Temperature cycling and the rate of the bainite transformation

H. S. Hasan[1,2], M. Peet[1], H. K. D. H. Bhadeshia*[1], S. Wood[3] and E. Booth[3]

The possibility that the thermal cycling of supercooled austenite, within the bainite transformation range, accelerates the kinetics of decomposition, is investigated both by analysing previous work and by conducting a series of new experiments. The cyclic variations in temperature do not seem to anomalously affect the rate of transformation.

Keywords: Bainite, Superbainite, Kinetics, Cyclic heat treatment

Introduction

There is a novel range of steels under development, based on bainite forming at exceptionally low temperatures.[1–6] The advantage of suppressing the transformation temperature is that incredibly fine platelets of bainitic ferrite are generated which are only 20–40 nm in thickness. This makes the steel strong and in combination with the austenite that is retained, gives a useful range of properties which have been exploited in the manufacture of armour.[7,8] There are other applications in the aircraft industry that are at a critical stage of development.

One characteristic of transformation at low temperatures is that the rate of reaction is slow, sometimes taking days in order to achieve the maximum fraction of bainitic ferrite. The reaction can be accelerated by refining the austenite grain size and by adding solutes which increase the free energy change accompanying transformation.[9]

Sista et al. have suggested an alternative method, that the reaction can be speeded up by cycling the austenite between two temperatures within the range M_s–B_s, the martensite and bainite start temperatures respectively.[10] Single step changes in the temperature during the course of the reaction has been investigated before,[11] to show indirectly that the stresses generated by phase transformation at low temperatures can stimulate transformation at higher temperatures.

As will be described later, there are some difficulties in interpreting the published data. The purpose of the present work was therefore to investigate the influence of thermal cycling on the kinetics of the low temperature bainite reaction. The paper begins with an assessment of the previous work[10] and goes on to present and interpret new experiments.

Previous work

In their experiments on SAE 1080 steel, Sista et al.[10] supercooled the austenite into the bainite transformation range, and cycled the temperature linearly between 260 and 300°C. It was claimed that the cycled samples formed bainite more rapidly than those which were simply isothermally held at 260 or 300°C. In particular, the extent of transformation was suggested to reach a limiting value earlier in the cyclic samples. The data were presented as separate graphs from each experiment and hence were difficult to interpret. Their data are replotted in Fig. 1 for the two cases reported.

A close examination of the data for the low time periods where most of the reaction is observed, shows that the cyclic treatment did not in fact increase the rate of transformation relative to isothermal transformation at 300°C. In the early stages of transformation, the cyclic curve was, as might be expected, enveloped between the two isothermal transformation curves. It is more difficult to assess what happens at the advanced stages; the cyclic curves do not level out but seem to show a maximum in strain. Nevertheless, an attempt has been made as follows. The extracted data in Table 1 show that the evidence is not strong for an acceleration of transformation due to the thermal cycling. It should be noted that in the experiments,[10] much of the transformation is completed before cycling is applied.

New experiments

Procedure

The steel used belongs to the class of low temperature bainite[1–6,12] but with cobalt and aluminium added in order to reduce the transformation time from days to hours.[9,13] This is necessary in order to conduct experiments on a thermomechanical simulator. The chemical composition of the steel is given in Table 2.

Cylindrical samples of 8 mm diameter and 12 mm length were austenitised at 1000°C for 15 min followed by cooling to the isothermal transformation temperature, or for a variety of cyclic heat treatments. All the heat treatments were carried out in a thermecmastor thermomechanical simulator which has been described elsewhere.[9] The results were supported with routine optical microscopy and Vickers hardness measurements.
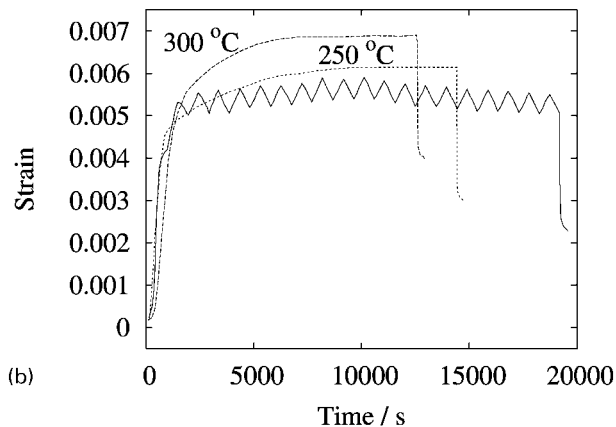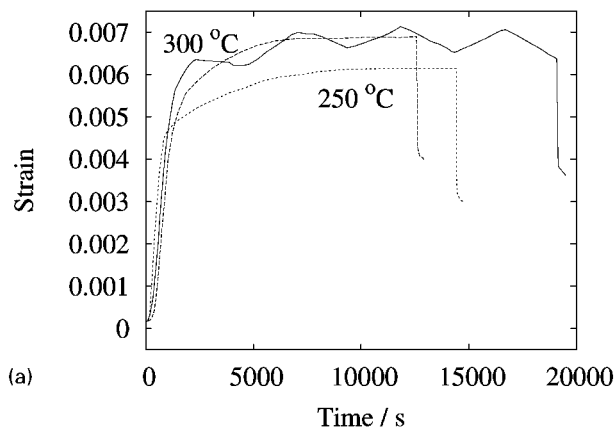
Results and discussion

