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INVESTIGATION OF PHASE TRANSFORMATION KINETICS AND MICROSTRUCTURAL EVOLUTION IN 1045 AND 52100 STEEL UNDER LARGE MAGNETIC FIELDS

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Abstract

Magnetic fields varying from ambient to 30 tesla were applied during austenite decomposition in 1045 and 52100 steels. Thermal recalescence due to the release of latent heat during austenite decomposition is observed in temperature measurements and provides an estimate of transformation temperatures. Microstructural analysis was performed using and electron microscopy along with microhardness measurements. The shift in transformation temperature was estimated at 3°C/tesla which corresponds to an apparent free energy shift of 12.6 J/mol/tesla in 1045 steel. This shift in transformation temperature was accompanied by an increase in ferrite content. In 52100 steel, the magnetic field altered the transformation product from martensite to pearlite for a single cooling rate. This result indicates that the transformation mechanism can be selected by an applied magnetic field for a fixed cooling rate and alloy chemistry.

Introduction

The use of large magnetic fields to add a third dimension to traditional phase diagrams in ferrous materials is an area of growing interest as technologies for efficiently generating large (>10T) magnetic fields becomes feasible. By modifying the thermodynamics with a magnetic field, new microstructures are possible for traditional thermal processing histories. Investigation of this effect has been reported by several researchers [1-2]. In a previous article [3], the current authors presented data showing a significant increase in transformation temperature during continuous cooling for 1045 steel. 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. Others work has relied on post-treatment metallography to assess the magnetic field effect. Additional research has shown that the application of a large magnetic field has produced very fine pearlite with a lamellar spacing of approximately 50 nm [4].

In this work, a study of the effect of various magnetic field strengths at levels between 0T and 30T were performed to characterize the effect on transformations in 52100 and 1045 steel. These measurements were used to develop an estimate for the effect of a magnetic field on transformation temperature and the associated free energy. Also, 52100 steel was annealed and subjected to continuous cooling transformations in the presence of various magnetic field

strengths. Microstructural and hardness evaluations are presented along cooling curves and associated analysis. The results presented are not intended to be comprehensive but represent highlights from our research.

Experiments

A high carbon 52100 steel and a medium carbon 1045 steel were used in this research. These two alloy compositions encompass a significant range of possible microstructures and are widely used in the automotive and heavy equipment industries. The 1045 steel was received in the annealed and furnace-cooled condition and the 52100 steel was in the spheroidized condition. Cylindrical specimens, 8mm diameter by 12mm long, were machined from the as-received rod with the axial direction consistent between rod and specimen. The chemical compositions for each steel are provided in Table I.

Table I. Chemical composition in weight percent for 52100 and 1045 steels.

Alloy	C	Cr	Cu	Mn	Mo	Ni	Si	Fe
52100	1.01	1.58	0.139	0.370	0.038	0.151	0.234	Bal.
1045	0.456	0.669	0.307	0.605	0.031	0.376	0.194	Bal.

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 of time. Temperature control was obtained using a type “S” (Pt-10%Rh) thermocouple spot-welded on the radial surface 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.

Specimens were heated to the annealing temperature using a two-step schedule where a rate of approximately 11ºC/s was applied to 700°C, followed by heating at 2.5ºC/s to the annealing temperature. For the 1045 steel, a 5 minute hold at 850ºC was performed to fully transform the initial microstructure to austenite. 52100 specimens were annealed for 30 minutes at either 800°C or 850°C. For cooling with a magnetic field, the ramping of the field was initiated approximately 2 minutes prior to cooling at a rate of 20T/minute. Specimen cooling was controlled by maintaining a constant helium gas flow during quench.

Results & Discussion

52100 Results

Temperature data for the 52100 steel continuously cooled with and without a 30T magnetic field are shown in Figure 1. The figure plots temperature versus log time during cooling from 850°C. For the case of ambient field, a subtle thermal recalescence was observed at ~250°C suggesting that a low temperature martensitic transformation occurred. With a 30T magnetic field applied, a significant recalescence event is observed at ~650°C. This is due to the release of latent heat associated with austenite decomposition. The dashed lines approximate the location of contours representing transformation start. The arrows indicate that the transformation start curve is shifted up and to the left showing increased transformation temperatures and accelerated kinetics.

