Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance

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Project Goal

- Demonstrate and understand a new industrial processing technology whereby alloys and microstructures can be developed with superior properties through ultrahigh magnetic field processing
  - This program will initially focus on ferrous alloys for documenting this effect.

Vision

- Magnetic Field Processing Using Ultra-High Magnetic Fields Has the Potential To Revolutionize Material Processing and Alloy Development Technologies
  - The major requirement for this concept to work on a material is that **the magnetic susceptibilities of the parent and product phases need to be different**.
  - Steels (ferromagnetic materials) clearly fit into this category.
- This research is **TIMELY** as advances in magnet material and design technologies provide magnetic field strengths of sufficient magnitude to demonstrate this research concept.

Benefits

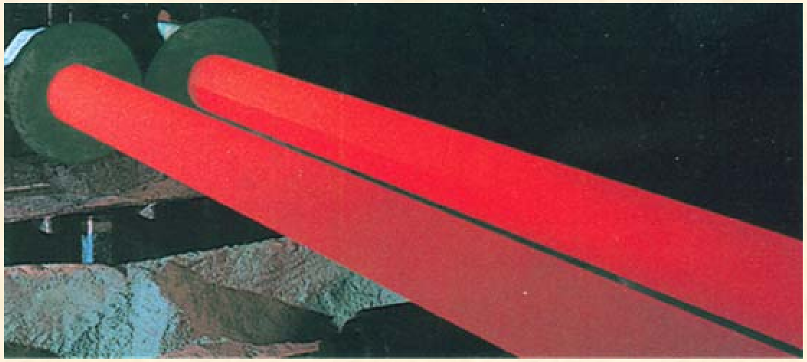
- A new class of materials with novel microstructures and superior properties
- Enhanced phase transformation kinetics
- A new industrial processing technology
- Energy Savings
  - e.g., the elimination of the final normalization heat treatment step through magnetic processing for bar and rod products alone would yield an energy savings in excess of 14 trillion BTU/yr.
- Environmental Benefits
  - Elimination of >0.15 MM TCE/yr.
- Major manufacturing/cost savings ($410M/yr)

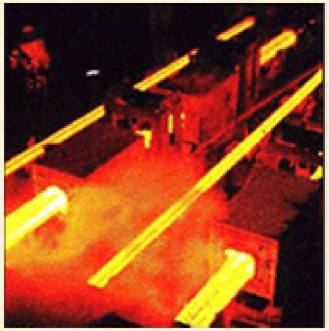
Ultrahigh Magnetic Field Processing Has Many Potential Applications and Therefore Can Impact the Following Industries

- Aluminum
- Casting
- Chemical
- Forging
- Heat Treating
- Steel
- Welding

Optimized Magnetic Field Processing Will Have Major Beneficial Impact on a Broad Spectrum of Industries

