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Effect of 30 T magnetic field on transformations in a novel bainitic steel

R.A. Jaramillo [a,*], S.S. Babu [a], G.M. Ludtka [a], R.A. Kisner [a], J.B. Wilgen [a], G. Mackiewicz-Ludtka [a], D.M. Nicholson [a], S.M. Kelly [b,c], M. Murugananth [d], H.K.D.H. Bhadeshia [e]

[a] *Metals and Ceramics Division, Oak Ridge National Laboratory, P.O. Box 2008 MS6064, Oak Ridge, TN 37831, USA*
[b] *Joint Institute for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[c] *Department of Materials Science and Engineering, Virginia Tech, 213 Holden Hall, Blacksburg, VA 24061-0237, USA*
[d] *School of Materials Engineering, Nanyang Technological University, Singapore 639798*
[e] *Materials Science and Metallurgy, University of Cambridge, Cambridge, CB2 3QZ, UK*

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Abstract

The continuous cooling transformation characteristics of novel bainitic steels have been studied, both under ordinary conditions and whilst subjected to a 30 T magnetic field. The magnetic field has been found to completely change the microstructure obtained, from a mixture of bainite and martensite to one containing an incredibly fine pearlite with an interlamellar spacing of about 50 nm. As a consequence, the pearlite is found to be much harder than any other examples found in the published literature.

Keywords: Steel; Transformtions; Magnetic field; Pearlite; Martensite; Bainite; Continuous cooling

1. Introduction

Novel bainitic steels have recently been developed with strengths in excess of 2 GPa [1–4]. The distinguishing characteristic of these steels is that they transform at such low temperatures that the bainite plates can be as thin as 20–40 nm; this, combined with the presence of carbon-enriched austenite between the bainite, ensures the impressive combination of strength and toughness [1–4]. This microstructure is generated during isothermal transformation at 200 °C for more than 400 h, depending on the alloy composition [1,4]. The rate of transformation can be accelerated without compromising the scale of the microstructure or the mechanical properties. This is done by increasing the magnitude of the free energy change accompanying the decomposition of austenite, with the addition of cobalt and/or aluminum [5]; in this case, the time required is reduced to some 100 h.

A further way of influencing the driving force for the transformation of austenite is to impose a magnetic field; this is because the ferrite is ferromagnetic below about 760 °C whereas the austenite in low-alloy steels is paramagnetic [6,7]. The subject has been reviewed by Shimizu [8]. Given these differences, it is expected that transformation under the influence of a magnetic

* Corresponding author. Tel.: +1 865 576 3768; fax: +1 865 574 3940.
E-mail address: jaramillora@ornl.gov (R.A. Jaramillo).

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field will increase the change in free energy as austenite transforms to ferrite. Thus, a 30 T magnetic field can raise transformation temperatures by ∼90 °C during continuous cooling [9]. It was therefore the purpose of the present study to attempt to accelerate the low-temperature bainite reaction using strong magnetic fields. Two steels have been studied, one which transforms more rapidly than the other because it has been alloyed with cobalt and aluminum.

2. Experimental procedure

The alloy compositions are shown in Table 1. The silicon is at a concentration which inhibits cementite precipitation from austenite, and the other alloying elements are added to control hardenability, the austenite grain size and temper embrittlement, as described elsewhere [1–5]. As stated earlier, the sole purpose of the cobalt and aluminum is to accelerate transformation. The terms "FK" and "SK" therefore refer to fast and slow kinetics, respectively. The steels were homogenized for 48 h at 1200 °C before the experiments. They were then subjected to austenitization at 1000 °C and continuous cooling magnetic field processing. Test specimens were rectangular with dimensions of 12 × 5 × 2 mm.

Table 1
Alloy compositions in wt%

Alloy	C	Si	Mn	Mo	Cr	Co	Al	V	Fe
SK	0.75	1.63	1.95	0.28	1.48	–	0.01	0.10	Balance
FK	0.78	1.60	2.02	0.24	1.01	3.87	1.37	–	Balance