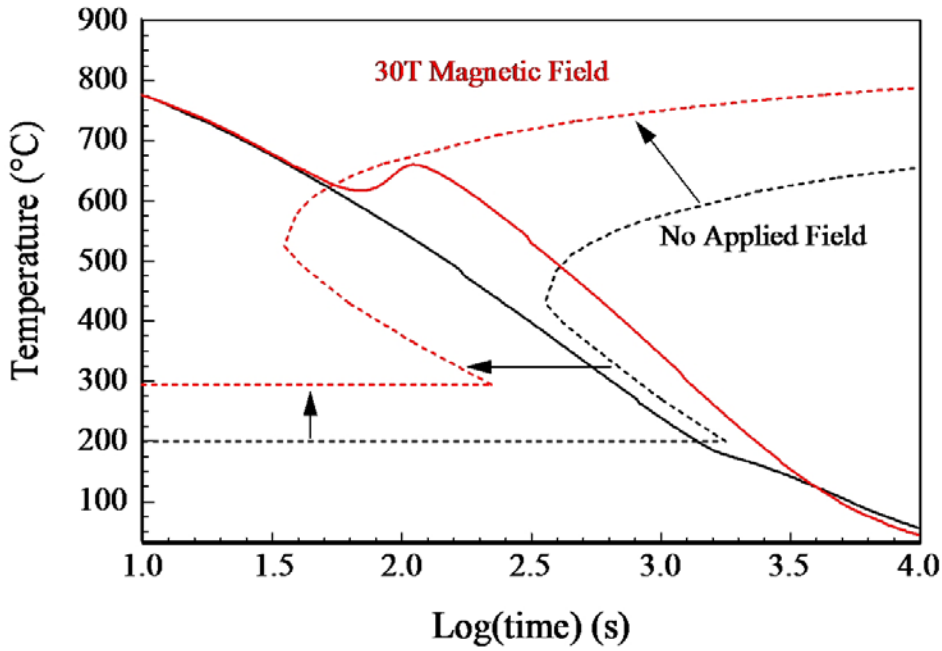

Figure 1. Log plot of cooling data for 52100 steel cooled with and without a 30T magnetic field. Dashed lines approximate transformation start contours for each case.

Subsequent SEM analysis of these samples, shown in Figure 2, verifies the interpretation of temperature data. Figure 2a shows the martensitic microstructure obtained without a magnetic field while Figure 2b displays a pearlitic microstructure induced by the 30T magnetic field. The spherical particles are undissolved cementite from the as-received material. These results clearly show that a 30T magnetic field has increased the driving force for austenite decomposition such that a diffusive transformation occurred instead of the martensitic transformation normally observed for this cooling rate.

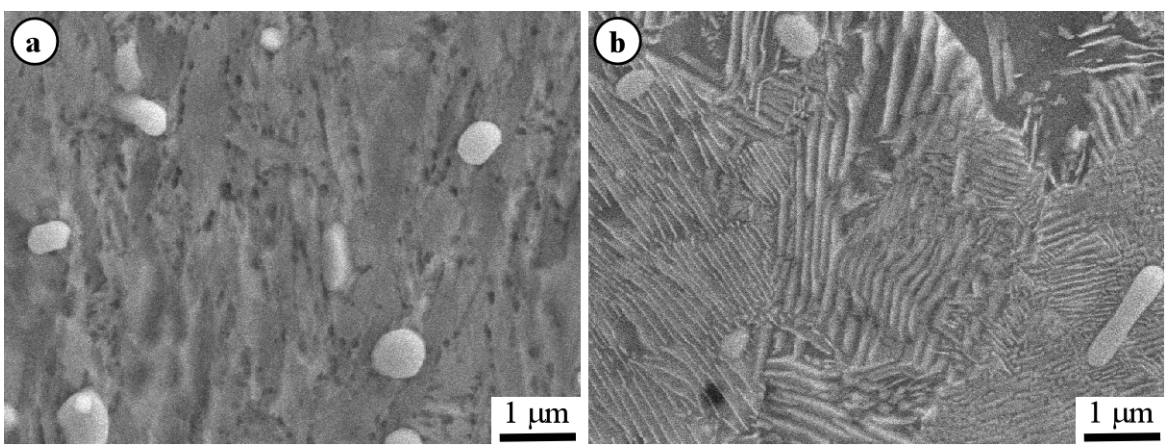

Figure 2. Microstructures for 52100 steel cooled from 850°C, a) with no magnetic field and b) with a 30T magnetic field. (SEM, 4% nital etch)