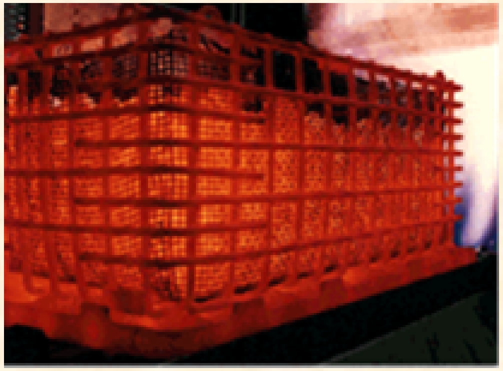
CASTING: Continuous Cast Iron Bar Stock





Forging

Heat Treating & Steel Applications



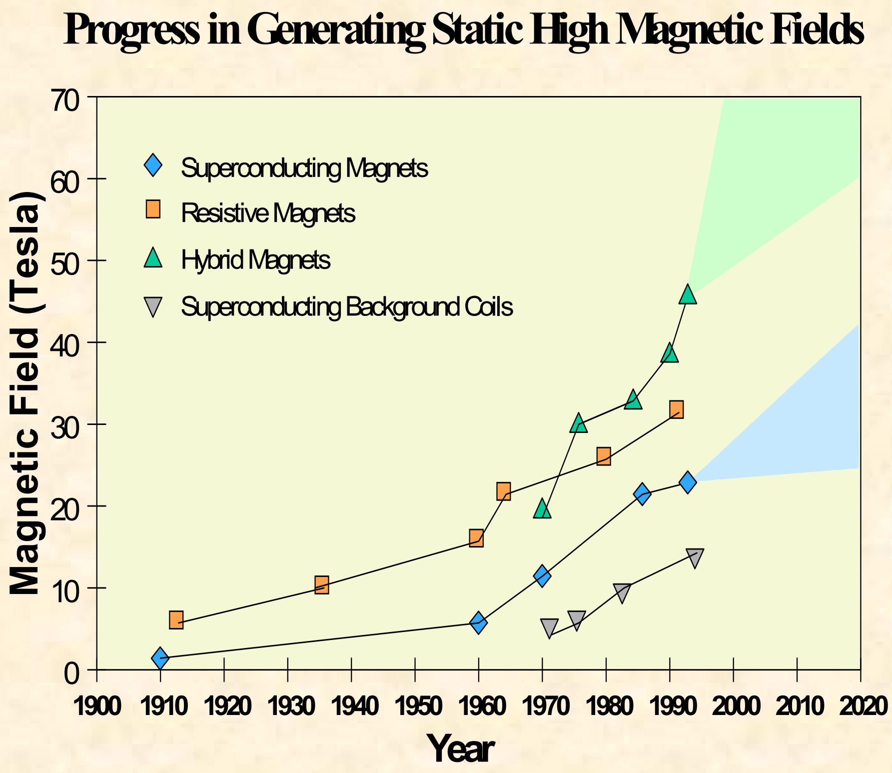
Magnetic Field Processing Influences Material Behavior by Two Mechanisms

- **Thermodynamic Effect**
  - The Gibbs Free Energy is influenced by the magnetic flux and induced magnetization in the material.
  - *Conventional* Phase Diagram Equilibria deals in the **f(P,V,T)=0** equation of state space.
  - This research will investigate phase stability and kinetics in a *new, relatively unexplored* equation of state space, namely: **f(M,H,P,V,T) =0**.
- **Effective Pressure Effect**
  - A.K.A. the "Forced Volume Magnetostriction Energy"
    - This can be a positive term equivalent of a pressure.
  - This effect can be very significant as $P \propto B^2$
    - 50 T ~ 10,000 Atmospheres or ~1000 MPa.

Relative Magnitudes of Magnetic Field Strengths

- Flexible Magnetic Strip (refrigerator magnet): 0.14 T
- Rare Earth Magnets, NdFeB-type: 1.22 T
- Rare Earth Magnets, SmCo-type: 0.82 T
- Magnetic Annealing Process: 0.04 T
  - For hard disk materials
- Best Superconducting Magnets: 17 – 20 T
- NHMFL Hybrid Magnet: 45 T
  - 10^6 > Earth's Gravity

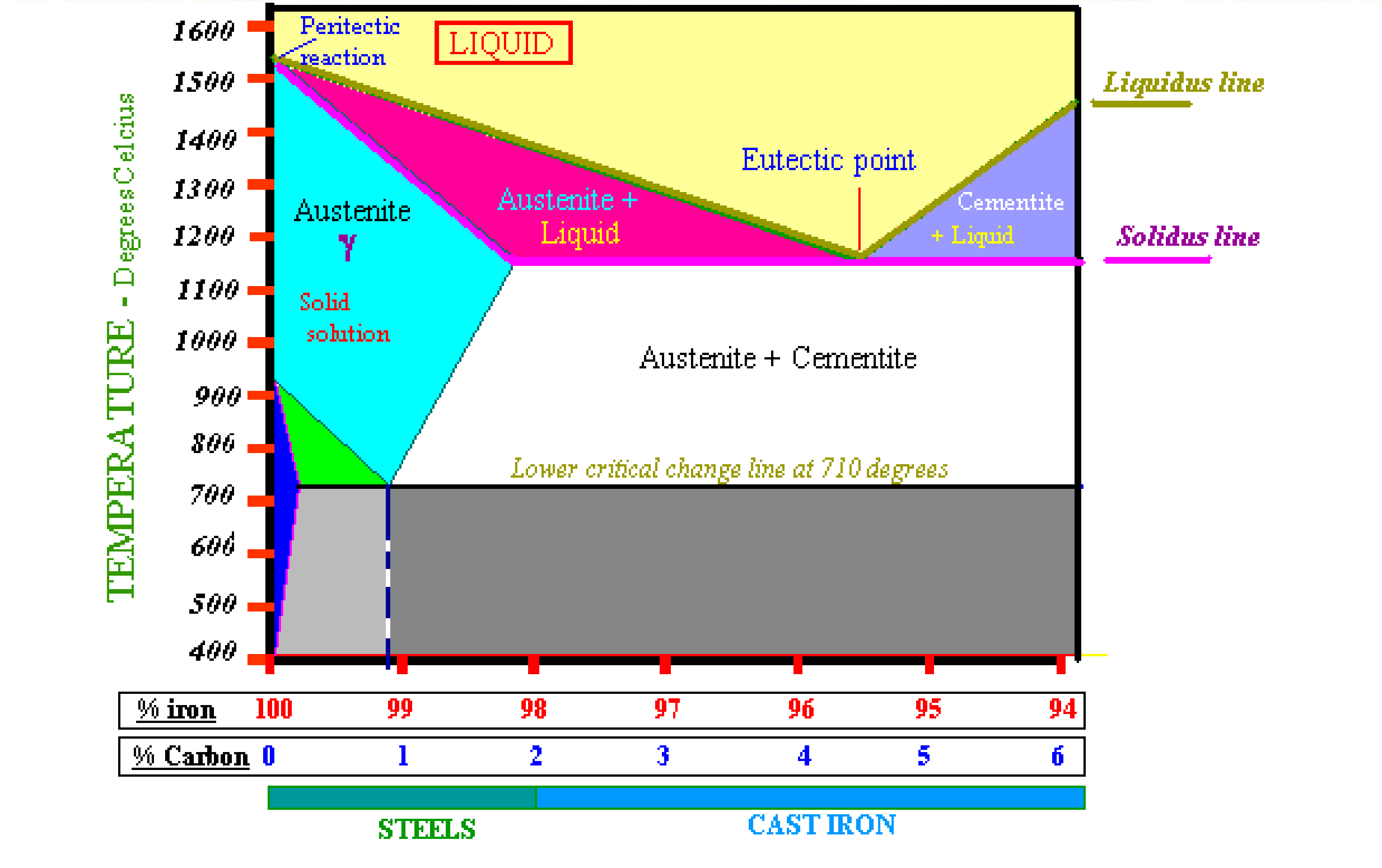
Magnetic Processing Has Commercial Viability Today Because of the Availability of Cost-Effective, High Field Superconducting Magnets