The results are presented in Fig. 2 for both isothermal and cyclic treatments, where the latter are said to be

[1]University of Cambridge, Cambridge, UK
[2]University of Technology, Baghdad, Iraq
[3]Rolls–Royce plc, Derby, UK

*Corresponding author, email hkdb@cam.ac.uk

	5% time, s	95% time, s
Isothermally transformed at 260°C	420	4600
Isothermally transformed at 300°C	180	5400
Cyclic treatment (80 min period)	300	5700
Cyclic treatment (16 min period)	370	6000

Table 2 Chemical composition of steel studied, wt-%

C	Si	Mn	Mo	Cr	Co	Al
0·78	1·6	2·02	0·25	1·01	3·87	1·37

symmetrical since the magnitudes of the heating and cooling rates were identical within each cycle. The diameter of each sample on reaching the designated temperature is plotted so that the vertical distance between any two curves at the beginning of the plot, corresponds exactly to the strain due to thermal contraction alone. All of the data show that cyclic transformation does not lead to an acceleration of the reaction, in the sense that the cyclic transformation curves fall between the high and low temperature isothermal transformation data. Note also that the transformation rates are such that much of the decomposition of austenite takes place during the cycling. Further confirmatory results are shown in Fig. 3, including one which has an asymmetrical cycle.

