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LIST OF ACRONYMS

ASTM	American Society of Testing Materials
CALPHAD	Computational Thermodynamics calculation of phase diagrams
DEFORM	An engineering software for design analysis
DFT	Density Functional Theory
ERC NSM	Engineering Research Center for Net Shape Manufacturing
fcc	austenite
Fe	ferrite
GPRA	Government Performance and Results Act
ITMP	Induction Hardening and Thermo Magnetic Processes
ORNL	Oak Ridge National Laboratory
OSU	Ohio State University
SAE	Society for Automotive Engineers
SC	Super conductor
UTS	Ultimate Tensile Strength
YS	Yield Strength

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EXECUTIVE SUMMARY

Within this project, Eaton undertook the task of bringing about significant impact with respect to sustainability. One of the major goals for the Department of Energy is to achieve energy savings with a corresponding reduction in carbon footprint. The use of a coupled induction heat treatment with high magnetic field heat treatment makes possible not only improved performance alloys, but with faster processing times and lower processing energy, as well. With this technology, substitution of lower cost alloys for more exotic alloys became a possibility; microstructure could be tailored for improved magnetic properties or wear resistance or mechanical performance, as needed.

Purpose

The purpose of this project was to reduce the carbon footprint and improve the energy efficiency through the Induction-Thermo-Magnetic-Processing (ITMP). Industrial components like gears and shafts are carburized and the intent here is to demonstrate the improvement in mechanical properties through ITMP, paving the way for the application of low cost steels without carburization.

Scope

Demonstrate the improvement in mechanical properties of the current carburized components using ITMP. Use this process to generate comparable or improved properties in steels, without carburizing.

Results

The project demonstrated 30% improvement in ultimate tensile strength (UTS) over the baseline carburized steels and a 43% decrease in retained austenite. The ductility improved over 100%. In high strength steel ITMP resulted in (compared to baseline) 7% improvement in UTS, 10% improvement in yield strength (YS), 90% improvement in elongation, and 40% improvement in wear (demonstrated using the Falex friction testing). The project demonstrated 77% improvement in magnetic permeability in low carbon steel over the baseline and developed the interaction of alloying elements like iron carbon (Fe-C) and iron nickel (Fe-Ni) phase stability in steel, processed in a high magnetic field using the First Principles modeling. This project developed the application of DEFORM modeling for efficient use of material in forging operation, resulting in energy savings. This demonstrates the viability of making components such as engine valves, gears, shafts for application in the transportation industry. Finally, this project demonstrated that the tempering time in a magnetic field of a quenched and hardened steel decreased from two hours to ten minutes with uniform hardness.

Conclusions

ITMP can be successfully used in suitable steels without carburizing to achieve similar or improved performance, with substantial carbon footprint reduction and energy savings. The report demonstrates that the new ITMP technology can be applied to commercial manufacturing operations through the replacement of traditional carburizing operation. Actual components used in the transportation automotive industry like gears and shafts have been processed by the ITMP process and tested by Eaton manufacturing operations.

Recommendations

ITMP should be commercialized in order to provide energy savings.

Energy Benefits

Calculations based on industrial plant demonstration indicate a significant savings in energy.

Commercialization

A prototype commercial unit has been developed to conduct processing of materials. Testing of this equipment has been conducted and results demonstrate the feasibility for industrial commercialization.

1.0 INTRODUCTION

The use of induction heating in combination with a high magnetic field is the key factor in achieving energy savings. This project focused on reduction of energy consumption, reduction of material scrap and reduction of the carbon footprint, associated with several key energy-intensive industrial manufacturing processes related to applications such as gears, dies, and forgings.

The primary technical solution focused on the use of a hybrid integration of high magnetic field heat treatment and induction heat-treatment processing to modify the metallurgy and performance of commercially relevant material systems.

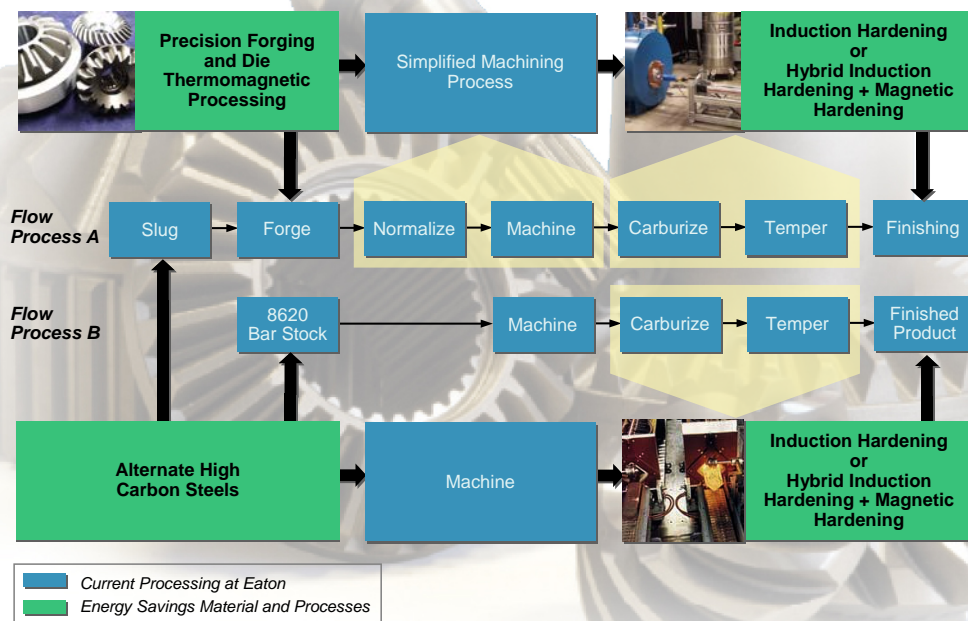


Figure 1 : Potential Modification with ITMP

Figure 1 above illustrates the Project Objectives and the implementation of induction heating and thermo magnetic processes (ITMP) in the manufacture of various products at Eaton. The blue boxes in **Figure 1** shows the “flow process A” representing the manufacture of bevel, spur, and helical gears and engine valves and “flow process B” representing the manufacture spur gears and gerotors. The green boxes indicate the focus of this project and how they are directly related to the project objectives; the green sections indicate how the ITMP technology is viewed both as a way to reduce energy and cost, but also as an approach for improvement in components performance.

The diagram in **Figure 2** below demonstrates the potential improvement that can be achieved with ITMP over the conventional processing. Therefore, the solution hypothesis is to offer material innovation (see the dotted line) that allows performance levels to be extended beyond what conventional limits allow (without increasing size) and at acceptable process energy and cost.

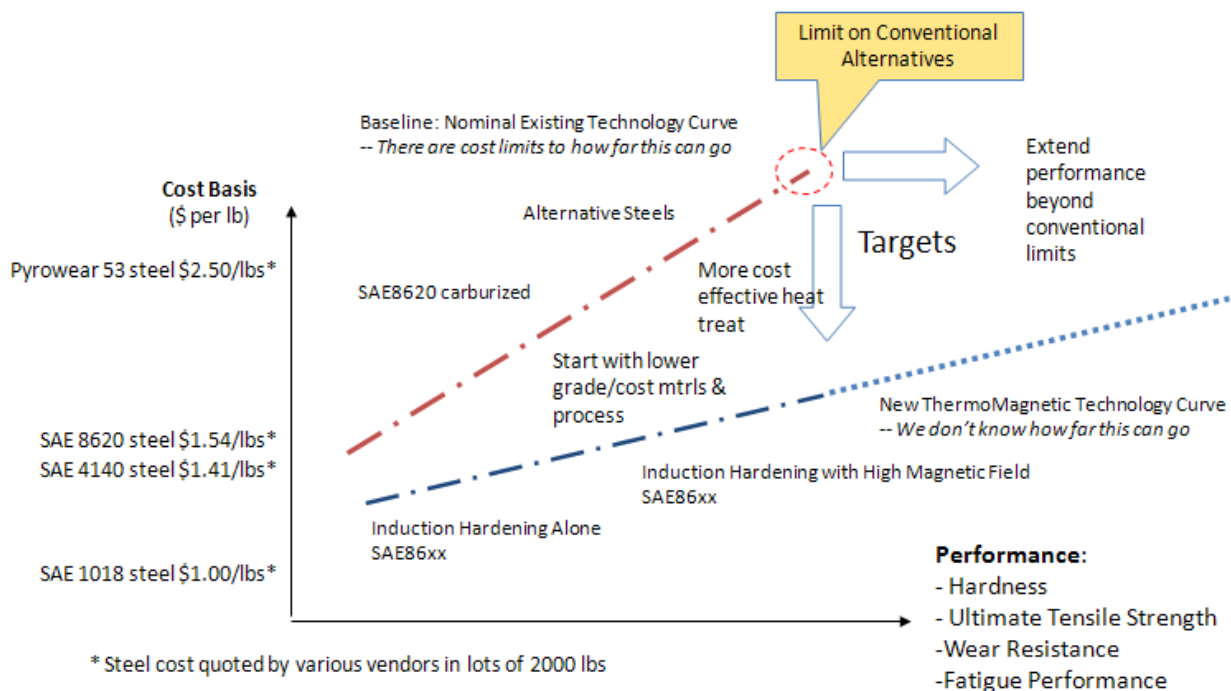


Figure 2: Cost Basis vs. Performance

1.1 Project Objectives

The focus of the project was to develop cross-cutting manufacturing technologies that would be applied over a broad spectrum of markets and industries, to enable the reduction of process steps, part counts, associated cost and energy intensity, in addition to CO2 emissions. This program has developed and demonstrated new lower-energy processing methods that will result in a minimum of 30% reduction in energy use. The project has investigated and implemented, through prototypes, advancements in heat processing of steels in addition to net-shape (and near-net-shape) forming, using novel process technologies, as described below. Overall, the intent was to employ an energy efficient alternative hybrid integrated heat treat method for general industrial materials processing, and that when applied to forging applications, results in additional significant energy savings by enabling wide spread use of net shape forging.

The specific project objectives were:

- Develop a transformational thermo-magnetic process technology approach for bulk and surface treatment;
- Develop more energy-efficient hybrid technology approaches that couple thermo-magnetic process (TMP), induction hardening (IH) and heat treatment, to replace conventional energy-intensive heat treatment and post-processing methods like carburizing for automotive gears;
- Use innovatively coupled ITMP processing approaches to extend die and die tool life, allowing the use of: a.) less expensive, lower grade steel alloys; and b.) more easily forgeable steel feedstock to achieve significantly enhanced performance otherwise unattainable;
- Use energy efficient thermal treatment technology for precision net-shaped forging of valves at lower forging temperatures resulting in significantly lower energy and carbon footprint;

- Design and build an industrial-scale prototype system to develop and demonstrate the novel coupling of ITMP technologies in order to accelerate the commercialization of this energy-efficient, high-temperature materials processing technology for a targeted set of commercial applications.
- Develop streamlined procedures based on first principles calculations for determining Thermo-Calc Field-Modified Phase Diagram. Developed/updated Fe-C phase diagram showing the effect of magnetic field on “ α ”, and “ $\alpha + \gamma$ ”, and “ γ ” regions.

The project team was made up of a diverse and focused collaborative group organized to include:

- Two End-Users of this technology (Eaton Corporation; Durabar)
- Two Equipment Manufacturers (Ajax Tocco; American Magnetics Inc.);
- Two Universities (Ohio State University; Northwestern University);
- And a National Laboratory (Oak Ridge National Lab).