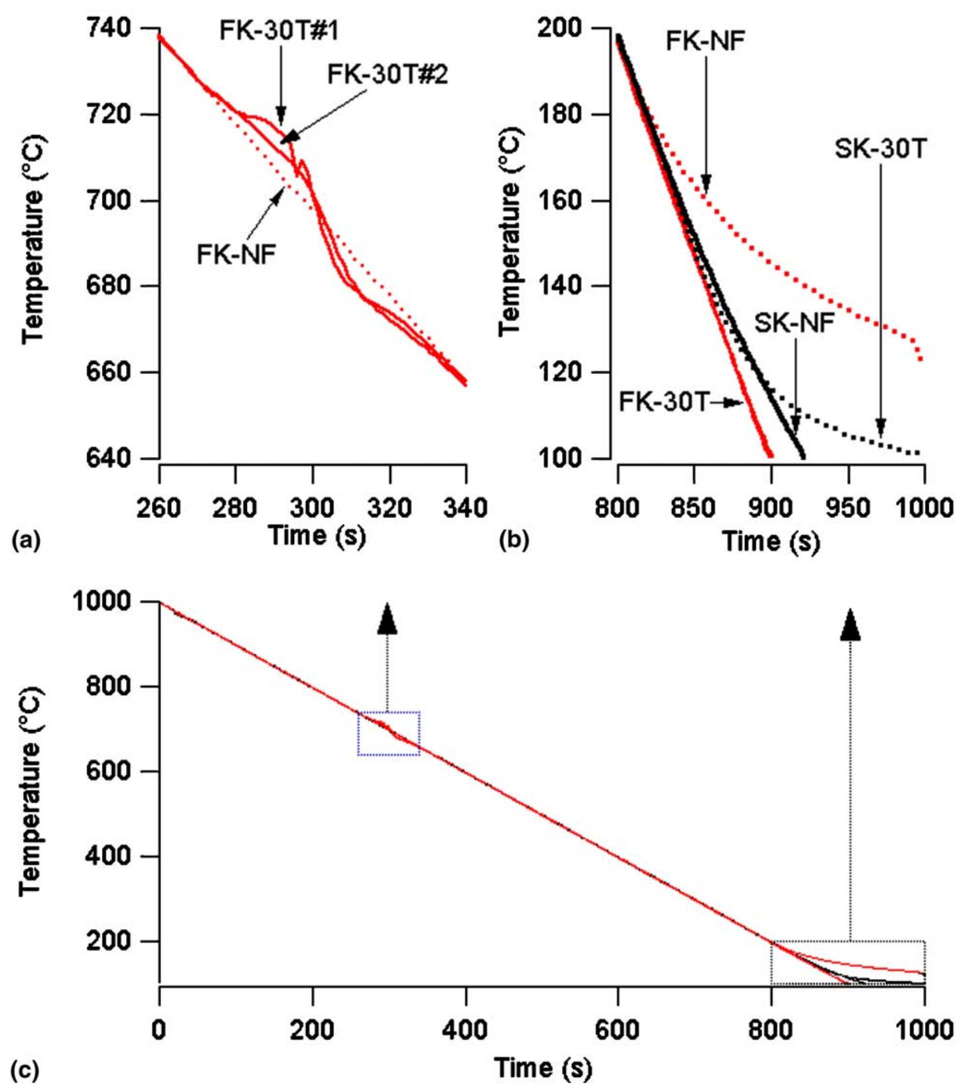

Fig. 1. Measured time–temperature plots. (a) FK-30 T, two runs; (b) FK-NF, SK-NF, SK-30 T; (c) as for (a), but placing the recalescence events in context.

A 32 mm bore diameter resistive-magnet with a 33 T maximum field strength at the National High Magnetic Field Laboratory was used for the experiments. A key component of the experimental work was the ability to heat and cool the specimen while inside the bore of the magnet. A custom designed induction-heating coil coupled with a gas purge system for atmosphere control and specimen cooling was fabricated for this purpose. The system locates the specimen in the center of the bore mid-length and can heat it up to 1100 °C and maintain the temperature for extended periods of time. The atmosphere is maintained by purging with argon. Rapid cooling is achieved using a helium gas quench. The magnetic field can be imposed at any stage of the heat treatment. Temperature measurements were made using a type "S" (Pt–10%Rh) thermocouple spot-welded on the surface at the mid-length of the specimen.

In all cases, the samples were heated at 11 °C/s to 700 °C, followed by heating at 5 °C/s to 1000 °C and held for 3 min in order to complete austenitization. The magnetic field was ramped up one minute after reaching 1000 °C and it took 90 s to reach 30 T. Specimen cooling was controlled via feedback loop such that by decreasing power to the induction coil, a 1 °C/s cooling rate was obtained. The sample temperatures were monitored continuously.

Throughout this paper, the designations SK-NF and SK-30 T refer to experiments conducted without and with a field (30 T), respectively, and the same adjuncts are used for the FK steel.