a 80 min to complete one cycle; *b* 16 min per cycle

1 Replotted isothermal transformation and cyclic treatment kinetic data from Ref. 10
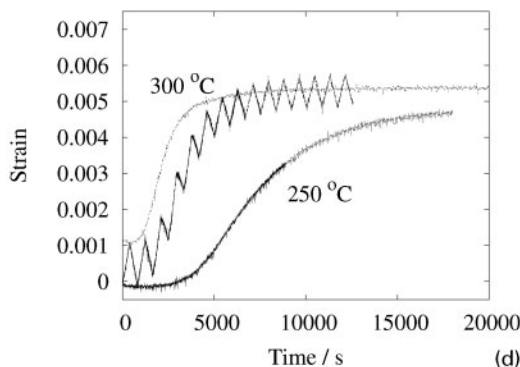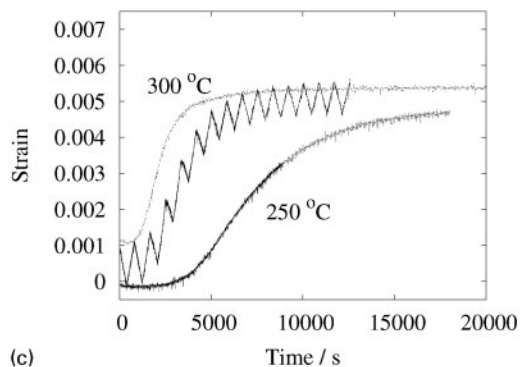
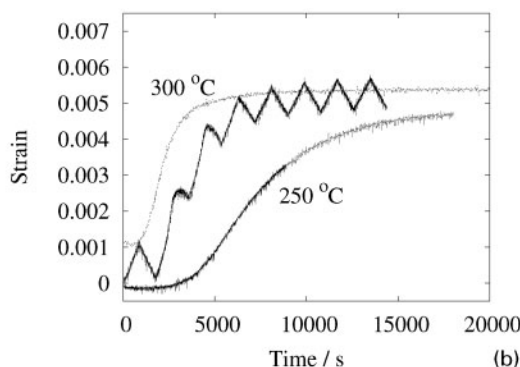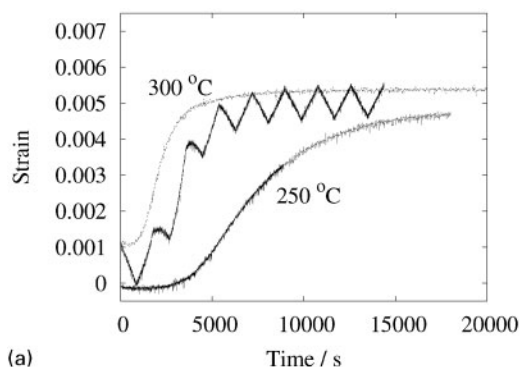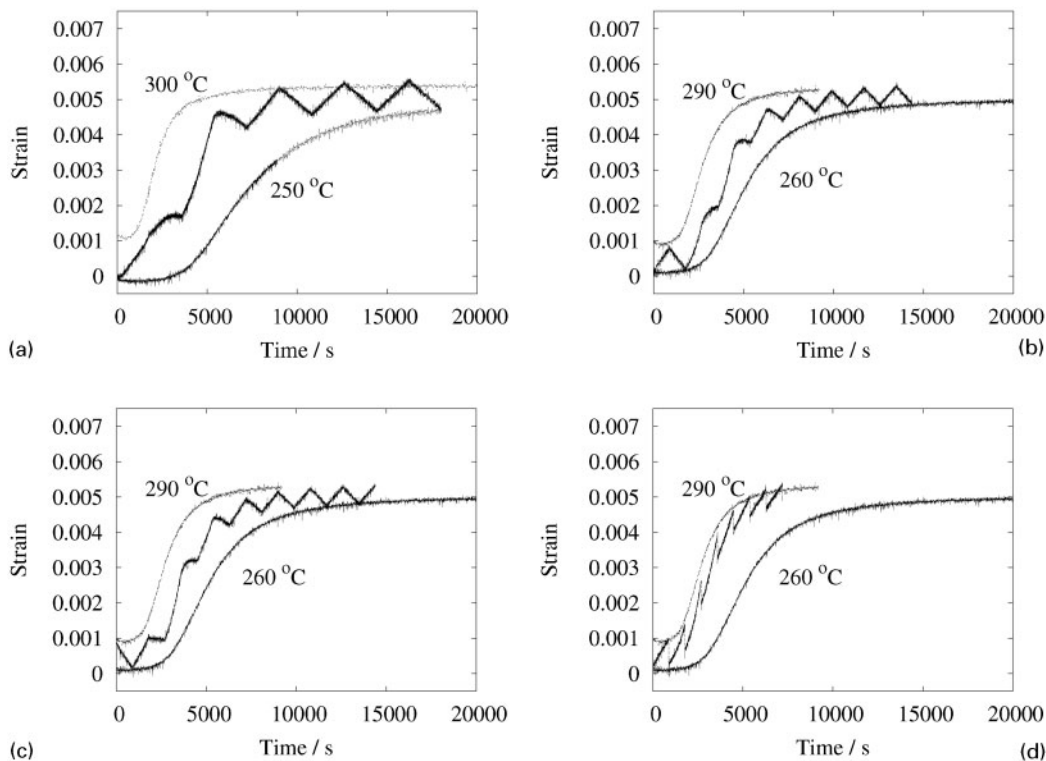*a* 30 min cycle from 300→250→300°C; *b* 30 min cycle from 250→300→250°C; *c* 15 min cycle from 300→250→300°C; *d* 15 min cycle from 250→300→250°C

2 Dilatometric data: in each case, upper and lower curves represent isothermal transformation at highest and lowest temperatures quoted respectively, and zigzag curves represent symmetrical cyclic treatments

