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ISOTHERMAL PHASE TRANSFORMATION CYCLING IN STEEL BY APPLICATION OF A HIGH MAGNETIC FIELD

Gerard M. Ludtka[1], Roger A. Jaramillo[1], Gail Mackiewicz-Ludtka[1], Roger A. Kisner[2], John B. Wilgen[2]

[1] Materials Science & Technology, Oak Ridge National Laboratory, Oak Ridge, TN 37831
[2]Engineering Science & Technology, Oak Ridge National Laboratory, Oak Ridge, TN 37831

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Abstract

A phase transformation reversal via the application and removal of a large magnetic field was investigated. Because a large magnetic field can alter the phase equilibrium between paramagnetic austenite and ferromagnetic ferrite, volume fractions for each phase constituent can be modified at constant temperature by changing the magnetic field strength. In this research elevated temperature isothermal hold experiments were performed for 5160 steel. During the isothermal hold, the magnetic field was cycled between 0 and 30 Tesla. As companion experiments, temperature cycling and isothermal holds were performed without magnetic fields. The resulting microstructures were examined using optical and SEM metallography. These microstructures indicate that a portion of the microstructure experiences isothermal transformation cycling between austenite and ferrite due to the application and removal of the 30T (Tesla) magnetic field.

Introduction

The application of a large magnetic field as a new tool for developing unique microstructures in ferrous materials is becoming realized as superconducting magnet technology for efficiently generating large (>10T) magnetic fields becomes feasible. It has been demonstrated that magnetic fields significantly affect the thermodynamics of phase equilibria and that new microstructures are possible for conventional alloy chemistries. Model predictions of this effect [1] and isothermal transformation experiments [2] have been reported. Data showing a significant increase in transformation temperature during continuous cooling for 1045 steel have been reported by the authors [3]. This result is significant in that in situ temperature measurements of thermal recalescence associated with austenite decomposition provide a relative shift in transformation temperature due the application of a 30T magnetic field. These results indicate a 3°C/T increase in transformation temperature. Additional research has shown that unique microstructures can be obtained via the application of a large magnetic field. A high carbon, high silicon steel exhibited very fine pearlite with a lamellar spacing of approximately 50 nm during continuous cooling with a large magnetic field [4].

In this work, the ability of a magnetic field to isothermally cycle the phase transformation between ferromagnetic ferrite and paramagnetic austenite was investigated. By holding the material at a temperature just above the austenite/ferrite phase boundary, the volume fractions of the phase could be modified through the application of a large magnetic field. Microstructural and hardness evaluations are presented that reveal significant modifications in microstructure associated with magnetic field cycling when compared to an isothermal hold without magnetic field treatment.

Theory

The magnetic field changes the free energy of the austenite-ferrite equilibrium such that the ferromagnetic ferrite is stabilized relative to the paramagnetic austenite. The magnetic field contribution to the change in free energy has been estimated to be 12.6 J/mol/T [5]. Applying this estimate, the effect of the magnetic field on the 5160 steel pseudo-binary is shown in Figure 1. The figure plots phase boundaries for 5160 steel as calculated using ThermoCalc Fe-DATA database [6]. The black lines represent phase boundaries without the magnetic field effect; red lines are shifted phase boundaries assuming that the free energy of the ferrite is changed by -378 J/mol due to the application of a 30T magnetic field. This estimate shows a significant increase in Ae1 and Ae3 temperatures due to the magnetic field. The boundary shift suggests that for certain temperatures, the $\gamma \leftrightarrow \alpha + Fe_3C$ transformation can be fully reversed by cycling the magnetic field between 0 and 30T. Our experiments were designed to test this theory.