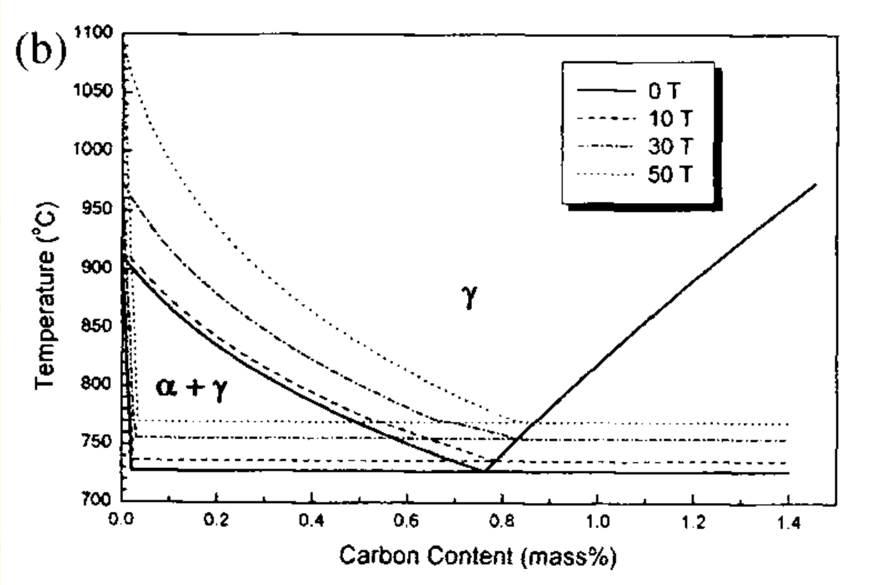
Superconducting Magnet System Cost as a Function of Field Strength

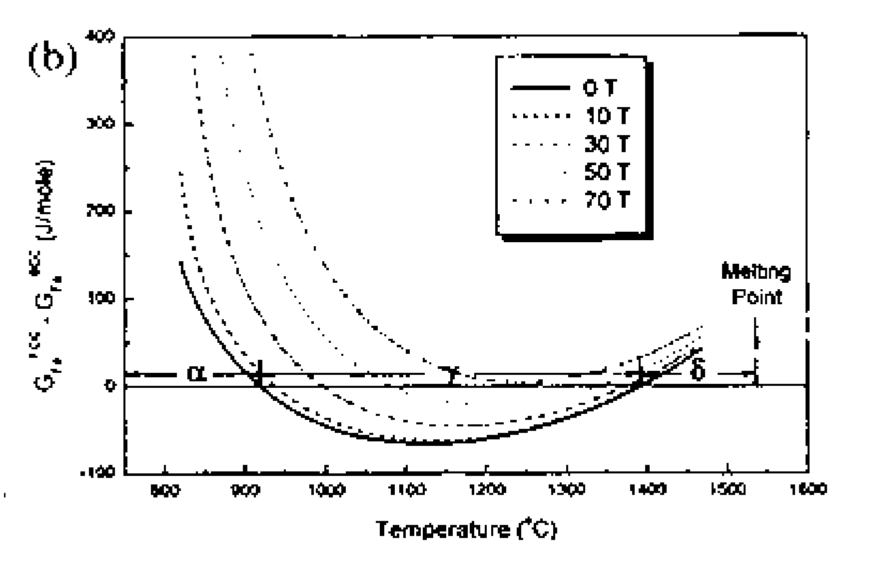
Field Strength (in Teslas)	Procurement Cost (in $K)
21	500
18	250
16	175