The microstructures were characterized using optical microscopy applying standard preparation and etching techniques. Vickers hardness distributions were measured with a Buehler Micromet 2001 tester equipped with Omnimet Advantage software, intervals of 200 μm with 300-g loads. Samples for transmission electron microscopy were prepared using standard electropolishing techniques and examined using a Philips Tecnai-20 operated at an accelerating voltage of 200 kV.

3. Results and discussions

The measured cooling curves from 1000 °C are presented in Fig. 1. The FK-30 T sample reproducibly shows a deviation from the programmed constant cooling rate at approximately 700 °C (Fig. 1(a)). Previous work [9,10] has shown that this is caused by recalescence, i.e. heating caused by the release of the latent heat of transformation. This unexpected behavior does not occur when the specimen is cooled without the influence of a magnetic field; instead, recalescence is observed at a much lower temperature (about 180 °C) due to martensitic transformation (Fig. 1(b)). By contrast, the SK-30 T sample recalesced at ≈130 °C, with no such event in the SK-NF condition because the martensite-start

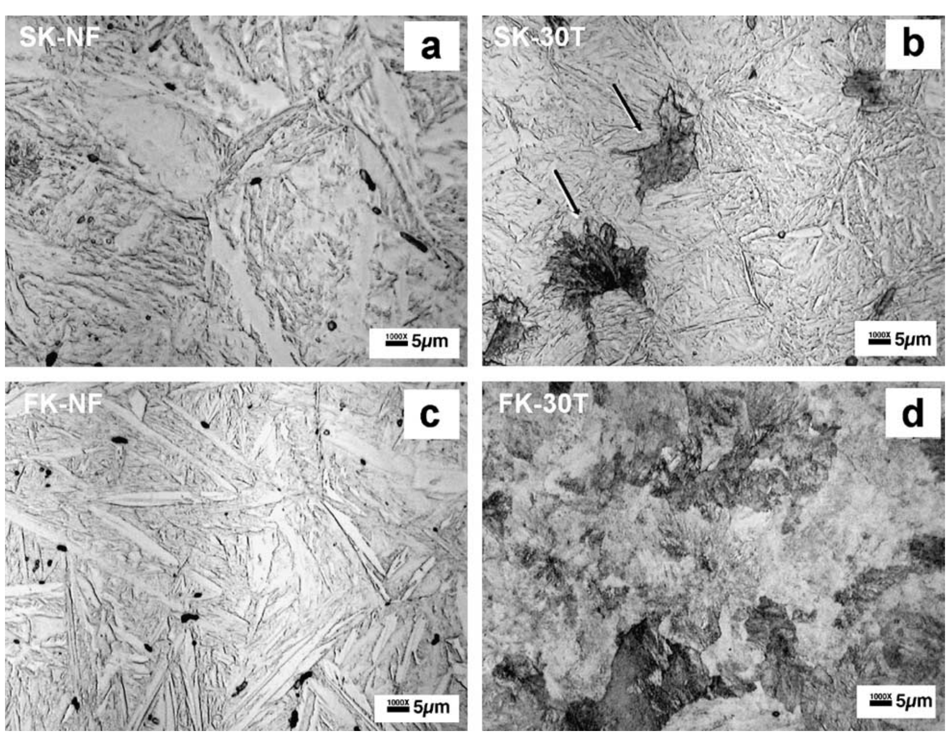

Fig. 2. Optical micrographs (a) SK-NF; (b) SK-30 T; (c) FK-NF; and (d) FK-30 T, the sample used for transmission electron microscopy.

temperature in this case falls below the temperature where data were collected.

To summarize, the effect of the field is to raise the martensite-start temperature for both alloys. In the case of the faster transformation FK steel, a further transformation at about 700 °C is promoted by the magnetic field.

The optical micrographs in Fig. 2 confirm this. The microstructures are a mixture of bainite and martensite when the transformation is in the absence of a field, and there are indications of pearlite when a field is imposed. The formation of pearlite would explain the recalescence event at ~700 °C for FK-30 T.

The clear presence of pearlite was confirmed using transmission electron microscopy on sample FK-30 T (Fig. 3). The interlamellar spacing is incredibly fine, approximately 50 nm. Electron diffraction confirmed that the lamella consist of cementite and ferrite. The cooling data indicate that the pearlite formed over a narrow temperature range of 725–700 °C so it is not surprising that the microstructure is rather uniform. The perturbations between 700 and 660 °C are associated with the system re-establishing temperature control.