The team members included:

- Eaton Corporation; a premier, diversified industrial manufacturing company, and a world-leader in hydraulic systems, truck and automotive drive and power-train systems, aerospace systems and electrical power management systems and solutions, is the prime and is a key end-user;
- Oak Ridge National Laboratory; with researchers, who are recognized experts in the ThermoMagnetic Processing technology, and who hold patents and open literature publications in this technology;
- American Magnetics Inc; a world-recognized leader in the design and production of commercial, superconducting magnets;
- Ajax-TOCCO Inc; a leading thermal processing and induction hardening expert equipment manufacturer;
- Dura-bar; an end-user company in industrial processes;
- The Ohio State University; with researchers who are recognized experts in precision forging and process modeling;
- Northwestern University; with researchers in first principles materials (quantum mechanical) modeling capability;
- and MultiSolutions Inc; with Dr. Vinod Sikka, (retired after decades of service to ORNL), a consultant in materials and the quantification and optimization of energy efficiency.

The Principal Investigator for the project team was Aquil Ahmad, a Senior Principal Engineer at Eaton Corporation, with thirty nine years of experience in engineering, research, development and process engineering.

2.0 BACKGROUND

2.1 Induction Hardening Process

Almost without exception, all ferrous materials used in industrial manufacturing go through a series of treatments to establish the desired properties of the end product. This includes, but is not limited to: heat treatment, quenching, tempering, carburization, nitriding, etc. Some of these processes are used to change bulk properties, others to change only the surface properties. Carburization is a widely used method to make surfaces harder and more wear resistant without hardening the core. It is used extensively throughout the industry in the manufacturing of gears, shafts, hydraulic rings, stars, rollers, etc. Conventional carburizing furnaces operate at an energy efficiency that is typically below 30%, with furnace capacity utilization typically 50% or less. Even when the furnaces are not utilized, they are kept hot during idle periods, resulting in massive waste of thermal energy. In addition, a significant amount of inventory is required for operating batch type conventional carburizing furnaces (for example stocking hob and shaved gears, holding in inventory sufficient machined components to justify the furnace load, etc.).

As a result, net energy efficiency of conventional carburization is on the order of 15% or less when taking into account the idling and the need to keep the furnace hot at all time, even when advanced heat recuperation techniques are employed. Besides the emissions associated with the conversion of fuel to thermal energy, carburization is based on the use of carbon-containing gas, e.g. methane and carbon dioxide, to implant carbon atoms in the interstices of steels and other materials. Thus, there is significant additional release of CO₂, a green house gas into the atmosphere from this process.

Induction field processing is an alternative surface treatment method to carburization. It employs high frequency magnetic induction which affects the microstructure of the topmost surface layers of the material inside the coil. In contrast to carburization, induction field processing uses a solid state power supply, which is 80% to 90% efficient, with overall energy efficiency of roughly 80%. There is no energy wasted in between batches, and no inventory build-up is required. Because of the need for high currents and variable size coils, induction hardening is traditionally used mainly in high volume applications. With rising energy prices and attention to emissions, induction processing is rapidly finding its way into more and more applications where carburization was typically used.

The optimization of induction processing requires comprehensive expertise in cross-disciplinary fields such as product design, materials engineering, manufacturing, and heat-treatment, to capitalize on the latest innovations in material science and heat treat processes as they relate to manufacturing operations, part performance, and cost feasibility. An important tool is the structured application of modeling and finite element analysis (FEA) to properly evaluate the often complex multivariant issues covering all manufacturing disciplines and product requirements; this often stretches the present use of simulation-based engineering science techniques.

2.2 Thermo-Magnetic Process

Materials properties are determined by composition and structure:

- Thermodynamics dictates the 'winning' structure given infinite patience.
- Kinetics determines how far you can get, given barriers & activation energy.
- Heat treatment and quenching is used to 'lock-in' desired structures.

- Applicable phase diagrams and kinetics change with magnetic field; to produce new material microstructures, compositions, and properties.

This technology builds on findings of a successfully completed ORNL Laboratory-led IMF project entitled “Exploring Ultrahigh Magnetic Field Processing of Materials for Developing Customized Microstructures and Enhanced Performance” (reference - contract DE-FC07-01ID14249). This previous project designed and developed proof-of-principle laboratory experiments on small scale samples that demonstrated magnetic field processing dramatically influences the phase transformations and kinetics in ferromagnetic material systems that cannot be achieved through any other processing avenue. Research at the Oak Ridge National Laboratory on ferromagnetic alloys has clearly shown experimentally that phase equilibria/stability and transformation kinetics can be dramatically altered through the application of a high magnetic field. These initial studies indicated that conventional high performance material systems that are typically Fe, Ni, and/or Co-based are prime candidates for developing significantly enhanced performance using magnetic field processing. The ability to dramatically influence the phase stability of parent and product phases provides the opportunity to produce enhanced performance, novel microstructures (even nanocrystalline spacing) in carbon-, alloy-, and stainless steels, nickel-, and cobalt-based systems that are not possible through any other means.

This new processing technology manipulates microstructural evolution and stability at the atomistic-level creating novel materials/microstructures with the potential for significant improvements in strength, toughness, fatigue, wear, and corrosion resistance, enabling major energy efficiency improvements during materials processing and in-service. Magnetic field processing has a direct thermodynamic influence on the Gibbs Free-Energy of the various phases in a material. The ramification of this effect is that totally new phase diagrams may evolve due to magnetic field processing, opening up a new dimension in materials process development. This unequivocally demonstrates that magnetic fields can totally replace energy-intensive thermal processes, or significantly reduce the thermal component, as a means to drive phase transformations to develop superior performance microstructures. The exciting aspect of these new microstructures is that they remain stable at ambient temperature after the magnetic field is removed. The free energy contribution of phases resulting from the application of large magnetic fields have been calculated directly with modern first principles electronic structure methods (Local Spin Density calculations) at the atomic structure level for the case where a uniform magnetic field is imposed. It is found that magnetic field processing influences microstructural development and evolution at this nanoscale level.

ORNL’s previous experimental feasibility studies confirmed/validated this earlier predictive modeling effort, and demonstrated that enhanced phase solubility occurs in the Fe-15Ni alloy due to magnetic field processing. The solubility of the Ni (a substitutional solute) in Fe at 500°C was substantially increased using thermomagnetic processing- ~30% beyond what’s possible using conventional processing methods. In addition, ORNL has demonstrated the capability to predict the atomic structure and magnetization of metallic glass, solid solutions, and ordered phases from first principles simulations. ORNL pioneered this technology on the first and only prototype TMP R&D processing facility in the US. This equipment integrates energy-efficient, superconducting (SC) magnet technology (requires no energy to maintain its magnetic field after reaching persistent mode) with induction heating capabilities integrated with unique ORNL-designed and developed materials handling (linear robotic device) and processing apparatus that enables rapid cooling capabilities.

This 5-inch diameter bore, 9-Tesla SC magnet with 8-inch uniform field zone was designed and fabricated by AMI (American Magnetics, Inc.) who also is a participant in this project and who will advance the current state-of-the-art significantly beyond these current system limitations through delivering the next generation system during this project.

2.3 Computational (Predictive) Modeling for Driving Process Development

During processing, materials at each temperature are pushed by the free energy toward specific equilibrium phases. Target microstructures and properties are achieved by carefully controlling the sequence of temperature and other parameters. However, thermodynamic or kinetic obstacles often occur that can only be circumvented by complex maneuvers. This may involve cyclical heating and cooling that causes the growth and then elimination of phases or temperature gradients that for example harden the surface while leaving the bulk microstructure unaffected. To a large extent phase diagrams provide maps through this process.

Perhaps it is not surprising that the ability to shift phase boundaries with a magnetic field can lead to materials properties that cannot be achieved by other means. Magnetic fields can nudge thermodynamic obstacles out of the way and lead to more direct, energy efficient processing often leading to previously unobtainable properties. For this emerging processing option new maps are required, i.e. field dependent phase diagrams. For zero field, there are commercial phase diagram software and associated thermodynamic databases that provide useful guidance. ORNL has augmented ThermoCalc by modifying its standard databases using enthalpies and entropies from first principles electronic structure calculations. These first-principles approaches are predictive in nature, in the sense that they can produce highly-accurate energetic, thermodynamic, and structural information about a given alloy system, with little or no experimental input. These density functional theory (DFT) calculations are used to form the integrated connections with other modeling efforts, such as kinetic Monte Carlo simulations, phase-field modeling of microstructural evolution, phase diagram calculations, and DICTRA (Thermocalc software) phase transformation calculations.

ORNL and NWU have a long track record of the use of DFT to study problems of phase transformations and mechanical properties in structural metals. Specifically, these studies involved some of the first-ever combinations of DFT with a wide variety of modeling approaches: Monte Carlo, kinetic Monte Carlo, phase-field modeling, vibrational entropy, metastable precipitate solvus curves, complex multicomponent precipitation, and the incorporation with thermodynamic modeling tools. The combination of these tools have proven useful in producing predictive models of yield strength behavior as well as a patented computational method to optimize heat treatment response and thermal stability of industrial alloys. The calculated phase boundary shifts for FeNi processed in a 29 Tesla field are shown in **Figure 3**. These shifts were confirmed by x-ray scattering on samples that had been annealed at 500°C in either 29T field or zero field.

There are several contributions to the free energy; for each of these there are different levels of approximation. As a starting point one adds the magnetic contributions to the free energy to the available zero field database. This allows the benefit from the years of work devoted to developing databases for widely used multicomponent steels. The field contribution is proportional to the magnetization which (for saturation fields) has two contributions, the value of the magnetization at a field just strong enough to align the domains and a smaller contribution due to the rotation and increased magnitude of the local moments in response to the strong field. The Vienna Ab-initio Simulation Package is used to calculate the saturation field at low temperatures and the Wang Landau-Locally Self-consistent Multiple Scattering code is used to calculate the effect of

temperature and field on the orientation and size of the local moments and the related change in entropy and enthalpy (reference - contract DE-FC07-01ID14249).

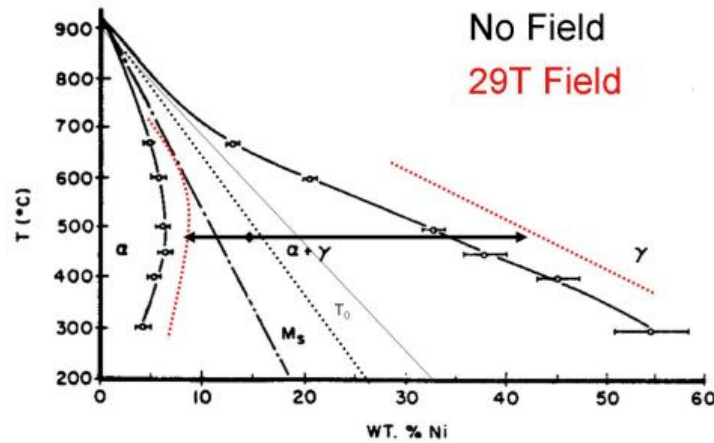


Figure 3: Previous modeling studies show significantly enhanced Ni solubility (red lines compared to black) in both the α and γ phases

Processing is dynamic; it is not sufficient to know what phase the system is drawn towards; the kinetics of transformation is critical. It has been observed the kinetic effect of magnetism in plots of Fe self-diffusion as the temperature is lowered through the Currie point. The enthalpies, upon which the phase diagrams are based, give an indication of the driving force toward transformation but the energy barriers such as those governing vacancy diffusion are often key to kinetics. For kinetics the perfect bulk is uninteresting; the defects, e.g. vacancies, dislocations, impurities, grain boundaries determine the kinetics. The magnetic structure around defects and the effect of the field on defect transformation barriers such barriers to diffusion and grain boundary motion are calculated. This is a new area where there are no established rules.