Fe-C (Carbide) Equilibrium Phase Diagram



Ultrahigh Magnetic Field Processing Will Enable Manipulation of Fe-C Phase Equilibria and Kinetics to Customize Microstructures and Properties Beyond Current Technology Capabilities





$$\Delta G_c^{\alpha\rightarrow\gamma} = RT[\ln(a_c^{\alpha})-\ln(a_c^{\gamma})] + \int_0^H (M_c^{\gamma} - M_c^{\alpha})dH$$

Where: M= Magnetization and H= Magnetic Intensity

A Precedent for Magnetic Field Processing Already Exists However Significant Unexplored Technology Applications Remain

- For years, magnetic annealing has been used to develop customized microstructures in magnetic materials
  - However, at relatively low magnetic field strengths of ~0.04 Tesla.
- High field processing is relatively unexplored
  - Limited literature references indicate significant potential for tailoring microstructures and impacting kinetics through ultrahigh (> 5 Tesla) magnetic field processing of ferromagnetic materials.
  - Tremendous opportunities exist for ultrahigh magnetic field processing.

Issues to Address to Exploit This Magnetic Processing Technology

- Existing ultrahigh field magnetic processing facilities were not designed to facilitate magnetic processing of materials via thermal processing characteristically used in the ferrous industry (e.g., continuous cooling quench)
  - ORNL has worked with the National High Magnetic Field Laboratory to develop initial capabilities to conduct these proof-of-principle experiments to demonstrate this technology concept on a ferrous alloy.

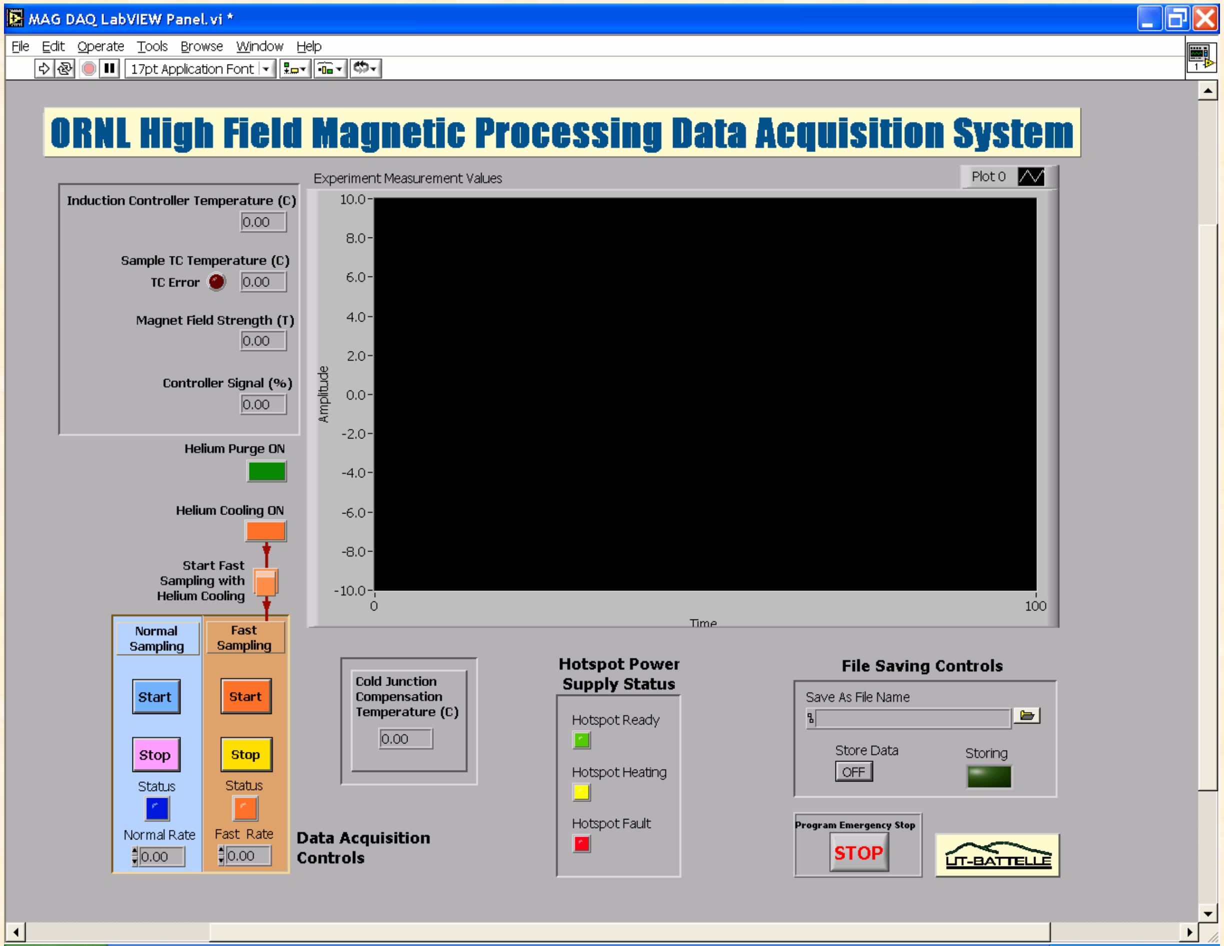
Issues to Address to Exploit This Magnetic Processing Technology (cont.)

