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In situ evidence of enhanced transformation kinetics in a medium carbon steel due to a high magnetic field

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Abstract

A medium carbon steel was cooled from 850 °C at various rates with and without a 30-T magnetic field. Due to the magnetic field, the onset of thermal recalescence associated with the release of latent heat showed 70–90 °C increase, indicating acceleration in austenite decomposition. The relative shift was cooling rate dependent. Microstructural examination revealed increased ferrite content and corroborated temperature measurements.

Keywords: Steels; Phase transformation kinetics; Magnetic field; Austenite decomposition

1. Introduction

Several researchers [1–4] have shown that the application of a high magnetic field can modify the Gibbs free energy of the Fe–C system such that the austenite/ferrite phase boundary becomes a function of the applied field. Because the magnetic susceptibilities of ferrite and austenite are substantially different, the magnetization of the material coupled with the applied field strength alters the free energy and, therefore, phase stabilities. Calculations for pure Fe by Choi et al. [1] suggest that the Ae3 temperature is increased over 50 °C by a 30-T magnetic field and the Ae1 temperature for the Fe–C binary increased by approximately 30 °C. Experimental validation has been limited to steels transformed in magnetic fields of 10 T or less and quantitative metallography served to verify the effect. Choi et al. [1] cooled a 0.44%C–0.23%Si–1.24%Mn steel at 5 °C/min and reported a 10% increase in ferrite volume fraction due to a 10-T magnetic field. Enomoto et al. [2] performed detailed quantitative metallography on a 0.39%C steel that had been isothermally transformed at 750 °C. Depending upon hold time, their analysis indicates a 5–10% increase in ferrite volume fraction for a 7.5-T magnetic field. While these studies validate the magnetic field effect, it is difficult to deduce the quantitative changes in transformation kinetics due to a magnetic field. In this work, steel cylinders were exposed to a 30-T magnetic field during cooling. Temperature measurements provided a quantitative measure of the shift in transformation kinetics due the magnetic field.

Thermocouple measurements were used to monitor the temperature behavior of a steel specimen undergoing phase transformation during continuous cooling with and without a magnetic field. Because release of latent heat associated with austenite decomposition is readily observed in temperature measurements [5], a phase transformation can be associated with specific times and temperatures during cooling. Therefore, for a given cooling rate, the shift in recalescence provides a relative measure of the effect of a high magnetic field on transformation kinetics. The enhancement of transformation kinetics associated with the magnetic field was

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reinforced by phase volume fractions observed in the resulting microstructure.

2. Experimental procedure

A 32 mm diameter bore resistive magnet with a 33 T maximum field strength at the National High Magnetic Field Laboratory (NHMFL) was used for 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 experiments. Fig. 1 is a schematic of the experimental apparatus. The apparatus locates the specimen in the center of the bore mid length and can heat the steel specimen up to 1100 °C and maintain the high temperature for extended periods of time. Atmosphere is controlled via an argon gas purge. For accelerated cooling, a helium gas quench can be rapidly imposed upon the specimen. Such a system allows for the entire thermal cycle or any portion of it to be exposed to a high magnetic field.

Experiments were performed using a medium carbon 1045 steel with a nominal composition of 0.45 wt.% carbon and 0.8 wt.% manganese. A 13 mm diameter rod was received in the annealed and furnace-cooled condition. Cylindrical specimens, 8-mm diameter × 12-mm long, were machined from the rod with the longitudinal axis aligned with the rod axis.

Temperature measurements were made via a type "S" (Pt–10%Rh) thermocouple spot-welded on the radial surface at the mid-length of the specimen. All specimens were heated to 850 °C using a two-step schedule where a rate of approximately 11 °C/s was applied to 700 °C, followed by heating at 2.5 °C/s to the annealing temperature. A 5 min hold at 850 °C was performed to fully transform the initial microstructure to austenite. For cooling with a magnetic field, the ramping of the field was initiated at the midpoint of the 5 min hold at 850 °C. A time of 1.5 min was required for the field to reach 30 T. Specimen cooling was controlled by modifying the pressure governing helium gas flow during quench. Table 1 provides a list of helium gas pressures used and the associated cooling rates. The reported cooling rates are an average of the rates measured between 850 and 700 °C.

A slow cooling rate of 10 °C/s was obtained by simply turning off the induction heater and allowing the specimen to cool "naturally" within the argon purged environment. Additional cooling rates of 55, 80 and 130 °C/s were generated by flowing helium at 35, 70 and 140 Pa, respectively.