In summary, the modeling effort calculates field dependent phase diagrams and kinetic factors to interpret the observations of the process.

3.0 RESULTS AND DISCUSSION

3.1 Progress by Task

Table 1 provides a summary of the tasks completed in this project over three years.

Table 1: Task Chart

Task No.	Task/ Description
1	Project Management and Associated Project Control Architecture
2	Commercial Feasibility
2.1	Energy Savings Feasibility
2.2	Technical Feasibility
2.2.1	Induction Hardening and ThermoMagnetic Feasibility
2.2.2	Precision Forging Feasibility
3	Fe-C Phase Diagram
4	ThermoMagnetic Generation 2 Design

3.2 Task 1 – Project Management and Associated Project Control Architecture

As part of project management, several activities outlined below were conducted to maintain the engagement of the team and action was taken immediately when required.

- Eaton, Innovation Center, Aquil Ahmad and John A. Kovacich used bi-weekly meetings to manage the work – generally of one hour duration on a regular basis. Issues relating to the project were addressed and specific detailed issues that needed to be resolved took place within separately organized meetings.
- Official Project Kick-off Meeting, 8-April-09, Eaton Marshall MI facility
- In addition, AjaxTocco and the project team used bi-weekly meetings and other technical meetings to manage the work involved with the induction/quench/part handling support system development under Task 4. In addition, Task 2.2.2 sub-team (Eaton and OSU) conducted bi-weekly meetings to manage this forging activity and progress.
- Quarterly reports and associated report deliverables were submitted on a regular basis on-time.

3.3 Task 2 – Commercial Feasibility

Task 2.1 – Energy Savings Feasibility

Energy, Environmental and Economic Analysis for Steel Components

Overall, ITMP processing has been shown to be energetically beneficial in several ways, including as an alternative to conventional heat treatment such as carburization, with the possibility of using lower austenitizing temperatures, and slower cooling rates. To improve the overall performance per energy input, for overall energy savings, ITMP offers the following:

- For the same compositions as used for conventional processing, component properties can improve significantly by ITMP.

- ITMP can lead to using less alloyed steel compositions to get the same performance as conventional processing with highly alloyed steels.
- ITMP can use simpler steel compositions and develop new microstructures that can result in improved properties.

In this section, energy savings validation results are presented on two levels:

- The first level deals with the energy savings calculated for Eaton components.
- The second level is the extension of the calculations for components at applicable companies in the United States and are presented within a DOE GPRA (Government Performance and Results Act) model framework.

Energy requirement was analyzed for Industrial Sector Orbital Drive components; these components were processed at ORNL using ITMP and tested at Eaton Corporation.

- This analysis used a production volume of 310,000 parts/year and electricity cost of \$0.057/kWh. The calculation compared the currently used heat treatment processes of carburization and tempering with the feasible replacement of current processes by induction hardening and induction tempering in the magnetic field. Analysis results demonstrated an 86% reduction in energy used for heat treatment of these components when ITMP is used. It must be noted that the induction tempering times were only of 10-minute duration (under magnetic field) as opposed to conventional times of 2 hour duration. Furthermore, the ITMP processed components showed improved properties over those using the currently used processes.

Government Performance and Results Act (GPRA) Results:

A GPRA analysis was conducted using the Department of Energy’s Excel model.

- The analysis was carried out based on Eaton data and energy data obtained from the Forging Industry Association. The most important parameters used in the GPRA analysis are:
 - a) Baseline energy: This data is based on actual values of the currently used heat treatment process; values were provided by Eaton.
 - b) Proposed new energy: This data was derived from results obtained in prototype component testing and analysis carried out by Eaton.
 - c) Units: This data cover the definition of “unit” and how many such units exist in USA. For this analysis, we have used Eaton as a “unit.” Fractions of the impression die components that are potentially feasible for ITMP process based on size and energy used are shown below in **Table 2**. (Forging Industries Association, Cleveland, OH)

Table 2: Fraction of Impression Die Components as a Function of Sector

Sector	Applicable Fraction (%)	Energy Used (tBtu)
Automotive and Truck	20.6	103
Aerospace	17.3	87
Others	8.6	43

Table 2 indicates that a total of 233 tBtu/year of energy could be affected by ITMP. To get the number of units, we divided the total possible energy used in forged components (233 tBtu) by the

energy for Eaton for the applications above. The result suggests that there are a possible 190 units of the size of Eaton. Based on the 2009 Annual Census of North American Forging Operations, the 190 units is a reasonable number of units (there are 286 closed-die forging plants, a number much higher than 190, but it may be compensated for by the fact that some of them may be larger and some may be smaller than Eaton).

Market input: The annual market growth rate used for the analysis is 5% based on typical growth rates for such a well-established manufacturing sector. At 5% growth rate, 10 plants per year will adopt the ITMP technology. Market penetration is assumed to be 80% based on the fact that the 20% of the industry will not change to new technology for various reasons including financials and life of the equipment in current use. The last and the most important input was the market timing. We have assumed that if pilot commercial introduction of technology begins in 2012, it will take at least 20 years for the market to saturate. This assumption seems reasonable, but it could change based on economic conditions.

The 2009 Annual Census of North American Forging Operations includes data on 380 forging plant sites in the United States. Forging operations range widely in size, ranging from small shops with fewer than 10 employees to large manufacturers that report more than 1,000 employees.

Primary Metal Forged data reflects the metal most commonly forged at each shop, representing the industry on a unit basis. The most commonly forged metal is carbon steel, which is the primary metal reported at 175 plants and among the metals forged at 295 total plants. Alloy steel is the primary metal forged by 102 plants and one of the metals forged by 286 plants.

The results of the analysis for two cases, one with a conservative estimation of benefits (Conservative Model) and one with an optimistic estimate of benefits (Extended Model) are presented in **Table 3**.

These models focus on taking advantage of savings from the replacement of conventional carburization and tempering processes with ITMP processing (i.e. induction heat treatment and induction tempering in the magnet) as well as benefits in the reduction of preheating and scrap. The conservative model assumes that preheating will be reduced by 5% over baseline, and scrap will be reduced by 20% over baseline. The extended model assumes that preheating will be reduced by 25% over baseline, and scrap will be reduced by 50% over baseline (as defects for the cleaner alloy will be greatly reduced). Both models assume that induction heat treatment will be 10% of the energy normally used for the carburization baseline. This table shows the range of potential benefits. Real benefits of ITMP technology will be significant when fully deployed; the potential benefit increase is significant for the Extended Model, where ITMP technology is taken advantage of at all levels.

Table 3: GPRA Analysis showing Values of Energy, Economic, and Environmental Benefits of ITMP Processing for Forged Steel Components in United States

Impact	Conservative Model			Extended Model		
	2025	2030	2035	2025	2030	2035
Energy (tBTU/year)	7.13	18.20	30.19	30.26	77.21	128.07
Economic (M\$/year) Energy Savings	35.80	96.70	160.40	151.45	409.37	679.00
CO (Metric tonnes/year)	203.97	520.37	863.10	868.38	2,215.45	3,674.66
CO ₂ (MMTCE/year)	0.10	0.26	0.44	0.44	1.12	1.85
NOx (Metric tonnes/year)	769.92	1,964.25	3,258.01	3,241.12	8,268.85	13,715.12

An additional analysis was performed which evaluated other applications for the ITMP process; in line with the spirit of commercialization intent. The ITMP process was assessed for impact to the heat treatment of electrical metals (non-ferrous) and corresponding performance enhancement.

Energy, Environmental, and Economic Analysis for Electrical Components

A broad range of electrical systems use Al and Cu as conductors. Some of the important systems that could benefit from the improvement in conductivity of Al and Cu are listed in **Table 4** along with the reference sources for the data. Among the systems listed, data systems are the fastest growing energy user systems. The ITMP processing of Al and Cu used in systems listed in **Table 4** have a strong potential for energy savings from a projected increase in electrical conductivity of Al and Cu based alloys by a market-need-based increase of 11%. In certain cases, Al alloys with an 11% improvement in electrical conductivity could replace Cu alloys. The Al alloys are 1/3 lighter, with great potential for additional benefits from ease of construction, lower cost of installation and maintenance, and, in some cases, increased operational efficiency.

A first approximation energy saving calculation is shown in **Table 4**. It used the following two assumptions:

- Only 50% of the systems listed in **Table 4** will benefit from the improvements cited here, based on the fact that these are very mature technologies and will resist rapid change.
- An 11% improvement (driven by market-need-based projection) in electrical conductivity made possible by ITMP processing.

Table 4 shows the significant energy savings benefit across the numerous impacted systems and components. Based on above assumptions, a maximum of 49.2 BkWh /year of energy savings is projected for the electrical systems using Al and Cu alloys. **Table 5** shows the GPRA analysis for a select example of electric motors (from **Table 4**) benefiting from ITMP processing of Al and Cu and their alloys, assuming the associated 11% improvement in electrical conductivity. Note that the significant benefits for the electrical systems will start from year 2030.

Table 4: Electric energy systems and energy used by them that will be affected by the electrical conductivity of Al and Cu to be processed by ITMP

System	Comments	Electric Energy Used (BkWh/year)	Data Source
Electric Motors	12,434,330 units 1-1000+hp	679	DOE EERE report 2002
Data Systems	2011 projected from 2006 data	100	EPA Report 2007
Electric Heaters	30.9M households with Main Systems	109	EIA data source 2001
Electric Heaters	12.9 households with Secondary Equip	6.5	EIA data source 2001
SystemsTotal		894.5	
Assume that 50% of the total electric energy will be affected		447.2	
Assume that ITMP can provide energy savings thru electrical conductivity improvement of 11%		49.2	

Table 5: GPRA Analysis showing Estimated Values of Energy, Economic, and Environmental Benefits of ITMP Processing for Electric Systems benefitting from ITMP processing of Al and Cu and their alloys

Impact	2020	2025	2030
Energy (tBtu/year)	15.15	89.39	119.33
Economic (M\$/year) Energy Savings	91.65	544.6	744.99
CO (Metric tonnes/year)	315.59	1861.92	2485.75
CO ₂ (MMTCE/year)	0.29	1.74	2.32
NOx (Metric tonnes/year)	2609.15	15393.6	20551.19

Task 2.2 – Technical Feasibility

Task 2.2.1 –Induction Hardening and ThermoMagnetic Feasibility

In this section, the major activities were to:

- Determine the mechanical properties of several steels processed by currently available non-integrated thermo-magnetic and induction hardening
- Confirm that the hybrid induction hardening and magnetic processing provide similar mechanical performance to carburizing using selected actual Hydraulics, Auto, and Truck components

Mechanical Properties of Steels

The investigation, involving various steels like SAE4350 and SAE8620c, was conducted initially using conventional induction hardening on coupon-size (65mm) samples. This task formed the basis for moving towards the eventual Induction Thermo-Magnetic-Processing technology of actual components.

