

ORNL Manufacturing Demonstration Facility  
Technical Collaboration **Final Report**

## Heat Treatment of Iron-Carbon Alloys in a Magnetic Field<sup>1</sup> *Cummins, Inc.*

Project ID: MDF-TC-2014-043  
Start Date: 06/18/2014  
Completion Date: 11/30/2014  
Company Size: Large Company (48,000 employees)

### Summary

ORNL researchers in partnership with materials scientists from Cummins, Inc. utilized the laboratory's unique experimental capabilities to understand the fundamental scientific principles underlying Fe-C material property improvements resulting from magnetic field processing. The application of a high flux magnetic field was found to increase the solubility of carbon in austenite by up to 22% which leads to improved properties in martensitic steels used for diesel engine components. This work also provides an experimental explanation for the smaller grain size and finer lamellar spacing seen in material quenched or solidified in a static magnetic field which leads to increases in physical properties including hardness, ultimate tensile strength, yield strength, and fatigue strength. The results of this collaboration will help enable commercialization of magnetic field processing for engine components such as gears and camshafts.

### Background

High flux magnetic field thermal processing has been shown to alter materials properties and could have significant commercial applications. Significant gains in critical material properties, such as a 300% to 500% increase in fatigue strength, when the material is heat treated in a magnetic field have been documented. However, experimental validation of models that predict the phase changes and fractions are a necessary step toward commercialization at Cummins. This project was designed to understand at a basic level some of the thermodynamic relationships and phase equilibria of select iron-carbon binary alloys subjected to thermomagnetic processing.

Enhancement of physical properties of materials has consistently been the cornerstone of technology developments for diesel engine performance and efficiency. Today's clean diesel engines run at higher temperatures and pressures than ever before, driving

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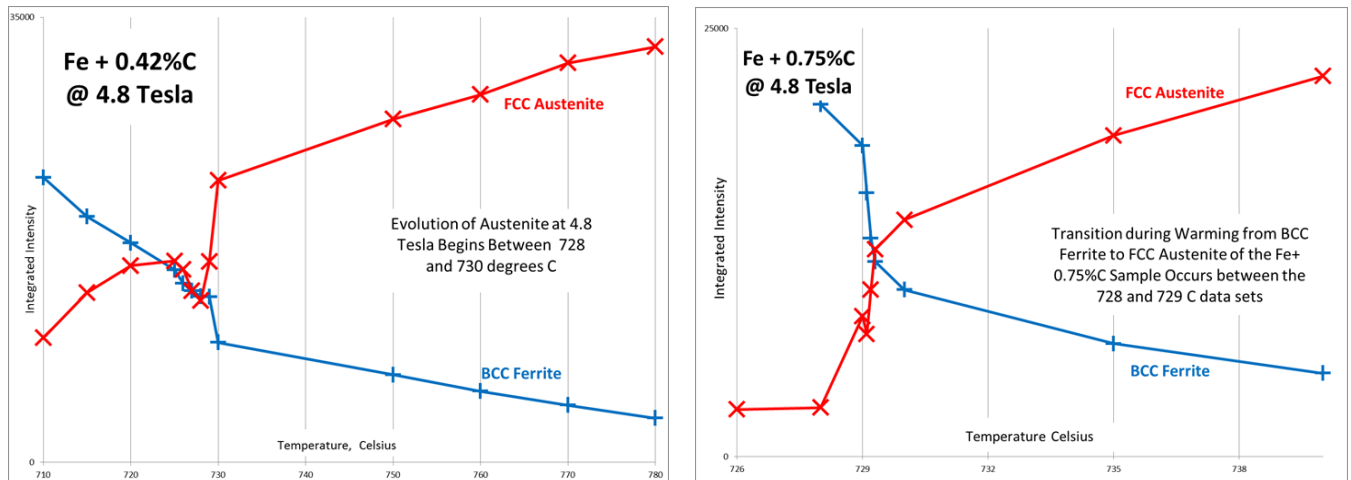
the need for improved materials physical properties to support this combustion regime. High flux magnetic field processing has shown some great advances in material properties such as fatigue strength, hardness, ductility, etc., while decreasing energy consumption during production. However, the fundamental relationship of the changes to the microstructure and improved physical properties was not well understood.