Cooling curves for samples annealed at 800°C and cooled under varying magnetic field strengths are presented in Figure 3. The figure plots data for cooling under 0, 10 and 20T magnetic fields. It is evident that as the magnetic field strength is increased, the temperature at which recalescence occurs also increases indicating an increase in transformation temperature.

Microhardness measurements were performed on specimens represented in Figure 3. The measurements confirm temperature data showing increased transformation temperature due to increasing magnetic field strength. For the 0T case, a subtle recalescence occurs near

approximately 250°C and a microhardness of 733 ± 28 HVN suggesting a predominately martensitic microstructure. A microhardness of 339 ± 16 HVN was measured for a 10T magnetic field which reasonably correlates with the ~530°C transformation start observed in temperature data. A 20T magnetic field induced transformation above 600°C and suggesting a pearlitic microstructure with a hardness of 291 ± 15 HVN. These results show that in 52100 steel for a specific cooling rate, a range of microstructures and hardness can be obtained by simply adjusting the applied magnetic field strength.

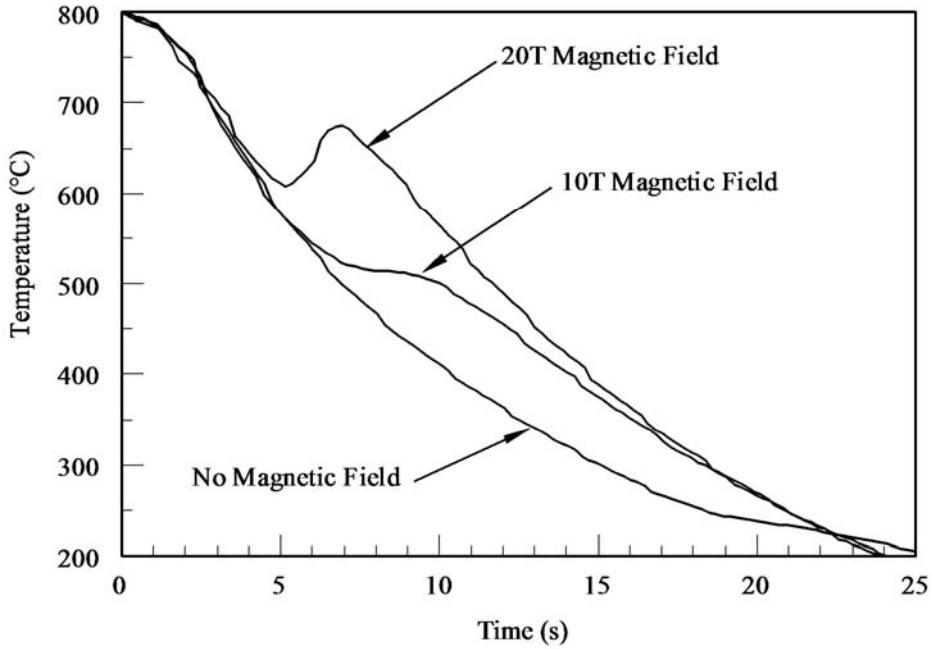

Figure 3. Cooling data for 52100 steel cooled from 800°C with magnetic fields of 20T, 10T and 0T applied.

1045 Alloy Results

Figure 4 shows cooling data for 1045 steel cooled with different magnetic field levels applied. The figure displays plots of temperature versus time for continuous cooling under magnetic field strengths of 0T, 10T, 20T and 30T. It is readily observed that by increasing the magnetic field strength, the recalescence associated with austenite decomposition is shifted to higher temperatures. By evaluating the derivative of the data in Figure 4, a method for evaluating the shift in transformation temperature is obtained. These data show transformation temperature shifts of 35°C, 63°C and 85°C for 10T, 20T and 30T, respectively.