Fixturing for the coupon samples and actual components was developed. It involved the design and development of induction coils, quench flow management and in-situ tempering. The initial work on coupon samples, due to the small size was conducted in the 9T 5 inches diameter magnet with helium quench means. A generic tensile test sample geometry (button-head tensile blank) was suggested by ORNL and agreed upon by Eaton for thermomagnetic processing. Preliminary experimental trials were completed for trial set-ups in order to establish the most appropriate experimental set-up conditions that will achieve as uniform a thermal profile as possible along the gauge length of the tensile blanks during ITMP.

During the preliminary set-up trials, the source of the temperature non-uniformity from end to end of these (65mm) long tensile samples was not the non-uniformity of the induction field, but rather non-uniformity of the oxidation/emissivity. Although processing in vacuum would resolve this, this was done with difficulty in the available space and in such a manner as to allow the high flow rates of helium during the quench. To maintain temperature uniformity from end to end, a susceptor was designed to indirectly heat these tensile samples, creating an oven environment nearly independent of the oxide/emissivity variations. Various susceptor designs and materials were investigated and tested. A final slotted copper tube geometry was found to provide temperature uniformity across the tensile gauge length that could be fully profiled using three thermocouples. The trials for the set-up and processing parameters led to the discovery of tempering for shorter times than what is needed without the magnetic field. Relative to the C diffusion calculation it is noteworthy that during tempering studies on SAE8680 alloy samples, a ten minute temper at 150°C under a 9 Tesla magnetic field achieves comparable to superior properties at 120 minutes at 150°C with no field applied. These experimental results indicate that either C diffusion is significantly enhanced, or the nucleation of the Fe₃C is dramatically enhanced below the 210°C Curie temperature for the Fe₃C phase.

The ITMP samples were made into tensile specimen, processed and tested for the mechanical properties. The tensile set-up is shown in **Figure 4** and the test results documented in **Figure 5**.

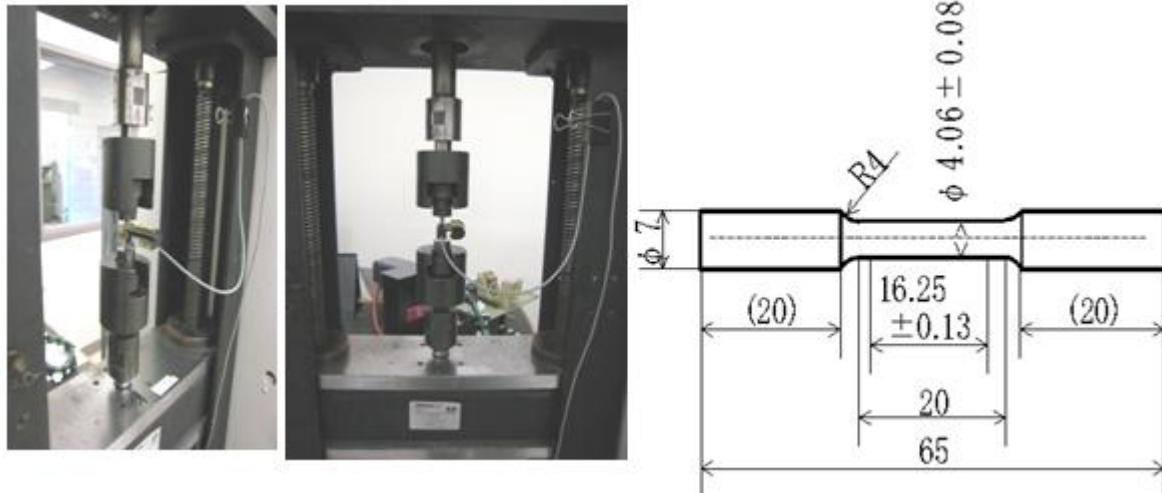


Figure 4: Tensile Testing Equipment

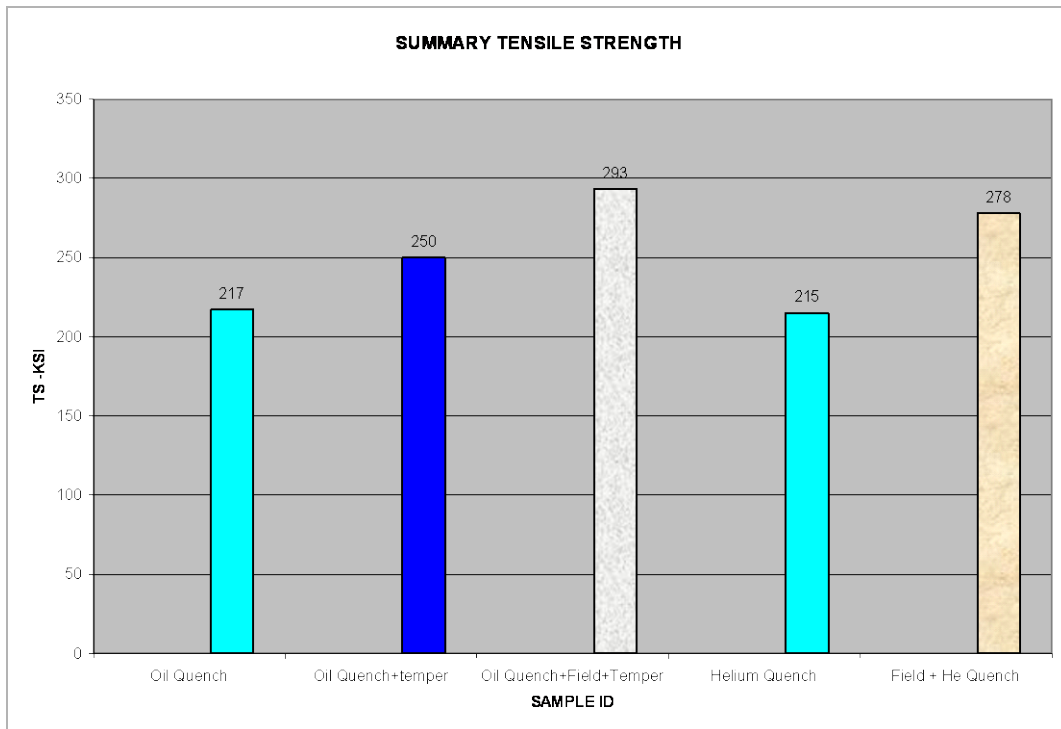


Figure 5: Summary Tensile Strength

Average tensile strength of samples processed in: as-quenched (no field); as-quenched & tempered(no field); quenched & tempered in field; no field, He quench and Field + He quench.

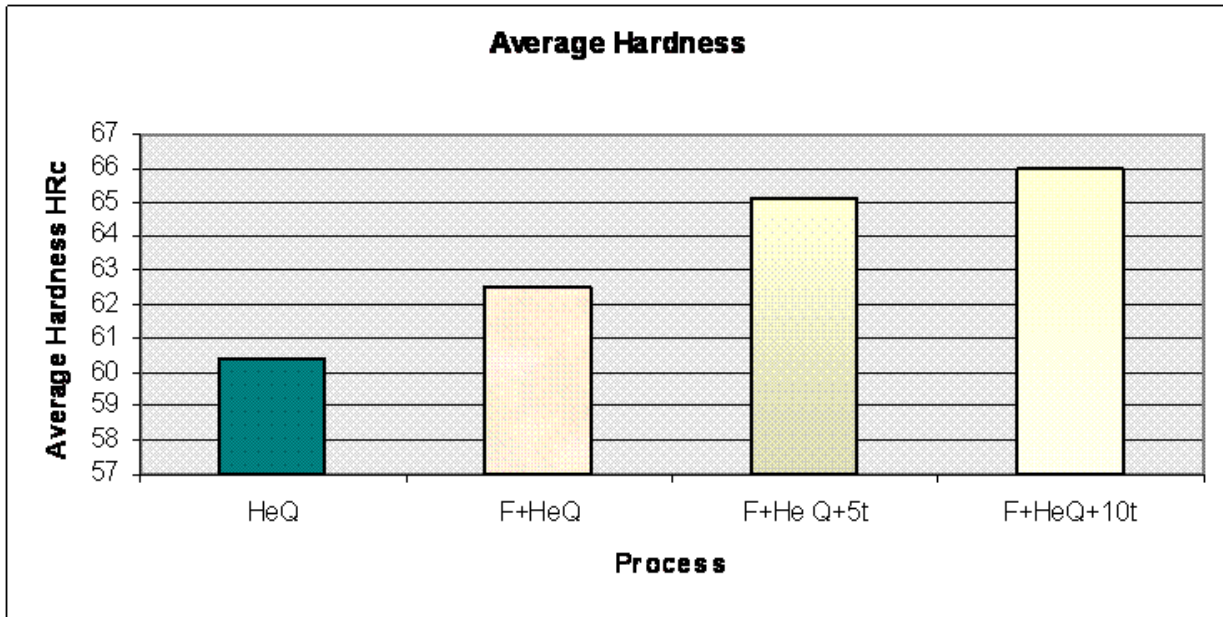


Figure 6: Average Hardness

Figure 6 shows the increase in hardness as a function of tempering in the presence of a magnetic field. Here the effective time of tempering decreased from two hours to only ten minutes. Not shown in the figure is the decrease in hardness as the tempering time is increased beyond ten minutes in the presence of magnetic field.

With ITMP processed samples, the comparison to base line SAE86XX demonstrated 30% increase in the tensile strength over the baseline. In addition, a decrease in volume percent retained austenite amounting to 43% was demonstrated.

Alternate Steel

Regarding the alternate Steel SAE4350 (this is a high strength steel), the tensile strength (see **Figure 7**) improved by 7%, the yield strength by 10%, the elongation (see **Figure 8**) by 90%, and the reduction in area by 200x compared to baseline.

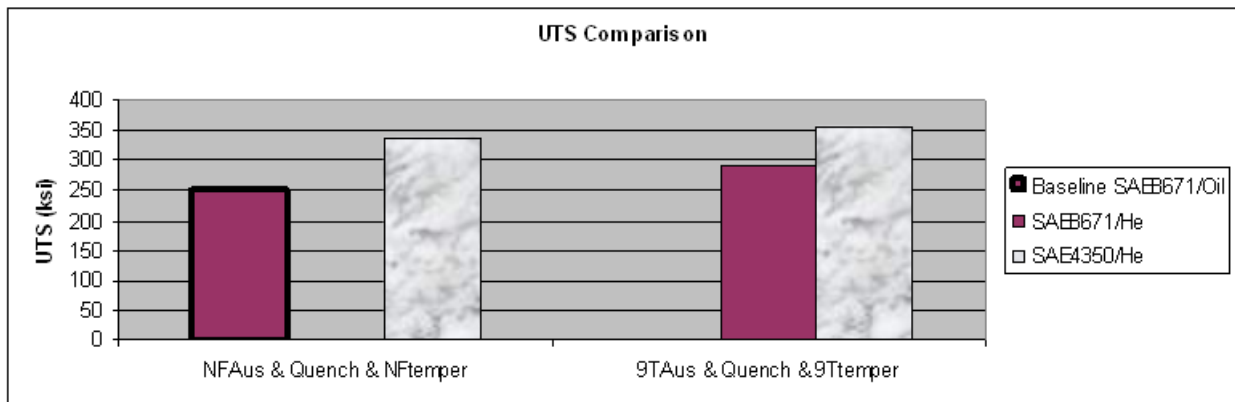


Figure 7: Correlation of baseline SAE4350 to Applied Magnetic Field SAE4350 Steel.