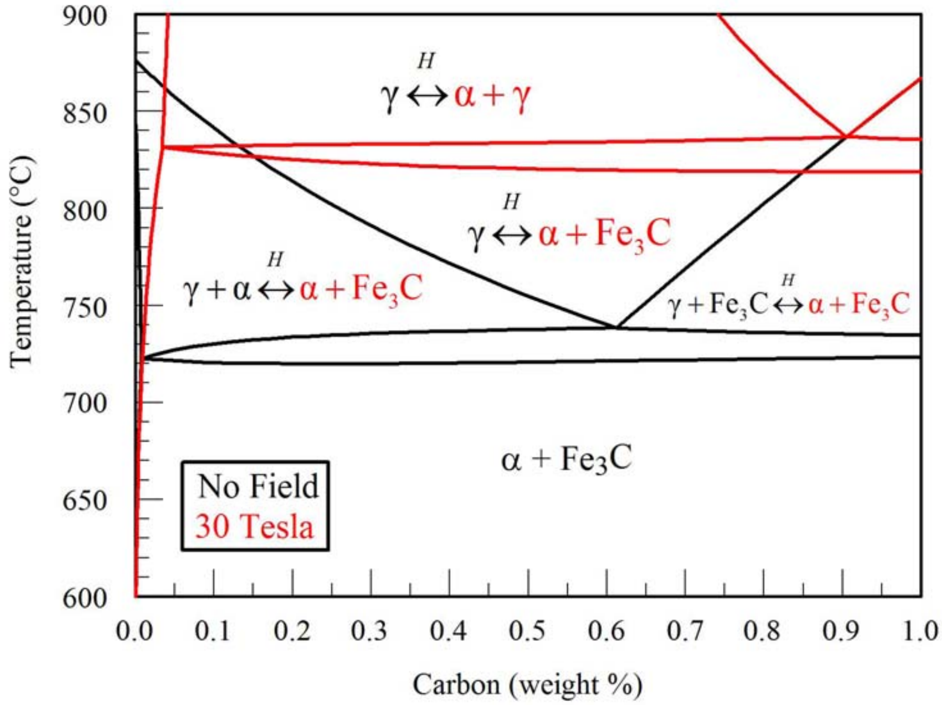

Figure 1. Calculated pseudobinary phase diagrams for a nominal 5160 steel chemistry. Black lines represent boundaries at 0 Tesla and red lines are boundaries with the application of a 30 Tesla magnetic field.

Experimental

Hollow cylindrical specimens with a 6-mm outer diameter, 1-mm wall thickness and 8-mm length were machined from a medium carbon 5160 steel. 5160 steel has a nominal composition of 0.80 wt.% Cr, 0.88 wt.% Mn and 0.60 wt.% C. Experiments were performed using a 32mm diameter bore resistive magnet with a 33T maximum field strength at the National High Magnetic Field Laboratory (NHMFL). Specimen heating and cooling was controlled using a custom designed induction heating coil coupled with a gas purge/quench system. The apparatus locates the specimen in the center of the bore (mid length) and can heat steel specimens up to 1100ºC and maintain the high temperature for extended periods. Temperature control was obtained using a type "S" (Pt-10%Rh) thermocouple spot-welded on the outer diameter at the mid-length of the specimen. The system allows for the entire thermal cycle or any portion of it to be exposed to a high magnetic field.

A schematic of the thermal-magnetic cycles used in the experiments is shown in Figure 2. The figure plots temperature and magnetic field strength as a function of time. The temperature is ramped to 745°C in two minutes and maintained until a prescribed quench at step 1, 2 or 3 as shown in the figure. During the isothermal hold the magnetic field was ramped up to 30T and held for 10 minutes including the ramp up time. Each additional step is 10 minutes with the magnetic field cycled between 0 and 30T. To capture the evolution of the microstructure, an experiment was ended at the end of each 10 minute period and identified as "Step1," "Step 2," and "Step 3." Also, 40 minute isothermal hold without any magnetic field treatment was performed. A helium gas quench was applied at the end of each experiment.