- Current lack of ability to predict the response of materials to an applied ultrahigh magnetic field
  – A methodology is being developed to incorporate magnetic field effects into a thermodynamic simulation code.
- Lack of data characterizing the magnetization response of materials to ultrahigh magnetic fields
  – Capability will be established to measure the magnetization response of candidate materials as a function of ultrahigh magnetic field strength.

Project Milestones

- Develop magnetic field processing capabilities to demonstrate this technology concept for ferrous alloys
  - Completed and experimentation is underway.
- Development of a predictive capability to understand this phenomena
  - In-progress activity.
- Determination of material magnetization response data for ultrahigh magnetic field exposures
  - Viable techniques are currently under evaluation.
- Phase transformation kinetic response evaluation
  - Future endeavor.

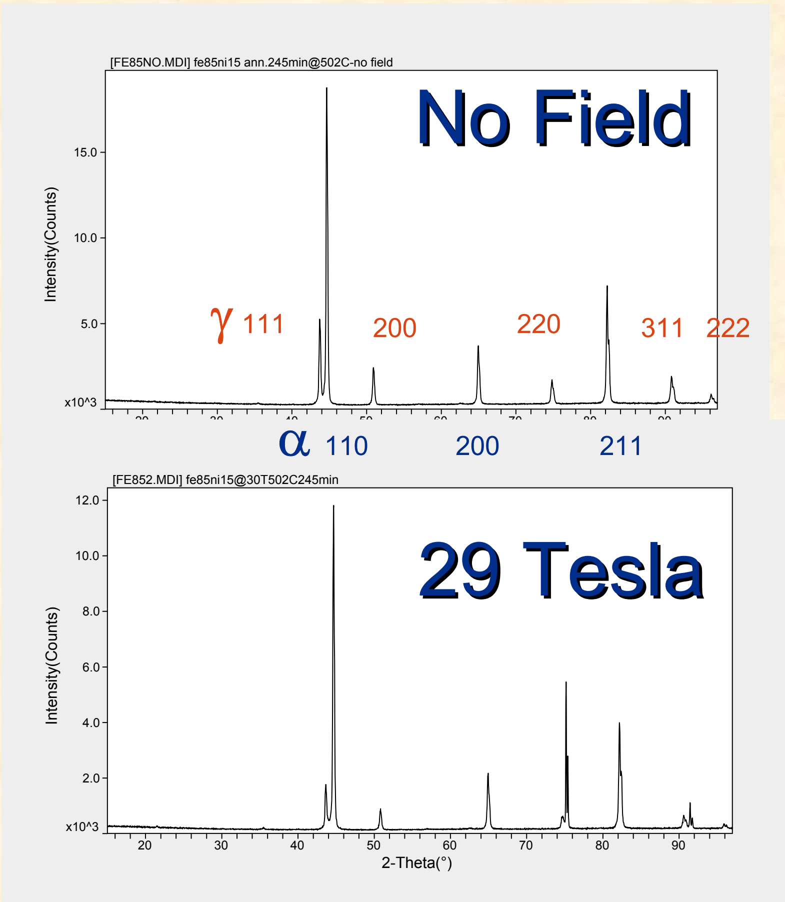
Thermal-Magnetic Processing Experiments Are Fully Automated Using LABVIEW Software