The Ultimate Tensile Strength was used as guidance in the processing of orbital drives from the previous design of experiments effort.

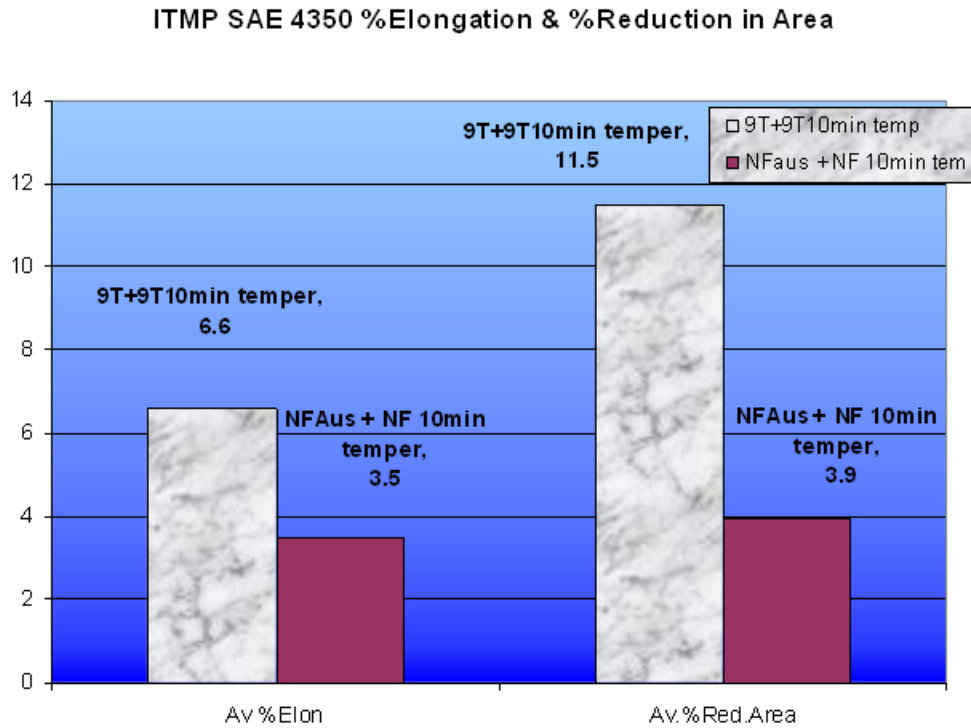
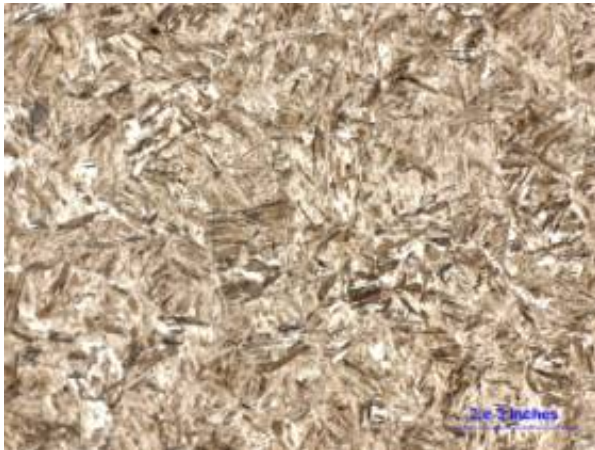


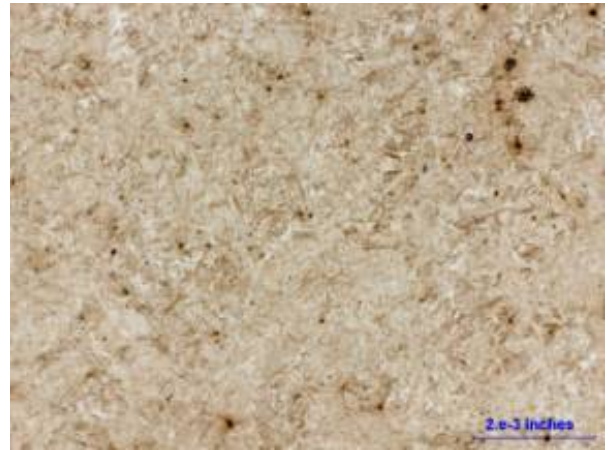
Figure 8: % Elongation and % Reduction in Area – SAE4350. Effect of magnetic field upon the ultimate tensile strength

The influence of magnetic field upon the mechanical properties is shown in **Figure 8** above. The samples were tested for mechanical and metallurgical properties to define the new processing of orbital shafts and gears (see **Figure 9**). The increase in Ultimate Tensile Strength is evident as a function of the magnetic field (see **Figure 10**).

The improvement in mechanical properties was applied to Eaton components like the orbital drive in hydraulic motors and pumps. The initial application was a “4k orbital drive” weighing about 1 pound. The results of ITMP processed orbital drives are compared to baseline SAE8620c. Torsion tests (see **Figure 11**) on ITMP-processed orbital drives (SAE8620c) reveals the energy absorbed was twice that of the conventional processed drives (or 100% improvement in ductility).



SAE 8680 Magnetic (C 0.47) before magnetic field @ 500x



SAE 8680 (0.47) Magnetic 18T>T Curie @ 500x

Figure 9: SAE 8680 Microstructures

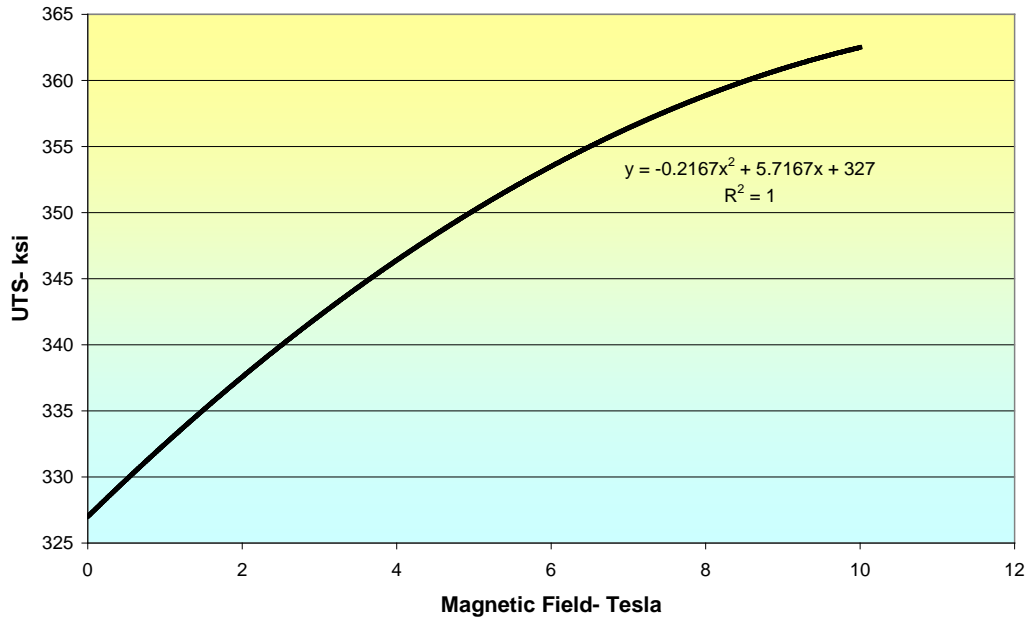
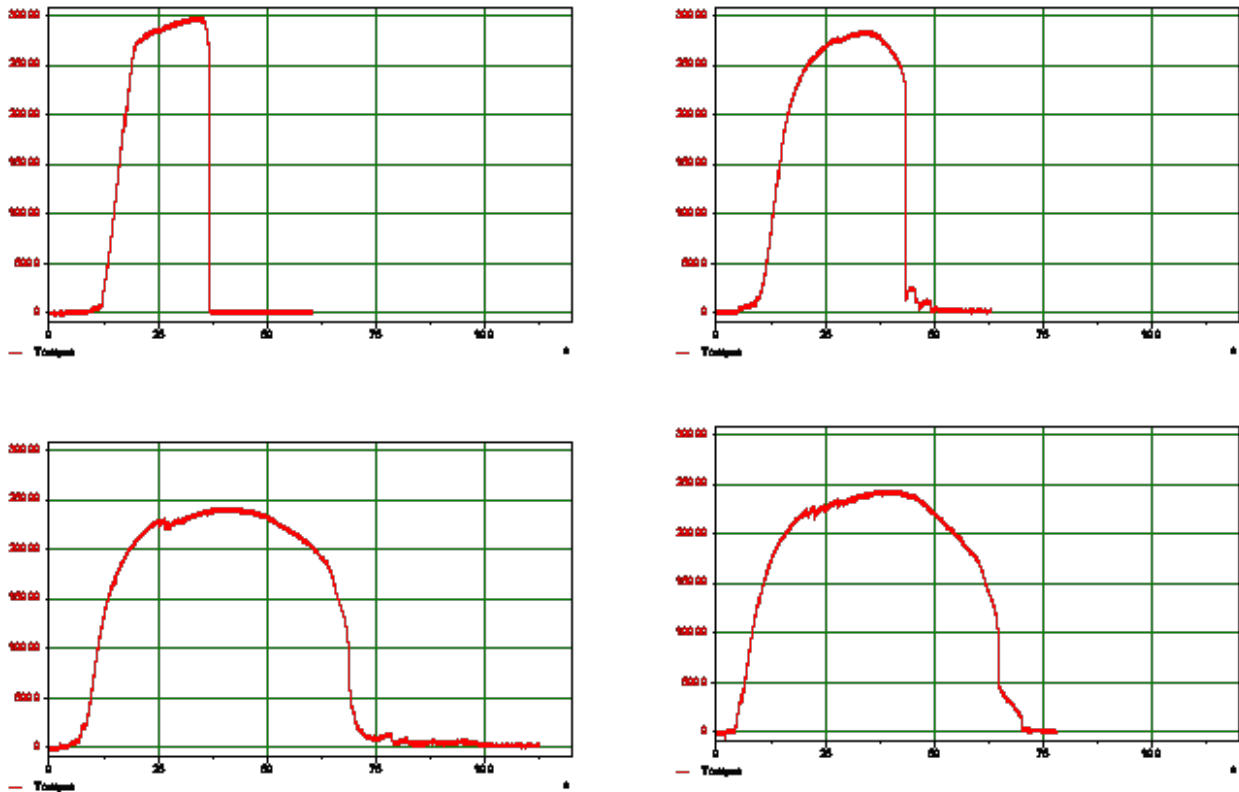


Figure 10: Effect of Magnetic Field on SAE4350



**Figure 11: Comparative Torsional Test SAE8620c
 Current production orbital drives versus ITMP orbital drives**

Based on the results of the “4k orbital drive”, Eaton went ahead with the “HP30 orbital drive” investigation for hydraulic motors because the business case hypothesis indicated that the “HP30” case was superior to the “4k” case. The size of the orbital drive for the “HP30” application was four times the original “4k” drive and an elaborate quench system to quench inside the magnetic field was required and therefore incorporated using polymer quench. These HP30 parts were ITMP processed, shot peened and assembled in Eaton hydraulic motors for fatigue testing. Testing was done at the Eaton manufacturing facility “dynamometer” test stand. A plot of the test performance in terms of fatigue cycles is shown in **Figure 12**. The fatigue life was compared to the SAE8620c part and also compared to a part made from an exotic (expensive high end) alloy called C-61. The testing was successful, however due to a multitude of test system variables, this test was classified as inconclusive. The team therefore addressed the test system variables issue by going to a test system with reduced degrees of freedom. New evaluations for the verification of the basic properties improvement using rotating beam bending fatigue testing and torsion beam fatigue testing were implemented.