It is interesting that the lamellar spacing obtained compares with patented wire (40–150 nm) [11]. The cementite lamellae exhibit frequent interruptions (Fig. 3(b)), perhaps due to changes at the pearlite–colony interface with austenite and because the transformation occurs during continuous cooling. It would be useful in future work to characterize the partitioning of alloying elements between the cementite and ferrite components of the fine pearlite.

All of the samples were evaluated by plotting hardness distributions (Fig. 4). There are clear differences between FK-NF and FK-30 T, the former with an average hardness of 875 ± 51 HV and the latter showing 484 ± 13 HV. This is expected since the pearlite will be softer than the microstructure containing martensite.

The average hardness of the SK-30 T sample (859 ± 51 HV) was slightly higher than the SK-NF sample (801 ± 54 HV), as shown in Fig. 4(a) and (b). The quantitative distributions are in Fig. 4(e) and (f). The huge difference between FK-NF and FK-30 T is clearly because of the fully pearlitic state of FK-30 T. The hardness data are therefore consistent with the microstructural data in Figs. 2 and 3.

Vertical sections of Fe–C phase diagrams calculated using the ThermoCalc software [12] and ThermoTech Fe database [13] are shown in Fig. 5; Fig. 5(b) is estimated by decreasing the free energy of ferrite in order to simulate the effect of the magnetic field in stabilizing ferrite and the effect on cementite is neglected. Given the Bohr magneton ($\mu = 9.3 \times 10^{-24}$ J/T), after converting to J/mol using Avogadro's number and multiplying by the magnetic moment per atom of iron in ferrite (2.2) yields a value of 12 J/mol/T. Multiplying this factor by 30 T approximates the free energy change as 360 J/mol.

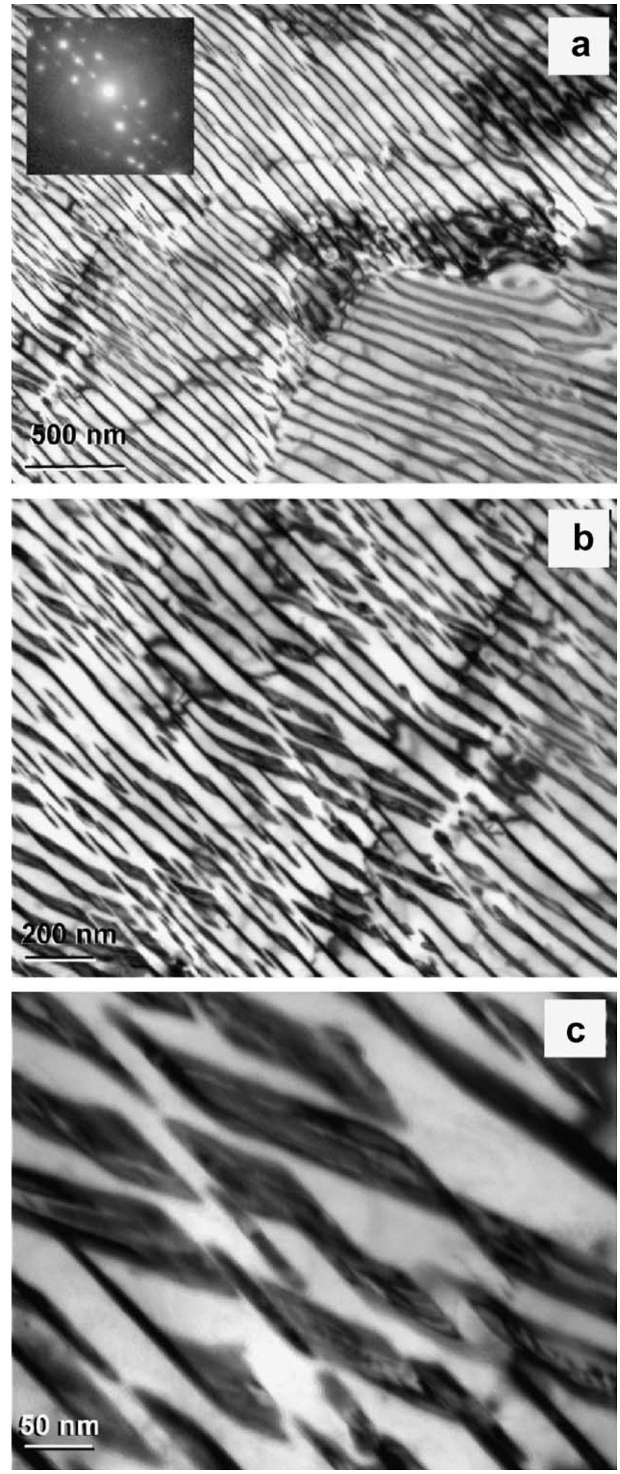

Fig. 3. Transmission electron microscopy images of samples subjected to 30 T magnetic field: (a) Low-magnification picture showing pearlite colonies with inset diffraction pattern obtained from the same area. High magnification micrographs show (b) the cementite lamellae and (c) fine substructure and morphology of carbides.