An estimate of free energy contribution to the decomposition of austenite due to the magnetic field was determined by the following analysis. Assuming that the heat capacities for the parent and product phases are the same and that the entropy is independent of the magnetic field, an expression for the change in free energy as a function of undercooling can be obtained [5]. Such a relationship is shown in Equation 1.

$$\Delta G^{\gamma\rightarrow\alpha+Fe_3C} = \frac{\Delta H^{\gamma\rightarrow\alpha+Fe_3C}}{T_{equilibrium}}\left(T_{equilibrium} - T^0\right) \quad (1)$$

Here, $\Delta G^{\gamma\rightarrow\alpha+Fe_3C}$ is the change in Gibbs free energy associated with austenite decomposition, $\Delta H^{\gamma\rightarrow\alpha+Fe_3C}$ is the latent heat, $T_{equilibrium}$ is the equilibrium temperature and T^0 is the transformation temperature without a magnetic field. For the sake of simplicity, it is assumed that Equation 1 is applicable for any product phases that result from diffusional transformation.

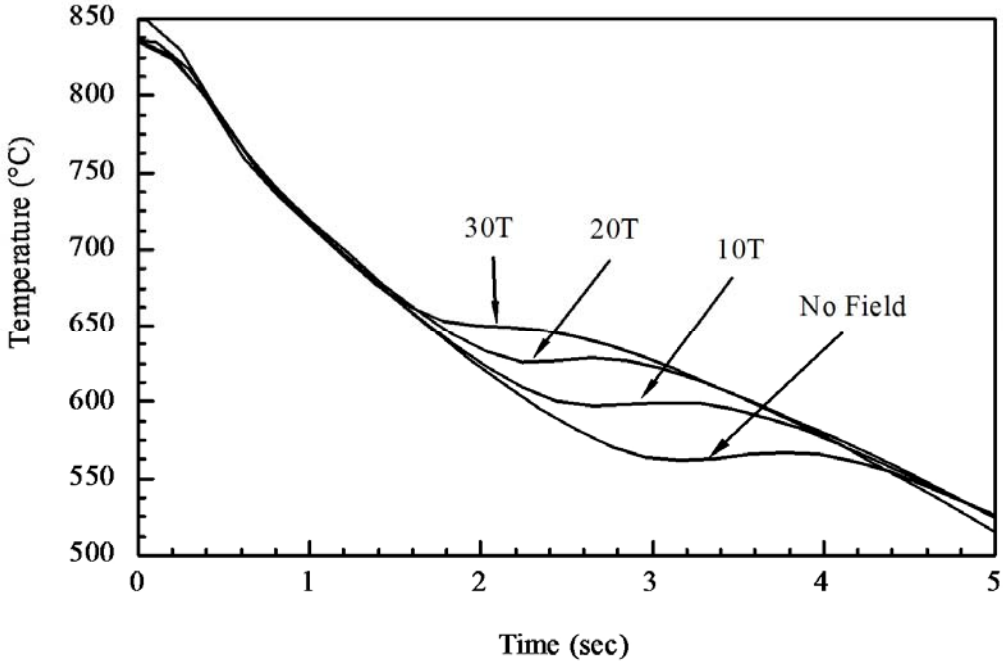

Figure 4. Continuous cooling data for 1045 steel cooled under different magnetic field strengths.

By assuming that the magnetic field provides an additive contribution to the change in free energy, Equation 3 can be rewritten as Equation 4.

$$\Delta G^{\gamma\to\alpha+Fe_3C} + \Delta G^{\mathrm{B}} = \frac{\Delta H^{\gamma\to\alpha+Fe_3C}}{T_{equilibrium}}\left(T_{equilibrium} - T\right) \tag{2}$$

Here, ΔG^{B} is the magnetic field contribution. Equation 1 is substituted into Equation 2 and rearranged to yield Equation 3.

$$\Delta G^{\mathrm{B}} = \frac{\Delta H^{\gamma\to\alpha+Fe_3C}}{T_{equilibrium}}\left(T^0 - T\right) \tag{3}$$

Equation 3 shows that the contribution of the magnetic field to the free energy change can be expressed in terms of the latent heat of transformation, the equilibrium temperature and the shift in transformation temperature relative to the no field case. The equation simply provides an energy value to the apparent decrease in undercooling due to the magnetic field. In actuality, the magnetic field has changed the equilibrium temperature as shown by others [1].