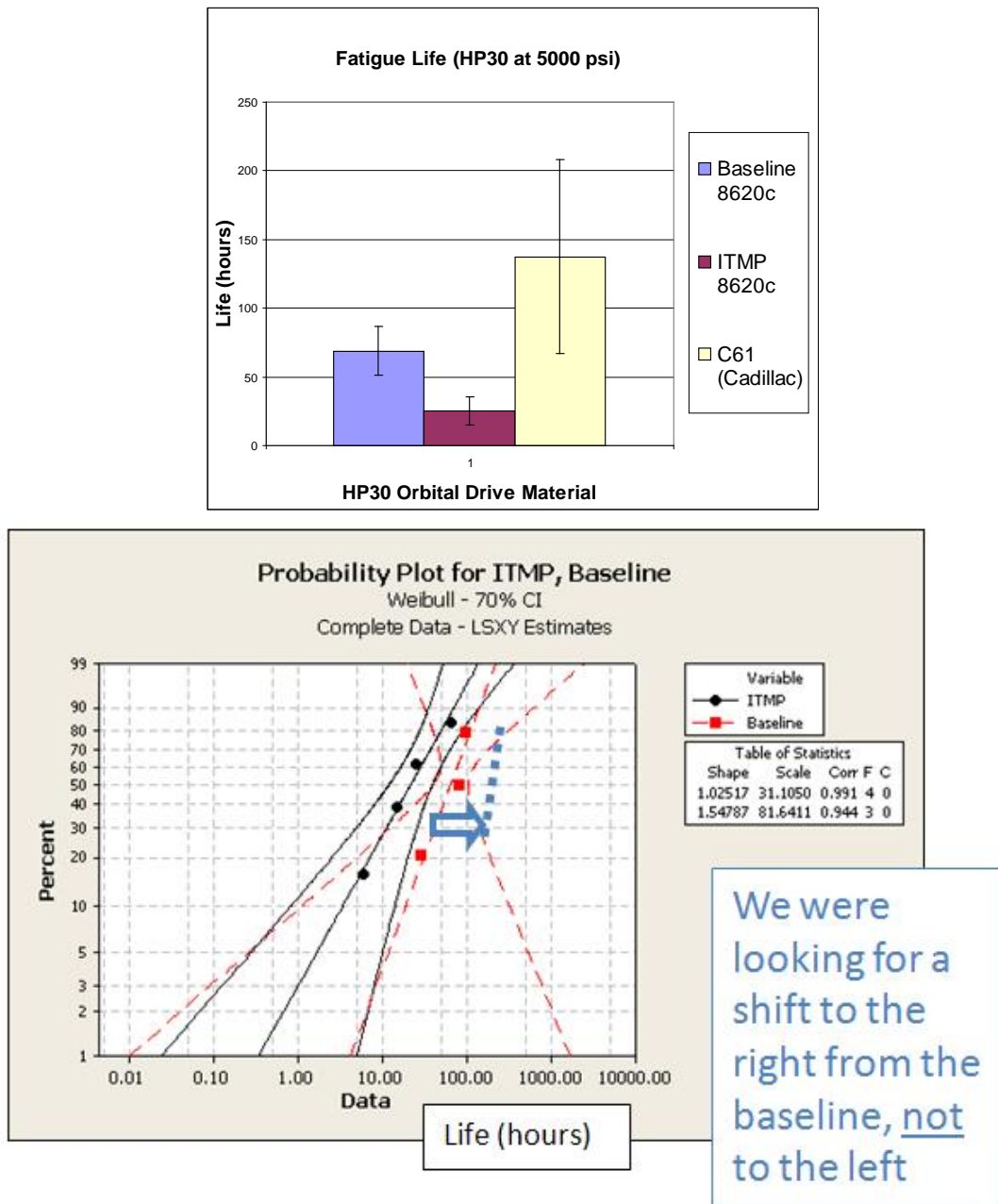


Figure 12: Orbital Drive HP-30 Fatigue Testing

Rotating Beam Bending Fatigue Test

For the purpose of determining the fatigue properties, SAE8620 samples were machined and carburized. A batch of these carburized samples was then processed by the ITMP process. These were then tested using the rotating beam bending test. Results are plotted in **Figure 13** (showing both linear scale and log scale for cycle count, as well as the probability plot at a specific stress level). Rotating beam bending fatigue test results show an improvement of >10% in endurance fatigue life, and an improvement in fatigue life at 150ksi of >5 times.

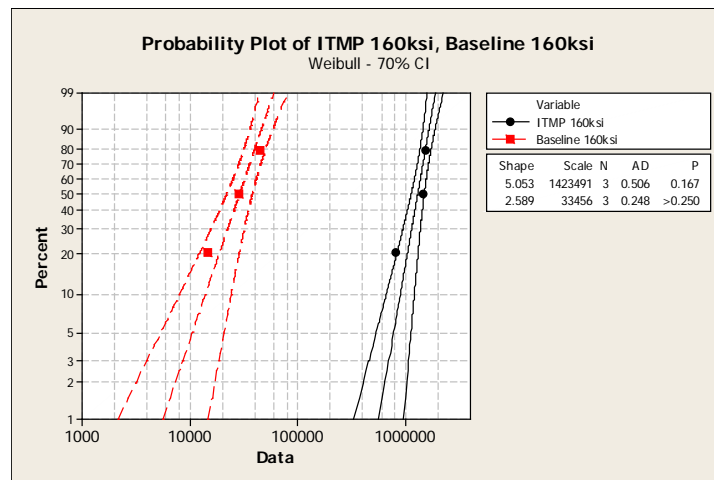
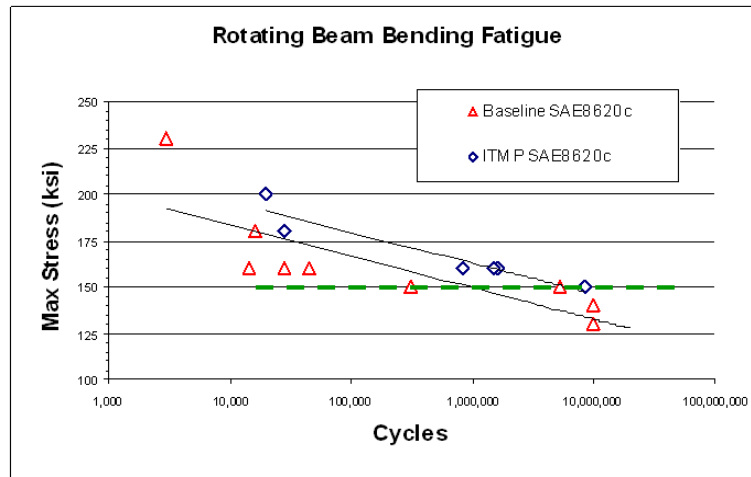
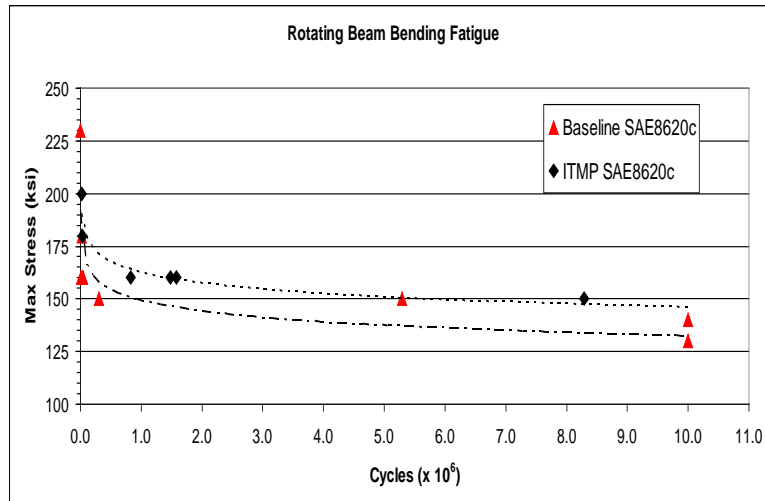


Figure 13: Rotating Beam Bending Fatigue Test-SAE8620c (top: linear scale; middle: log scale; bottom: probability plot)

Torsion Fatigue Test

The torsion fatigue test was considered to be a requirement, on a parallel path to rotating beam bending fatigue testing, for application of ITMP to orbital drives, shafts and gears. ITMP processing (using the 9T 5 inch magnet) was completed on the first iteration and the results are plotted in **Figure 14**. Next, the second iteration of the Torsion Fatigue Parts was run, based on earlier results (from the first iteration that included the oxidation issue and resulting surface roughness. For this second iteration, a “Sealmet” coating was applied to prevent any surface oxidation, without affecting the quench rate of the component. This coating adheres to the surface after the ITMP process, and is removed by grit blasting the surface of the part. These torsion samples were prepared slightly oversized (+0.012” diameter), such that after the ITMP process, surface change due to the application of the coating is removed and the dimensions are machined to the finish dimensional tolerances, to be similar to the baseline samples. This process eliminates any variables in the surface condition and dimensional tolerances, such that the baseline and the ITMP process can be directly compared. The macro-hardness was measured to be HRc60 or higher. Surface roughness in the test region was measured to be 4-8 μ-inches.

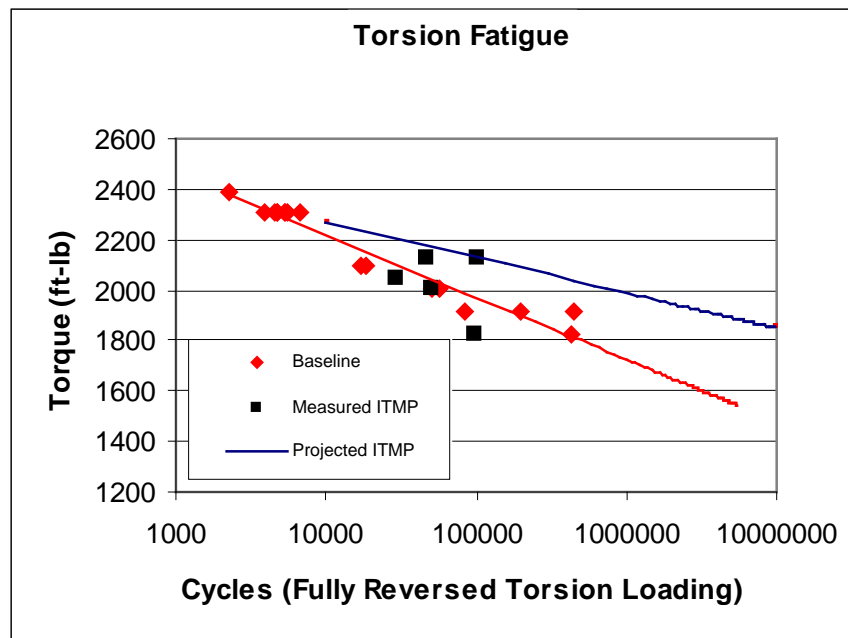


Figure 14: Torsion Fatigue Test

This additional effort (with rotating beam bending fatigue testing and torsion fatigue testing) caused a delay in proceeding further with HP30 samples. However, towards the end of the project, the 9T 8 inches diameter magnet system became available. HP30 orbital drives were successfully ITMP-processed to prove the capability of the new 9T 8” magnet system and also improvement in metallurgical parameters has been achieved (see below).