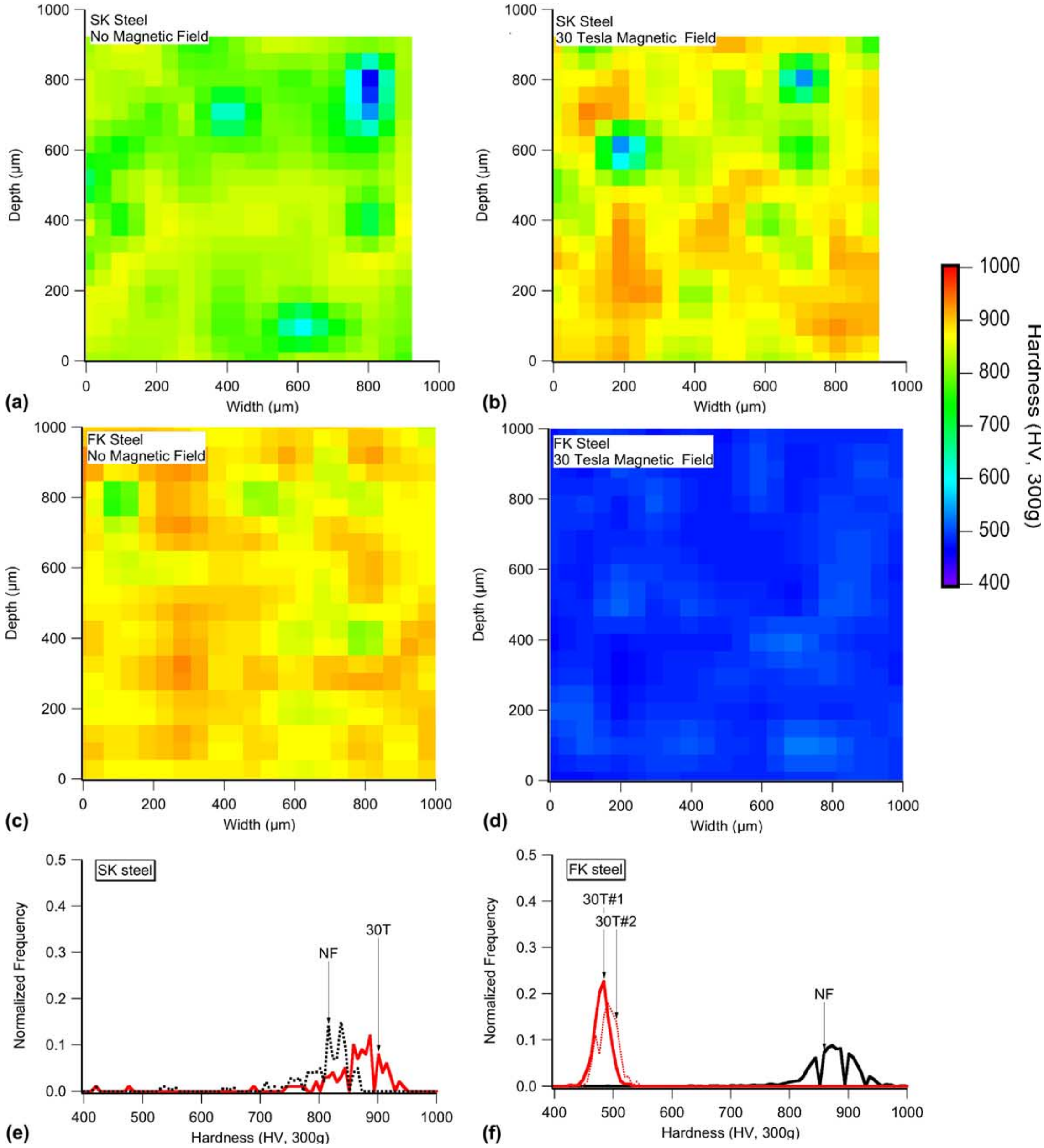

Fig. 4. Interpolated image representations of spatial hardness measurement from all samples are shown. (a) SK sample—continuously cooled at 1 °C/s without magnetic field; (b) SK sample—continuously cooled at 1 °C/s with 30 T magnetic field; (c) FK sample continuously cooled at 1 °C/s without magnetic field; and (d) FK sample—continuously cooled at 1 °C/s with 30 T magnetic field. Hardness frequency distributions from (e) SK and (f) FK steels are also presented.