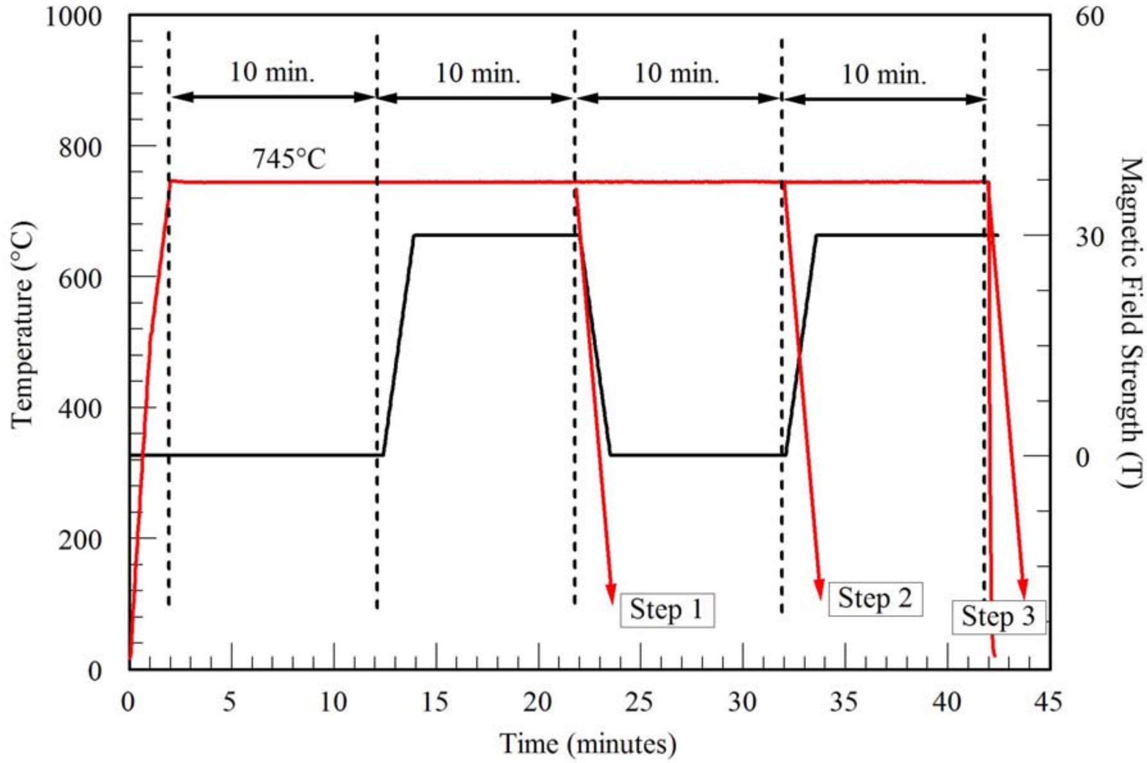

Figure 2. Schematic illustrating the temperature and magnetic field histories used for magnetic field cycling experiments. Black plot is magnetic field strength and Red (lighter) lines are temperature.

Results and Discussion

As a basis for comparison with magnetic field cycling experiments, a specimen was heat treated with an isothermal hold at 745°C for 40 minutes without any magnetic field treatment. This is the same thermal treatment represented as step 3 in Figure 2. The resulting microstructure is shown in Figure 3. The microstructure is predominantly martensitic (light gray) with isolated regions of ferrite (white). The presence of ferrite indicates that the material did not fully transform to austenite at 745°C and was a mixture of austenite and ferrite. During the quench, the austenite transforms into martensite and the ferrite remains constant. However, the volume fraction of ferrite is small and the application of a magnetic field should increase the amount of ferrite, therefore enriching the austenite in carbon and/or forming spherical cementite carbides.

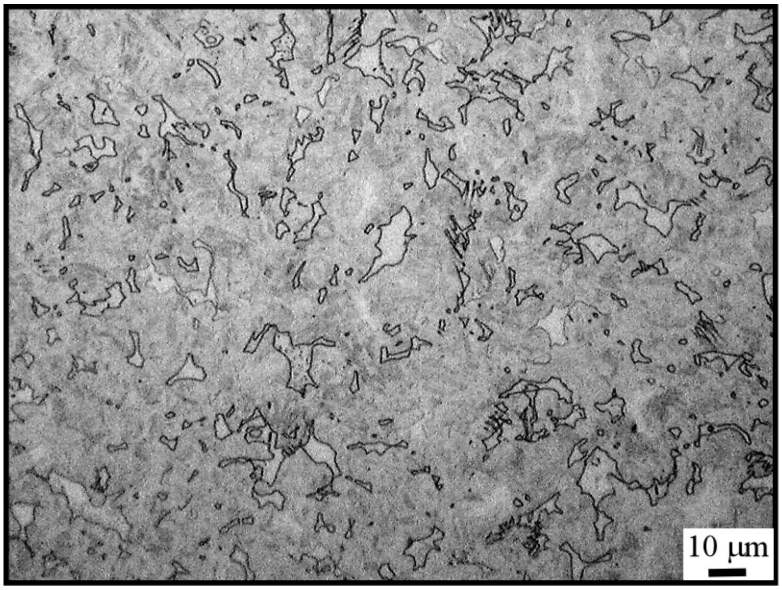

Figure 3. Micrograph showing microstructure for a 5160 steel heated to 745°C and held for 40 minutes without a magnetic field and quenched.