Table 1
Helium quench pressure and the associated cooling rate

Helium gas pressure (Pa)	Measured cooling rate (°C/s)
0	10
35	55
70	80
140	130

Cooling rate is an average of the rate between 850 and 700 °C.

3. Results and discussion

Temperature histories for the 10 °C/s cooling rate with and without a 30-T magnetic field are shown in Fig. 2. The figure plots temperature versus time for a specimen cooled with an applied magnetic field (solid line) and without a field (dashed line). The recalescence associated with austenite decomposition is observed in both plots. However, the presence of a 30-T magnetic field has clearly shifted the onset of recalescence from approximately 670 °C without the field to approximately 760 °C with it. Also, the plot for the 30-T experiment shows a secondary recalescence event at approximately 700 °C. The initial event at 760 °C is associated with the formation of proeutectoid ferrite and the second event at 700 °C is transformation of the remaining austenite.

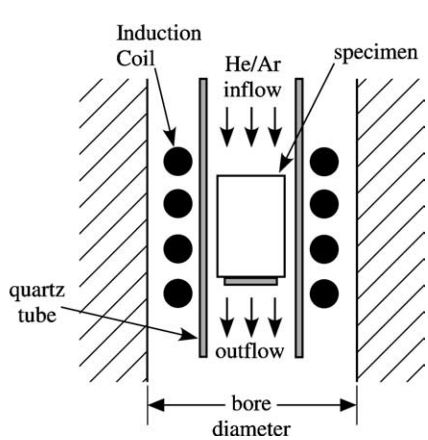

Fig. 1. Schematic of experimental apparatus used for heat treatment of specimen within the bore of the magnet.

Fig. 2. Cooling curves for cooling at 10 °C/s. Specimen held at 850 °C for 5 min prior to cooling.

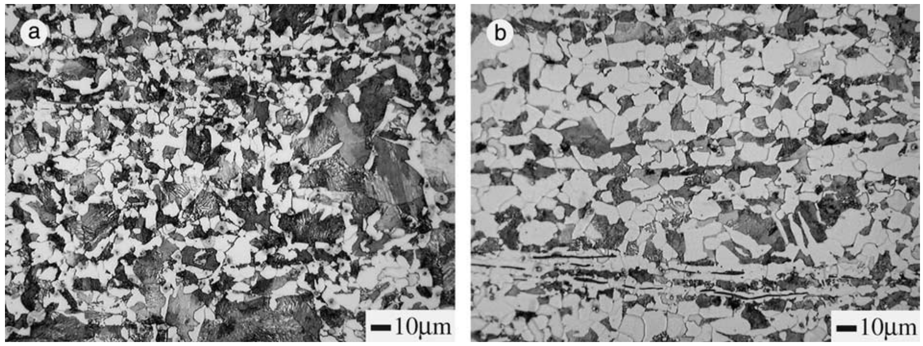

Fig. 3. Microstructure for 1045 steel specimens cooled at 10 °C/s. For (a) without magnetic field and (b) with 30-T field (light micrograph, 2% nital).

The formation of proeutectoid ferrite is not apparent in the data without field. It is speculated that the volume of ferrite formed was not enough to create an observable recalescence event.

Fig. 3a and b shows microstructures corresponding to the 10 °C/s cooling rates plotted in Fig. 2. The figures are light micrographs of the microstructure at the mid length of the longitudinal plane for each specimen. The light grains are ferrite and the dark regions are pearlite. Fig. 3a displays the microstructure obtained for cooling without a magnetic field. A substantial increase in ferrite volume fraction is observed in Fig. 3b, where the 30-T field was applied. An estimate of the phase composition indicates that the 30-T magnetic field increased the ferrite volume fraction from 40% to 65% ferrite. The application of the 30-T magnetic field has changed the majority constituent from pearlite to ferrite without significant coarsening of the microstructure. Because the chemistry and cooling rates are unchanged, it is evident that the free energy of the system has been altered by the application of a 30-T magnetic field.