Therefore, the ferrite free energy was reduced by 360 J/mol in the calculations. It is obvious from these results that the kinetics of the pearlite reaction will be accelerated by the application of a magnetic field.

4. Summary

Two novel, high-strength steels designed for a bainitic microstructure have been studied. Continuous cooling transformation experiments both with and without the influence of a magnetic field have been conducted. From recalescence and microstructural observations, it is clear that the effect of the magnetic field is to accelerate the transformation of austenite. The acceleration manifests in two ways, first in promoting the formation of pearlite and secondly in raising the temperature at which martensite forms.

The pearlite that forms has an incredibly fine spacing even though the transformation temperature is quite

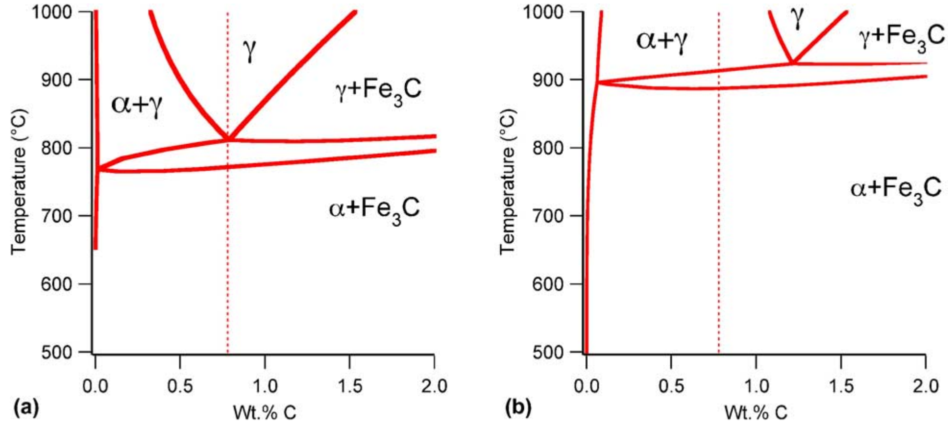

Fig. 5. Calculated quasi-binary Fe–C diagram for FK steel: (a) without modifying the ferrite Gibbs molar free energy, and (b) by reducing the ferrite Gibbs molar free energy by 360 J.

high. In fact, the spacing compares with the best of patented pearlitic wire where transformation temperatures as low as 450 °C are used. It is suggested that with appropriate alloy design, "magnetic patenting" might become a commercial proposition.

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References

[1] Caballero FG, Bhadeshia HKDH, Mawella KJA, Jones DG, Brown P. Mater Sci Technol 2002;18:279–84.
[2] Garcia-Mateo C, Caballero FG, Bhadeshia HKDH. ISIJ Int 2003;43:1238–43.
[3] Garcia-Mateo C, Caballero FG, Bhadeshia HKDH. J Phys IV 2003;112(part 1):285–8.
[4] Peet M, Babu SS, Miller MK, Bhadeshia HKDH. Scripta Mater 2004;50:1277–81.
[5] Garcia-Mateo C, Caballero FG, Bhadeshia HKDH. ISIJ Int 2003;43:1821–5.
[6] Zener C. Trans Am Inst Min Metall Eng 1955;203:619–30.
[7] Kaufman L, Clougherty EV, Weiss RJ. Acta Metall 1963;11:323–35.
[8] Shimizu K. Mater Trans 2002;45:2050–7.
[9] Ludtka GM, Jaramillo RA, Kisner RA, Nicholson DM, Wilgen JB, Mackiewicz-Ludtka G, et al. Scripta Mater 2004;51:171–4.
[10] Lee KJ. Scripta Mater 1999;40:735–42.
[11] Porter DA, Easterling KE, Smith GDW. Acta Metall 1978;26:1403–22.
[12] Andersson JO, Helander T, Hoglund L, Sundman B. CALPHAD 2002;26:273–312.
[13] Thermotech Fe-Data Thermodynamic Database, Thermotech Ltd./Sente Software Ltd., Surrey Technology Centre, 40 Occam Road, GU2 7YG, United Kingdom.