New 9T 8” System Validation:

ITMP-process validation (using the new 9T 8 inch magnet) was completed using industrial test parts to show the completion and capability of the new ORNL 9T 8 inch thermomagnetic processing system. The new system has been exercised throughout the 0T to 8.5T magnetic field range under a variety of applied induction power settings and quench scenarios.

The test samples in the configuration of HP30 orbital drives show uniform hardness with a high compressive residual stress (low volume percent retained austenite). The uncoated sample did not show significant oxidation. The heating time at-temperature was 20 seconds, as opposed to 20 minutes in the earlier studies. **Figure 15** shows the trial test run with and without the “Sealmet” coating. The samples were processed at a relatively fast rate (20 seconds) which reduced the oxidation of the component surface. Also shown in the figure is the set-up for surface preparation for residual stress and retained austenite at three locations. The residual stress was high compressive (~100ksi) and the volume percent retained austenite was very low (~<4%).

Table 6 shows the hardness distribution, taken at 15 locations (equal intervals) for each part. Hardness is very uniform indicating uniform heating and quenching of the components.

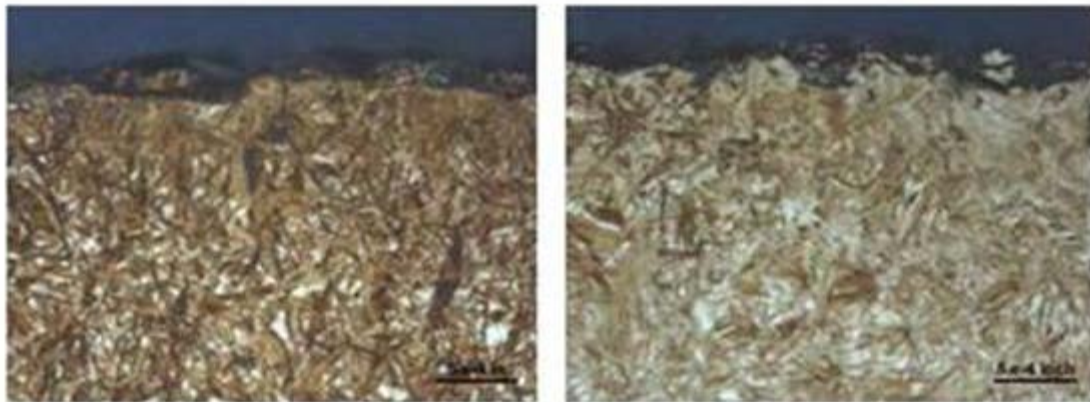


Figure 15: ITMP Orbital Drives with and without Coating

Table 6: Hardness Distribution

Sample ID	Area 1 (HRC)	Area 2 (HRC)	Area 3 (HRC)	Area 4 (HRC)	Area 5 (HRC)
91C - 0 Degrees	65.3	64.8	66.4	66.2	66.7
91C - 120 Degrees	65.7	66.6	66.1	65.1	67.2
91C - 240 Degrees	66.8	66.7	65.1	67.4	65.7
Average	65.9	66.0	65.9	66.2	66.5
75UC - 0 Degrees	66.4	66.0	65.8	63.7	66.9
75UC - 120 Degrees	66.5	64.7	67.2	66.5	67.6
75UC - 240 Degrees	65.9	67.5	66.8	67.3	66.7
Average	66.3	66.1	66.6	65.8	67.1
76C - 0 Degrees	65.7	64.9	65.2	68.3	66.7
76C - 120 Degrees	66.2	66.9	66.8	66.1	65.9
76C - 240 Degrees	68.0	65.4	65.1	66.0	67.1
Average	66.6	65.7	65.7	66.8	66.6
77C - 0 Degrees	66.7	66.6	66.3	67.6	66.0
77C - 120 Degrees	66.2	66.2	67.8	67.9	68.0
77C - 240 Degrees	67.9	68.1	67.5	66.1	66.3
Average	66.9	67.0	67.2	67.2	66.8

Figure 16 shows the microstructures in the as-quenched condition. The tempering in a magnetic field significantly reduces the (volume percent) retained austenite, compared to that obtained in the conventional tempering.



Sample#75 1500x with 8.5T Field

Sample #91 1500x no magnetic field

Samples quenched in-situ, no temper; difference in the volume percent retained austenite evident in sample processed without magnetic field

Figure 16: Comparison HP30- 8" Dia Magnet

Altered Microstructures

Besides the tests for improved mechanical properties, the team conducted testing for improved magnetic properties using basic steel like SAE1215. The parts were processed in a magnetic field and then tested for permeability improvement. The results and the improvements are documented in the figure below. The concept clearly demonstrates that permeability in steels is altered (see **Table 7**, **Figure 17** and **Figure 18**).

- 77% permeability improvement with respect to baseline hot rolled SAE1215 steel
- 20% increase in flux density (Bs)
- 22% decrease in coercivity (Hc)

An important item to note is that microstructure changes as a result of processing in a magnetic field. The inclusions are broken-up and the grain structure is modified.

In addition to magnetic properties testing, the team also conducted testing regarding the wear resistance of certain steels (see **Figure 19**). Steel used for a vehicle application under wear stress conditions is SAE9254. The following figures show that the ITMP process clearly demonstrates wear property improvements, including 18% reduction in wear area and 40% reduction in scar depth, using the SAE9254 steel compared to the baseline.

Table 7: SAE1215 Permeability Improvement

1215 Permeability

	Hot Roll	NF-A	NF-B	9T @ 735°C T< T Curie #1	9T @ 735°C T< T Curie #2	9T @ 800°C T> T Curie #1	9T @ 800°C T>T Curie # 2	9T @ 735°C Sample #E	9T @ 735°C Sample #F	9T @ 800°C Sample #C	9T @ 800°C Sample #D
Bs	15633 G	16432 G	16382 G	16062 G	17108 G	17450 G	17454 G	18797 G	17279 G	16302 G	16365 G
Br	7588 G	9017 G	8506 G	10762 G	11445 G	10195 G	9618 G	12946 G	12623 G	8572 G	9461 G
Area	0.39562 cm ²	0.37515 cm ²	0.3779 cm ²	0.37792 cm ²	0.37884 cm ²	0.38688 cm ²	0.38223 cm ²	0.36992 cm ²	0.35791 cm ²	0.37669 cm ²	0.38223 cm ²
Hm	59.885 Oe	59.885Oe	59.880 Oe	59.884 Oe	59.883Oe	59.889 Oe	59.884 Oe	59.885 Oe	59.884Oe	59.883 Oe	59.881 Oe
Hc	4.59 Oe	3.58 Oe	3.53 Oe	3.53 Oe	3.49 Oe	3.61 Oe	3.44 Oe	3.43 Oe	3.53 Oe	3.68 Oe	3.55 Oe
μ	888	1058	1133	1538	1428	1240	1271	1571	1500	1062	1049
%	0	19	28	73	61	40	43	77	69	20	18

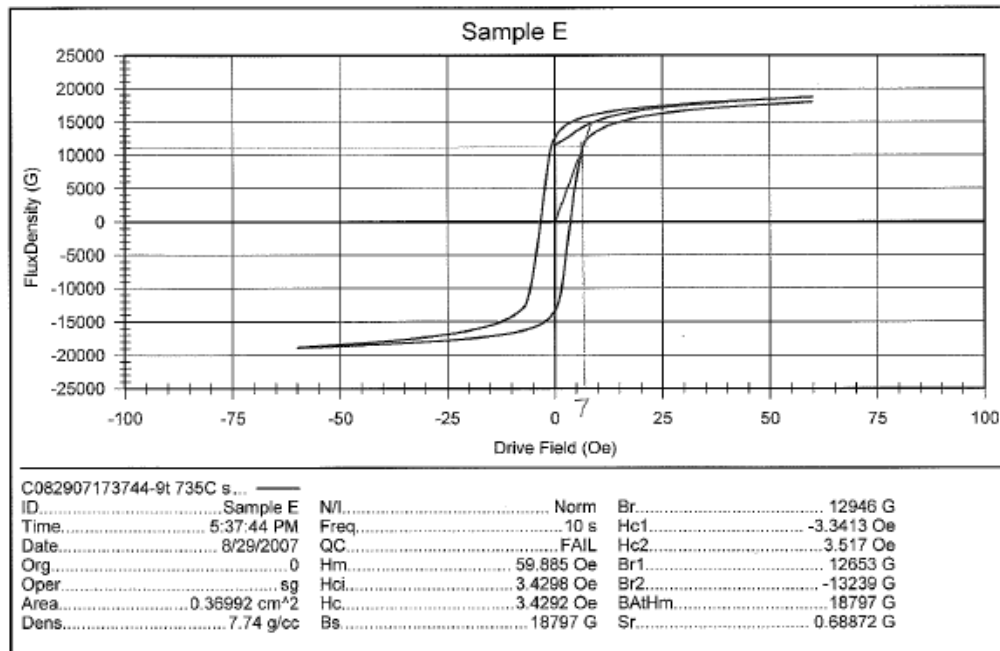
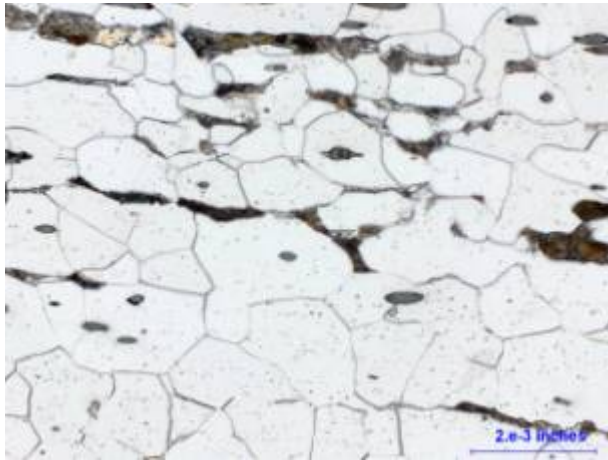
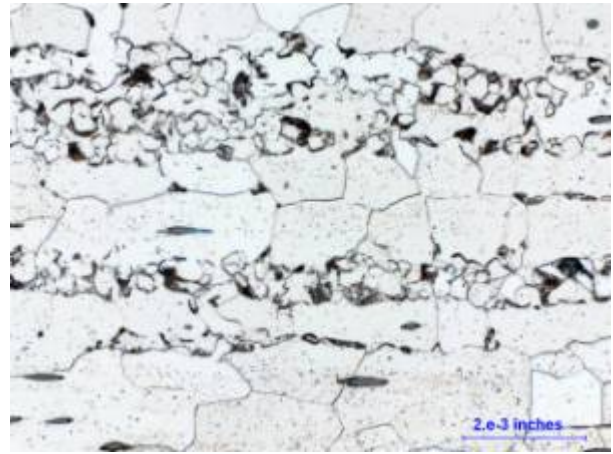