a 60 min cycle from 250→300→250°C; *b* 30 min cycle from 260→290→260°C; *c* 30 min cycle from 290→260→290°C; *d* 15 min asymmetrical cycle from 260→290→260°C
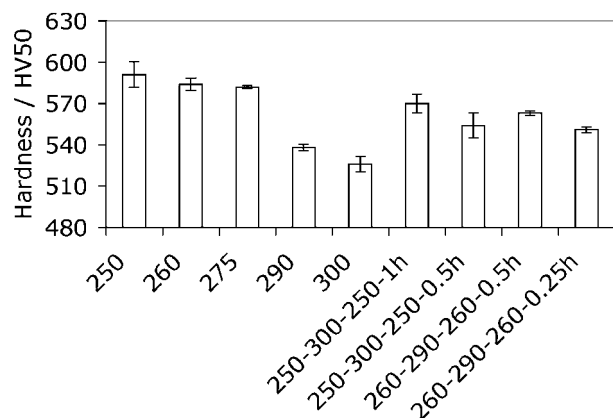
3 Dilatometric data: in each case, upper and lower curves represent isothermal transformation at highest and lowest temperatures quoted respectively, and zigzag curves represent symmetrical cyclic treatments

There are some detailed features of the experiments which need discussion. If T_H and T_L represent the high and low isothermal transformation temperatures, then at long transformation times, Figs. 2 and 3 show that the peak strains recorded for cyclic curves exceed the values corresponding to the isothermal curves for T_H. This is because transformation at T_H saturates before that at T_L. The fraction of bainite V_L possible at T_L is greater than that at T_H because of the incomplete reaction phenomenon in which the maximum extent of transformation to carbide free bainite decreases as the transformation temperature is raised.[14] This means that at long transformation times, cyclic transformation will stop when the fraction of bainite reaches V_L and when this is heated to T_H, the dilatometer strain recorded will

be greater than that associated with isothermal transformation at T_H since $V_L > V_H$.

The second detail to observe from short time events in Figs. 2 and 3 is that during cyclic transformation, the majority of the reaction occurs during the heating part of the cycle. This is expected since the kinetics of reaction are faster at the higher temperatures.

Figure 4 shows Vickers hardness data: mean values from five measurements in each case are plotted along with their standard deviations. The hardness is a good indicator of the progress of transformation at long times.[5] It is evident that in all cases, the hardness of the cycled samples falls between that of the bounding isothermal tests.

Conclusion

We do not find that alterations of temperature within the bainite transformation range perceptibly affect the reaction rate when compared with isothermal heat treatment.

Acknowledgement

4 Vickers hardness data: temperatures on horizontal axis are in °C and cycle period is quoted where relevant

References

1. F. G. Caballero, H. K. D. H. Bhadeshia, K. J. A. Mawella, D. G. Jones and P. Brown: *Mater. Sci. Technol.*, 2002, **18**, 279–284.
2. F. G. Caballero and H. K. D. H. Bhadeshia: *Curr. Opin. Solid State Mater. Sci.*, 2005, **8**, 186–193.

3. F. G. Caballero, H. K. D. H. Bhadeshia, K. J. A. Mawella, D. G. Jones and P. Brown: *Mater. Sci. Technol.*, 2001, **17**, 512–516.

4. F. G. Caballero, H. K. D. H. Bhadeshia, K. J. A. Mawella, D. G. Jones and P. Brown: *Mater. Sci. Technol.*, 2001, **17**, 517–522.

5. C. Garcia-Mateo, F. G. Caballero and H. K. D. H. Bhadeshia: *ISIJ Int.*, 2003, **43**, 1238–1243.

6. C. G. Mateo and H. K. D. H. Bhadeshia: *Mater. Sci. Eng. A*, 2004, **A378**, 289–292.

7. H. K. D. H. Bhadeshia: *Mater. Sci. Technol.*, 2005, **21**, 1293–1302.

8. P. M. Brown and D. P. Baxter: in 'Materials science and technology 2004', 433–438; 2004, Warrendale, PA, TMS.

9. C. Garcia-Mateo, F. G. Caballero and H. K. D. H. Bhadeshia: *ISIJ Int.*, 2003, **43**, 1821–1825.

10. V. Sista, P. Nash and S. S. Sahay: *J. Mater. Sci.*, 2007, **42**, 9112–9115.

11. R. H. Goodenow, R. H. Barkalow and R. F. Hehemann: in 'Physical properties of martensite and bainite', special report 93, 135–141; 1969, London, Iron and Steel Institute.

12. H. K. D. H. Bhadeshia: *Mater. Sci. Eng. A*, 2008, **A481**–**A482**, 36–39.

13. H. I. Aaronson, H. A. Domian and G. M. Pound: *Trans. Metall. Soc. AIME*, 1966, **236**, 781–796.

14. H. K. D. H. Bhadeshia and D. V. Edmonds: *Acta Metall.*, 1980, **28**, 1265–1273.