Optical micrographs displaying the magnetically cycled specimens are shown in Figure 4. The figure shows microstructures for results produced with thermal-magnetic treatments shown in steps 1, 2, and 3 as described in Figure 2 and identified as 4a, 4b, and 4c, respectively. The first 30T step is shown in Figure 4a, a large fraction of martensite is seen with a loosely connected network of ferrite and fine cementite particles sprinkled within some areas of ferrite. The application of a 30T magnetic field has increased the amount of ferrite relative to Figure 3 and shows the presence of cementite particles within the ferrite. Figure 4b shows the step 2 microstructure which experienced a 10 minute 30T treatment followed by another 10 minutes without the magnetic field prior to quench. The volume fraction of martensite has increased relative to Figure 4a suggesting that some austenite reformed during the final 10 minutes without a magnetic field. However, like Figure 3, some ferrite remains in the microstructure indicating that 745°C was not a high enough temperature to obtain a fully austenitic microstructure. The final micrograph in the series (Figure 4c) shows the microstructure after a final 10 minutes with a second 30T treatment. The microstructure is substantially different from Figures 4a and 4b. As expected the volume fraction of martensite has again decreased due to the isothermal transformation of austenite to ferrite and cementite. Additionally, the second 30T treatment step appears to have increased the amount of austenite transformed isothermally compared to the amount indicated for the first 30T treatment shown in Figure 4a. The amount of ferrite and spheroidized cementite provide strong evidence of isothermal transformation due to the application of a 30T magnetic field.

The interpretation of the microstructures shown in Figures 3 and 4 are substantiated by microhardness measurements. Table 1 shows the results of microhardness measurements performed on the four specimens. A 500 gram load was used and the reported HV is the average of five indentations.

Table I. Microhardness measurements for magnetically cycled and isothermal-only treated specimens. (500 g load, 5 indentations)

	Step 1 (Fig 4a)	Step 2 (Fig 4b)	Step 3 (Fig 4c)	No Magnetic Field (Fig 3)
Hardness (HV)	219	382	226	451
Std. Dev.	45	127	72	133

