isothermal transformation corresponds to the complete transformation of austenite.

## Acknowledgements

The authors are grateful to Professor D. Hull for the provision of laboratory facilities at the University of Cambridge, and to the Nippon Steel Corporation for funding this research.

## References

1. H. K. D. H. BHADESHIA, *J. Physique* **43** (1982) C4-443.
2. N. RIDLEY, H. STUART and L. ZWELL, *Trans. AIME* **245** (1969) 1834.

*Received 22 August*
*and accepted 29 September 1988*