The scope of this work was to heat treat simple Fe-C alloys within a magnetic field, determine the phases and microstructures that are formed and validate basic thermodynamic models. Binary alloys of carbon and iron were selected for thermomagnetic treatment. The composition of these binary alloys covers a key region of the iron carbon phase diagram, including the carbon solubility limit and the eutectoid. These are the most common iron carbon alloy regions in the phase diagram to be employed in commercial manufacture of steel. For Cummins, the ability to predict the effect of thermomagnetic processing in this region was required prior to any commercial application of the technology.

### **Technical Results**

In order to eliminate effects from other alloying elements, high purity binary Fe-C samples were prepared. The unique characterization facilities at ORNL offered opportunities for neutron crystallographic data at high temperature in a high flux magnetic field. The measurement of phase transformations required the addition of a heating source and a superconducting magnet to the neutron goniometer at ORNL's High Flux Isotope Reactor (HFIR). The experimental challenges with this data collection are described in detail in the manuscript "Measurement of Phase Transformation Temperatures Using Neutron Diffraction in a High Flux Magnetic Field" which will be submitted to "Materials Characterization" in the first quarter of CY2015.

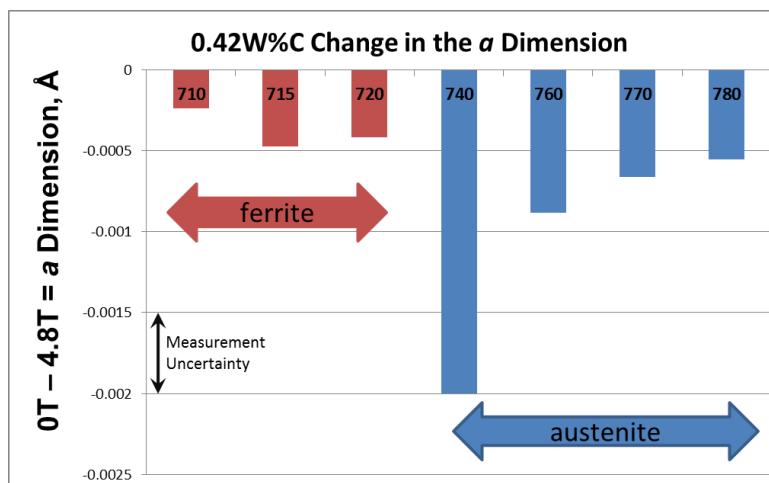
The neutron crystallographic data indicated that the temperature of the transformation from the alpha phase ferrite to the gamma phase austenite was independent of carbon level and occurs near 729°C for both the 0.42 weight percent carbon and the 0.75 weight percent samples (Fig. 1). Figure 1 is a plot of integrated intensity of one neutron diffraction two-theta peak for each phase as a function of the temperature that the neutron diffraction data were measured. The intensity tracks a single peak for each phase (ferrite versus austenite) and so gives relative volume fraction values for the ferrite and austenite phases.



**Fig. 1. The phase transition temperature for ferrite to austenite at 4.8 Tesla occurs just below 730°C for both 0.42%C and 0.75%C alloys.**

The measured two-theta diffraction data for each alloy were converted to lattice spacing using equations from Cullity's Elements of X-Ray Diffraction starting from Bragg's Law. For the 0.42 weight percent carbon sample at 740°C, the lattice parameter "a" dimension measurement of the (022) plane was calculated as 3.6564 +/- .0005Å absent any applied magnetic field. Under the 4.8 tesla applied magnetic field the "a" dimension at 740°C was increased to 3.6584 +/- .0005Å. This increase in the lattice spacing with the addition of a high flux magnetic field was caused by an increased amount of carbon in solution in the austenite. The carbon occupies the octahedral and tetrahedral interstitial sites, and the addition of the magnetic field was proven to increase interstitial density.

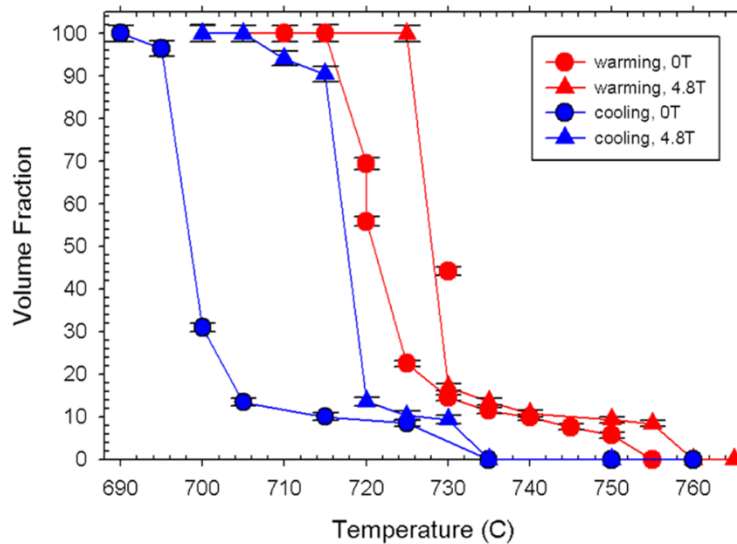
This change in the "a" dimension of the lattice correlates to a 22% increase in carbon solubility due to the addition of a 4.8 tesla magnetic field. This finding is not reported in any search accessible published literature, and the intellectual property implications are being investigated by the team as novel processing paths are viable that may lead to significantly enhanced performance dual phase steels with great impact for the automotive industry.