The Proof-of-Principle Experiments Have Validated Our IMF Hypothesis: Magnetic Processing Can Exhibit a Major Effect on Phase Equilibria

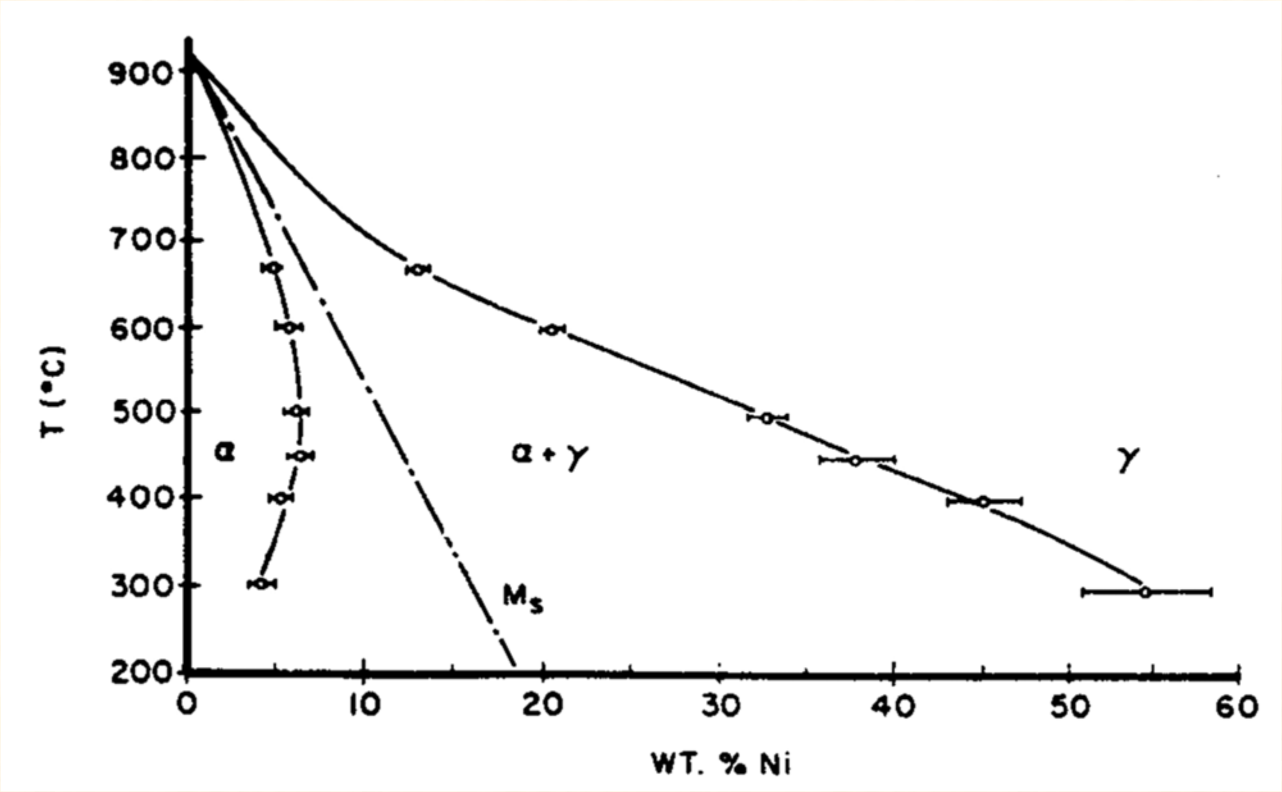
- **85Fe-15Ni FCC solid solution:**
  - **Large effect: BCC to FCC phase volume fraction increased (doubled from 14 % to 28 %) by a 29 Tesla Field!!!**
    - **MAJOR phase equilibria effect of magnetic processing.**
    - **Implication is that the austenite phase can be destabilized to eliminate retained austenite in quenched steels.**
      - Elimination of cryogenic treating or double-temper heat treatment cycles in higher carbon and carburized quenched steels.

85Fe-15Ni Alloy
Annealed With and Without a Magnetic Field



- Relative areas of bcc and fcc peaks shows a 2±0.1 fold increase in volume fraction intensity of ferromagnetic bcc phase due to annealing in 29 Tesla field.
- Nearly all sources of error in bcc to fcc ratio cancel. Results are very reliable.
- Analysis by C.J. Sparks.