Temperature data for experiments performed using a He gas quench are plotted in Fig. 4. The figure plots temperature versus time for three cooling rates with the 30-T field (solid lines) and without the field (dashed lines). The figure clearly shows a significant and consistent increase in the kinetics of austenite decomposition

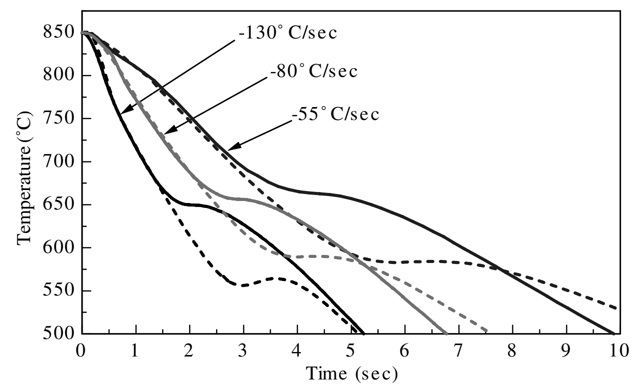

Fig. 4. Cooling curves for various cooling rates with (solid line) and without (dashed line) a 30-T magnetic field. Specimen held at 850 °C for 5 min prior to cooling.

due to the 30-T magnetic field. If the recalescence seen in the data is employed as a reference, an approximately 70–90 °C increase in transformation temperature due to the magnetic field is suggested. This increase in transformation temperature decreases the time between transformation start and finish. These results reinforce those shown in Fig. 2 and indicate that the thermodynamic effect is evident over a range of cooling rates.

Microstructures for material cooled at the fastest rate (130 °C/s) without and with a magnetic field are shown

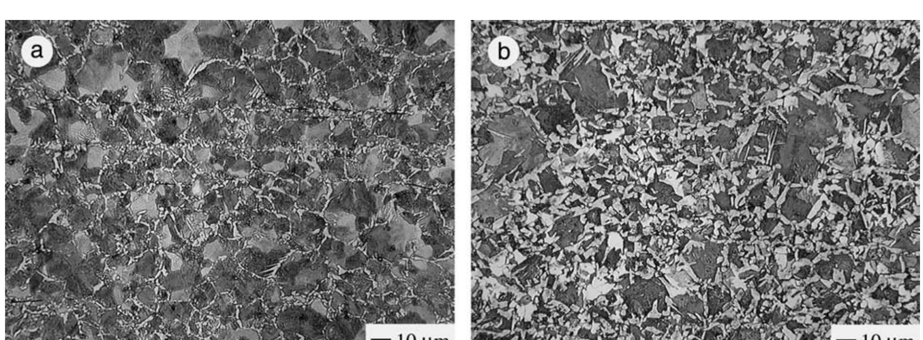

Fig. 5. Microstructures for specimens cooled at −130 °C/s (a) without and (b) with a 30-T field (light micrograph, 2% nital).

in Fig. 5a and b, respectively. The effect of the high magnetic field on the resulting ferrite content is readily observed, even at the highest cooling rate. The non-field case in Fig. 5a shows ferrite predominately located along prior austenite grain boundaries with the remaining microstructure composed of pearlite and bainite. Again, a significant increase in ferrite volume fraction is observed for the material cooled with a 30-T magnetic field. Estimates of ferrite volume fraction indicate an increase from 20% to 50% ferrite due to a 30-T magnetic field.

4. Conclusions

Continuous cooling experiments were performed with a 1045 steel to investigate the effect of a 30-T magnetic field on the kinetics of austenite decomposition. Specimens were cooled at four different rates with and without the magnetic field. Temperature measurements identify the occurrence of phase transformations because of the release of latent heat and the associated interruption in specimen cooling. By comparing the recalescence for cooling with and without a magnetic field, the shift in the onset of austenite decomposition due to the field is determined.

The results of the experimental work clearly reinforce the postulate that a high magnetic field will alter the thermodynamics and, therefore, the transformation kinetics and microstructure of plain carbon steel during austenite decomposition. Temperature measurements indicate a 70–90 °C increase in transformation temperature and quantitative metallography suggests a 25–30% increase in ferrite volume fraction due to a 30-T magnetic field.

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References

[1] Choi J-K, Ohtsuka H, Xu Y, Choo W-Y. Scripta Mater 2000;43:221.
[2] Enomoto M, Guo H, Tazuke Y, Abe YR, Shimotomai M. Metall Mater Trans A 2001;32:445.
[3] Liu W, Ou DR, Zhou HH, Tang GY, Wu F. J Mater Res 2001;16:2280.
[4] Joo HD, Kim SU, Shin NS, Koo YM. Mater Lett 2000;43:225.
[5] Lee KJ. Scripta Mater 1999;40:735.