**Fig. 2. "A" lattice dimension changes from 0T to 4.8T as a function of temperature for the 0.42%C alloy.**

During the work at HFIR, the material was measured during both heating and cooling cycles at temperatures across the allotropic phase transformation, and a unique influence of the magnetic field was discovered which allows for the measurement of the change in Gibbs free energy caused by the addition of the magnetic field (Fig. 3). The direction of temperature change was shown to influence the phase transformation temperature. This is due to the change from the ferromagnetic phase of ferrite and pearlite thru the Curie temperature changing to paramagnetic austenite phase. The magnetic field always favors the ferromagnetic phase, so the transition is retarded during heating and delayed during cooling. This phenomenon was not seen in ambient field samples, proving this was not an instrument created effect.

The addition of the 4.8 tesla field moved the warming transformation temperature initiation to 730°C. This change in temperature correlates to a change in the Gibbs free energy of  $-3 \text{ kJ/mole} \cdot \text{Tesla}$  or  $1^\circ\text{C/Tesla}$ . During cooling with the 4.8 Tesla field, the transformation initiated at 718°C, which correlates to a change in the Gibbs free energy of  $-8 \text{ kJ/mole} \cdot \text{Tesla}$  or  $3^\circ\text{C/Tesla}$ .



**Fig. 3.** The direction of temperature change influences the phase transformation temperature enabling the measurement of the change in Gibbs free energy caused by the addition of the magnetic field.

The change in physical properties created by treatment in a high flux magnetic field was next found to be related to the change in the critical radius of nucleation. Using a magnetic field definition of critical radius, a high magnetic field drives the system to a smaller critical radius of the ferrite under a magnetic field upon cooling, and the opposite, an increased  $R^*$  for the nucleating austenite under a high magnetic field upon heating when compared to the no field case. This theory supports the smaller grain size and finer lath spacing seen in material quenched or solidified in a static magnetic field. Therefore, the increases in physical properties (hardness, UTS, YS, fatigue strength) seen in practice correlate to the Hall-Petch relation, which states that the strength of a material is inversely proportional to the square root of the grain size.

## Impacts

This effort is necessary to model the changes associated with heat treating steel in a high flux magnetic field. Industrial application of this technology will require a more complete understanding of the process, as the design critical physical properties must be well understood and predictable for full commercialization. The ability to directly relate the changes in these physical properties to the Hall-Petch relation will also aid in gaining commercial acceptance. The conclusions presented here support the smaller grain size and finer lamellar spacing observed in material quenched or solidified in a high flux static magnetic field.

This work has significant implications for production of diesel engine components manufactured from martensitic steels such as gears and camshaft rollers. High magnetic field processing can improve the hardness, ultimate tensile strength, yield strength and fatigue strength of both current commercial alloys and potential lower cost substitutes. These components lead diesel engines to achieve higher power density, better fuel efficiency, and lower carbon emissions.

## Conclusions

This ORNL/Cummins technical collaboration has demonstrated some of the basic information needed to model changes in material properties as a result of high flux magnetic fields. This knowledge also provides a scientific explanation for the smaller grain size and finer lamellar spacing that lead to material property improvement, and will help to accelerate commercial acceptance of this technology. The project demonstrated a 22% increase in carbon solubility in austenite which will have positive ramifications for improved martensitic steel properties and diesel engine components. This discovery is an area for follow on work in a second phase of the project, as this is the first time this has been successfully measured.

## About the Company

Cummins is a global power leader that designs, manufactures, sells and services diesel engines and related technology around the world. Cummins serves its customers through its network of 500 company-owned and independent distributor facilities and more than 5,200 dealer locations in over 190 countries and territories.

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