Fe-Rich Section of the Conventional Fe-Ni Phase Diagram



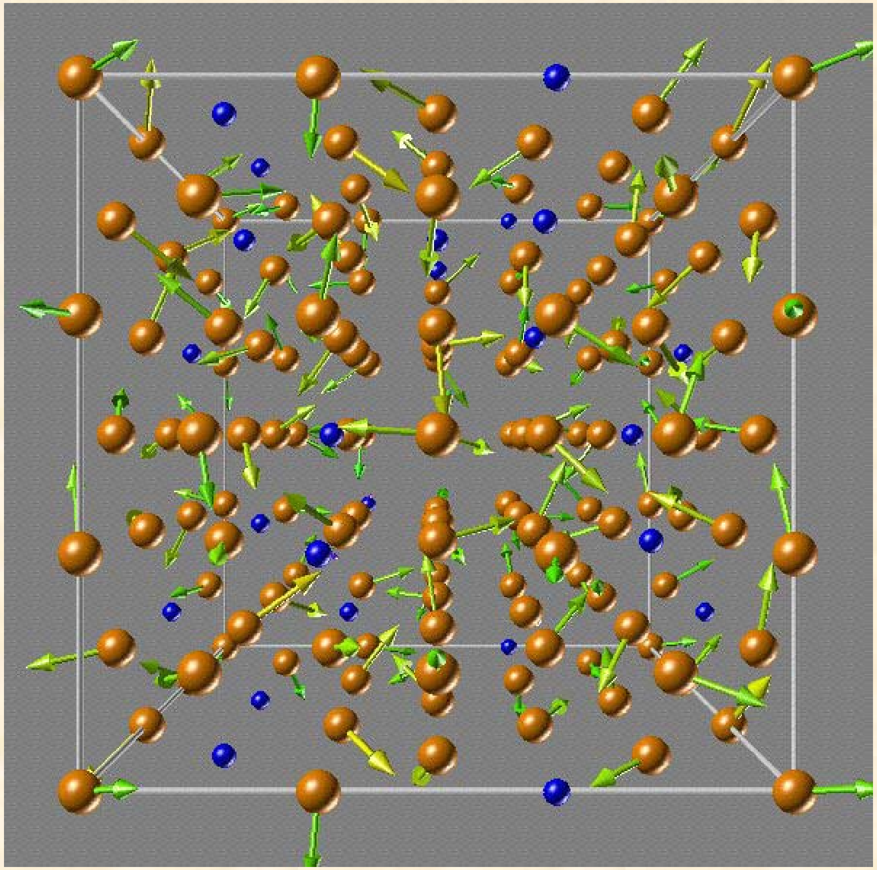
Example Heat-Treating Application

- Elimination of cryogenic treating or double-temper heat treatment cycles to eliminate retained austenite in higher carbon or carburized quenched steels by raising the Martensite Start and Finish Temperatures via magnetic processing during the initial quench cycle.