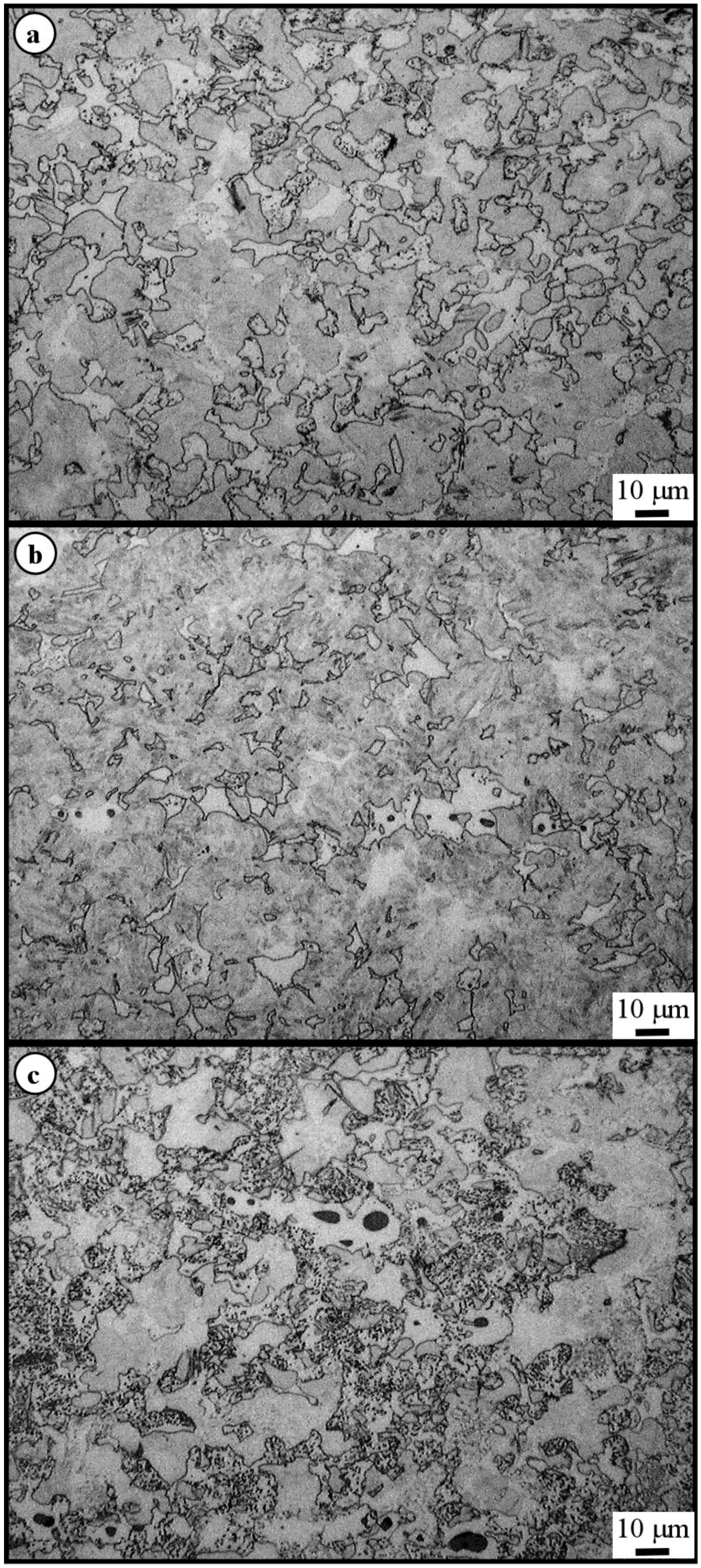

Figure 4. Optical micrographs of magnetically cycled 5160 steel. Microstructures in a), b) and c) correspond to steps 1, 2, and 3, respectively, from Figure 2.

The specimens with a magnetic treatment in the final step are softer than those without. This is due to the reduction in martensite associated with greater amounts of isothermal transformation during magnetic field treatment. The large standard deviations for the non-magnetically treated specimens would be expected given the limited number of indentations and the mixture of soft ferrite and hard martensite.

Summary and Conclusions

Magnetic field cycling experiments were performed to investigate isothermal transformation reversal via the application and removal of a large magnetic field. A 5160 steel was heated to 745°C and held while a 30T magnetic field was cycled. A specimen was quenched out at each step of the cycle and a simple isothermal treatment without a magnetic field was performed for comparison. The subsequent metallographic analysis and micros hardness measurements confirm the phenomenon of isothermal phase transformation reversal. Micrographs show modified amounts of martensite and ferrite/cementite due to the application of a 30T magnetic field. A large volume fraction of martensite is indicative of limited isothermal transformation of austenite during the 745°C hold and most transformation occurring during the subsequent quench. However, for the case when a magnetic field was applied in the final step, a reduced amount of martensite was observed and for the case of a second 30T treatment in the cycle, a well developed phase constituent of ferrite and spheroidized cementite was seen.

These results validate the use of a large magnetic field for phase transformation cycling. Such a processing tool could provide a means of microstructural refinement and accelerated spheroidization treatments. Also, the permeability of the magnetic field eliminates gradients that would typically occur when cycling a transformation via thermal cycle. These capabilities could promote the development of advance microstructures and components with superior performance.

Acknowledgements

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References

1. J-K Choi et al., "Effects of a strong magnetic field on the phase stability of plain carbon steels," *Scripta Materialia*, 43 (2000), 221-226.
2. M. Enomoto et al., "Influence of Magnetic Field on the Kinetics of Proeutectoid Ferrite Transformation in Iron Alloys," *Metall. Mater. Trans. A*, 32A (2001), 445-453.
3. G. M. Ludtka et al., "In situ evidence of enhanced transformation kinetics in a medium carbon steel due to a high magnetic field," *Scripta Materialia*, 51 (2004), 171-174.
4. R. A. Jaramillo et al., "Effect of 30T magnetic field on transformations in a novel bainitic steel," *Scripta Materialia*, 52 (2005), 461-466.
5. R.A. Jaramillo, G.M. Ludtka, R.A. Kisner, D.M. Micholson, J.B. Wilgen, G. Mackiewicz-Ludtka, N. Bembridge, and P.N. Kalu, "Investigation of phase transformation kinetics and microstructural evolution in 1045 and 52100 steel under large magnetic fields", in Solid-to-Solid Phase Transformations in Inorganic Materials 2005, Vol. 1: Diffusional Transformations, (Eds. J.M. Howe, D.E. Laughlin, J.K. Lee, U. Dahmen, W.A. Soffa), TMS, PA, pp. 893-898 (2005).
6. N. Saunders, "Fe-DATA, a database for thermodynamic calculations for Fealloys," Thermotech Ltd., Surrey Technology Centre, The Surrey Research Park, Guilford, Surrey GU2 7YG, U.K.