Applying a value -4200J/mol for the latent heat of austenite decomposition into ferrite/pearlite [6] and the Andrews equation [7] for Ae1 = $T_{equilibrium}$ = 720°C, an estimate for ΔG^{B} can be obtained. Figure 3 plots the shift in transformation temperature and associated ΔG^{B} as a function of magnetic field strength. A linear fit was employed to estimate a coefficient describing the relationship between magnetic field strength and transformation temperature and free energy. These results are plotted in Figure 5 and a linear fit to the data yields a magnetic field effect of 3.0°C/T on the transformation temperature or an apparent contribution to the change in Gibbs free energy of 12.6J/mol/T.

Summary and Conclusions

Continuous cooling experiments were performed with 52100 and 1045 steels under the influence of a large magnetic field. Specimens were austenitized and subjected to magnetic field strength of 10T, 20T and 30T during cooling. The release of latent heat associated with austenite decomposition produced an obvious recalescence in temperature data showing an increase in transformation temperature with increasing magnetic field strength. In 52100 steel, a 30T

magnetic field provided additional driving force such that pearlite was realized for a cooling profile that produced martensite without a magnetic field. Temperature data from experiments performed with the 1045 steel were used to quantify the effect of the magnetic field on transformation temperature and an apparent change in free energy. These data indicate a 3.0°C/T increase in transformation temperature and an apparent contribution to the change in Gibbs free energy of 12.6J/mol/T are realized by the application of large magnetic fields.

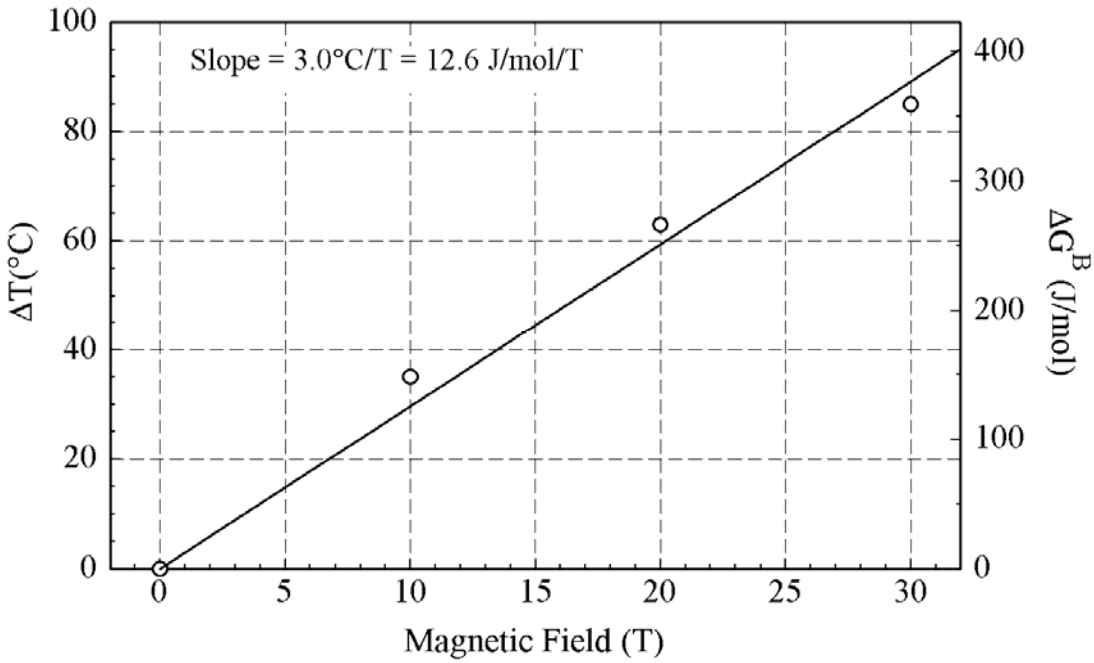

Figure 5. Measured transformation temperature increase and apparent contribution to change in free energy as a function of magnetic field strength for continuous cooling transformations in a 1045 steel.

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