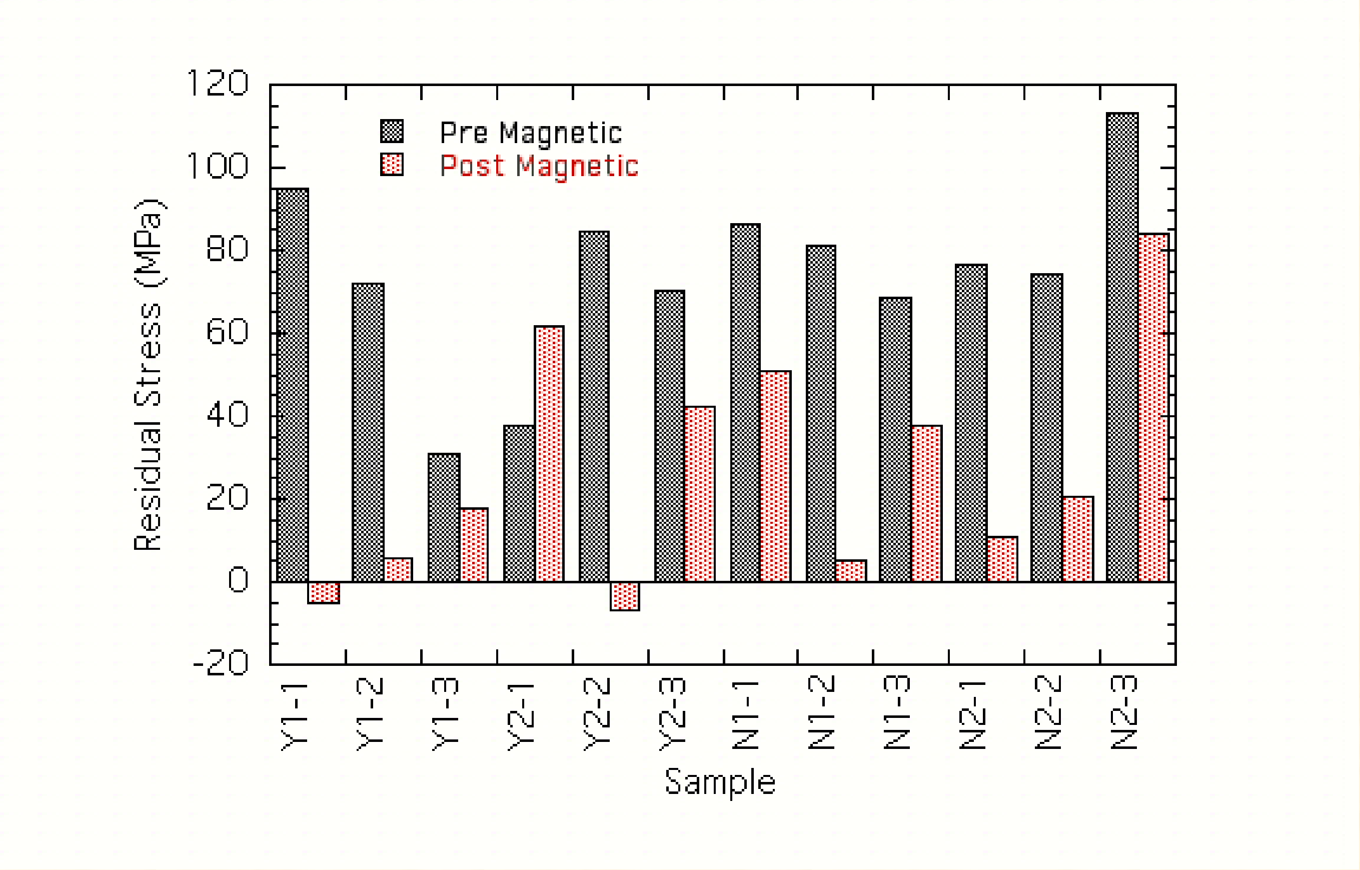
Significant Energy and Environmental Benefits are Achievable Immediately

- **Immediate Return**
  - Elimination of Steel Bar & Rod Normalization Heat Treatment (conservatively based on only 20% of 32M tons per year)
    - > 14T BTU/yr
    - > $410M/yr reduced manufacturing costs
    - >0.15 MM TCE/yr.
    - Immediate application confirmed by both Timken and Cummins Company R&D and Manufacturing Staff.
- **Maximum Energy Savings (>1 Quad) would occur if the ULSAB Design could be implemented**
  - *Existing Implementation Problem*: Steel property non-uniformity.
  - Tailoring microstructures via magnetic processing could achieve property uniformity and enable thinner product for auto body use.
  - *Results*: Improved fuel efficiency of 1.02×10^{10} gal/yr of gasoline (or >1.4 Quads of energy).

Modern First Principle Local Spin Density Electronic Structure Modeling is Being Accomplished to Predict the Thermodynamic Contribution of the Magnetic Field on Microstructure Evolution & Phase Stability



An Example of Another Application of the Magnetic Field Processing Research at ORNL Is The Reduction of Residual Stresses in a Quenched Ferrous Alloy



Implications of Residual Stress Relief Activity

- **Residual stress reduction during or after component fabrication processes**
  - Design stresses can be higher enabling smaller, lighter-weight, more energy efficient components.
  - Ingot solidification or welding stresses can be reduced.
  - Corrosion reduction in deformed regions.
- **Component “Life Extension” via magnetic processing as a scheduled maintenance operation**
  - Periodically reduce residual stresses induced during component life cycle that can lead to failure.
  - Increase forging tooling life.
  - Reduced operating costs for part replacement.

Magnetic Field Processing Opens Up a Whole New World of Potential Novel Material and Processing Developments

- Ultra Fine (even nanoscale) Grain Size Capability
- Unique Metastable Microstructures
- Customized Phase Transformation Sequences
- Unique Solid Solution Chemistries (rewrite Phase Diagrams as we know them today)
- Produce More Uniform Deformation Processing Techniques
- Improved Solidification Microstructures & Processes
- Unique Single Crystal Growing Technologies
- Enhanced Powder Consolidation Kinetics/Densification
- Destabilization of Retained Austenite
- Residual Stress Reduction

Summary

- This IMF Project has demonstrated and is continuing to pursue the development of a new, high-payoff industrial processing methodology whereby novel alloys and microstructures can be developed with superior properties via magnetic processing that normally would be impossible to achieve with conventional thermomechanical processing techniques.