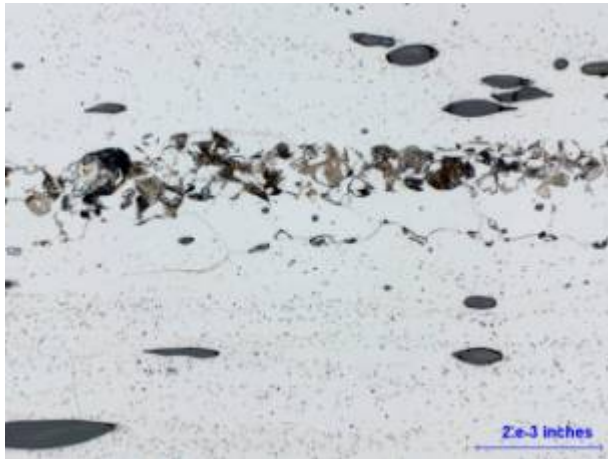
Figure 17: SAE1215 Permeability – Effect of Magnetic Field



SAE1215 Hot roll structure @500x (no field)



SAE1215 Reference @500x (15% ferrite increase)



SAE1215 18T < T Curie @500X (40% ferrite increase)



SAE1215 18T > T Curie @500X (30% ferrite increase)

Figure 18: Effect of Magnetic Field SAE1215 Steel

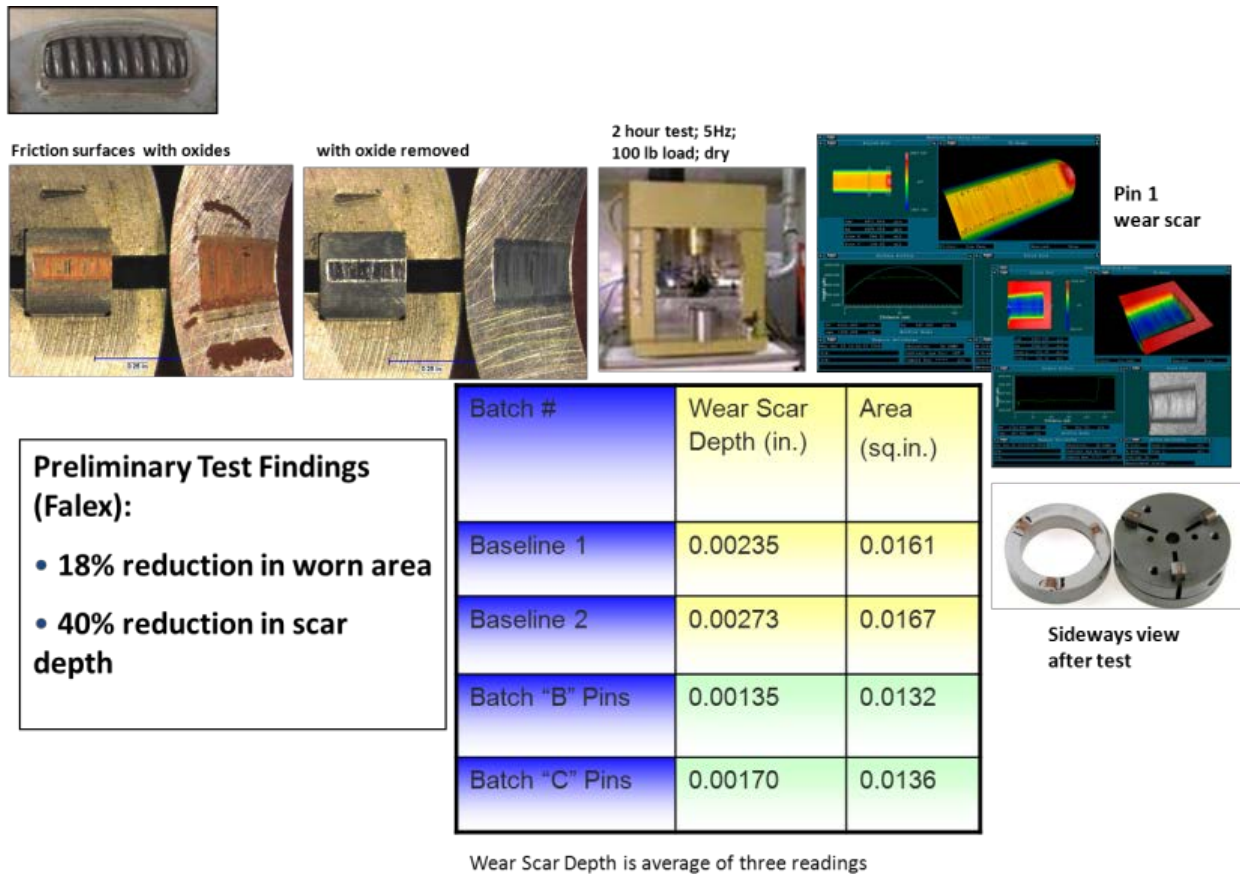


Figure 19: Truck Component – Wear Test

Task 2.2.2 – New Precision Forging Feasibility

The goal of this task was to determine the feasibility of using ITMP in the forging operation to allow net shape and precision forging to reduce scrap and reduce energy use. The primary activity involved was the development and application of the DEFORM modeling tool to assess the effective and efficient use of material in forging and a resulting savings in energy.

Die materials and die wear conditions were identified as they exist in forging operations at a number of Eaton plants. Potential die materials and potential coatings were identified which could provide improvements in die life. These included materials already in use as well as potential alternatives, to establish the full baseline, against which the ITMP process could be compared for improvement and commercial value. This baseline of alternative materials was compiled through an expansion of the already existing database/knowledge base at OSU/Eaton Innovation Center, with additional information obtained through literature and global forging die material suppliers, in addition to experimental and modeling validation.

The modeling task was done using a commercially available software package known as DEFORM, in both 2D and 3D versions of the analysis. The 2D analysis was used when axis-symmetric geometries allowed an accurate assessment; 3D analysis allowed for the more complex part geometries and when part variation was included in the analysis set. The computational

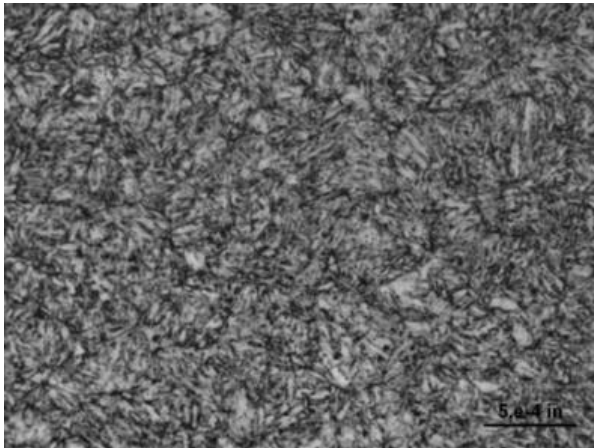
modeling of the valve forging operation included heat transfer analysis of the billet, the determination of maximum temperatures and temperature variation on the extrusion die, coining die, and billets, the effects of lubrication on die temperatures, and the associated comparison of measured temperatures versus predicted temperatures.

Eaton Plants were visited in both the United States (Kearney NE plant – Eaton Automotive) and Europe (Torino Italy plant – Eaton Automotive), to address the forging operations and how energy savings can be realized.

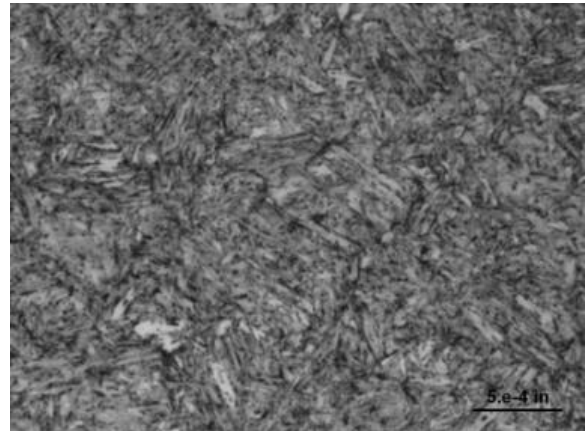
Die stress analysis for the estimation of die wear was provided for the extrusion process, wherein extrusion die wear and plastic deformation was studied. Effects associated with press speed on extrusion die and coining die wear were determined, along with dimensional predictions regarding regions of wear and plastic deformation during production. Extrusion die shape was assessed for effects on die temperature and wear. A key outcome of this investigation was to suggest that there be a search for die materials with high hot hardness such as ceramic dies, carbide dies, and hard coatings with dies. From a baseline perspective, it became clear that a true comparison of ITMP to a competitive approach would need to include these new alternatives for true commercial value assessment. Alternative material (Ceramic) extrusion dies studies, therefore, were conducted for a more fully evaluated baseline. The design of hot extrusion tooling with ceramic extrusion die material was modeled and investigated. With an optimized ceramic approach, the extrusion die life was demonstrated to improve by a factor of seven, and the valve stem straightness was observed to improve significantly such that an improvement like this would enable precision forging capability, significant cost savings, and improved productivity.

Samples of engine valve “extrude dies” were selected for the ITMP study. Preparation was made for initial tests for valve extrude rings and buttons. Test parts, that included 50 buttons and rings from H10 tool steel, were produced. Heat treated 25 rings and buttons, were provided, through the normal Kearney fluidized bed heat treat process. Kearney shipped another 25 rings and buttons for processing through the ITMP process. All rings and buttons were then to be used in the forging of engine valve part number 102655 and evaluated to compare component life and performance. ITMP processing (using the 9T 5 inch magnet) was completed using the Engine Valve Extrude Die Parts. The metallurgical results show a decrease in the volume percent retained austenite, accomplished by a single tempering operation as opposed to double or triple temper of the H10 alloy. Also uniform dispersion of carbides is evident in all the samples examined, different from the typical baseline extrude die sample (without the magnetic field). Hardness distribution is very uniform from the surface to the core.

The microstructure, shown in **Figure 20** at 1500x magnification, is much finer in the ITMP-processed part compared to the baseline extrude-die. Lower volume percent retained austenite is shown in the photographs for the ITMP process (single temper only). Baseline was conventionally double tempered. Volume percent retained austenite was verified by x-ray diffraction. The hardness of the two processes was comparable (i.e. in the range of HRC 56 to HRC58).



ITMP- Extrude Die Sample 15G



Baseline Extrude Die 1500 x magnification

Figure 20: Extrude Die – Microstructure

3.4 Task 3 – New Fe-C Phase Diagram

This task involved the modeling effort, using first principle calculations along with existing modeling tools and databases (e.g. CALPHAD/ThermoCALC), to theoretically evaluate the magnetic structure, of steel-based material species on an atomic scale, as a function of magnetic field, to provide an understanding of the magnetic contributions to the enthalpy and entropy that will be used in the creation of the modified phase diagram. Defect and diffusion barriers, as impacted by magnetic field, are a part of the kinetic mechanisms involved during heat treatment. Streamlined procedures were needed to be developed to allow first principles results and their associated input into the ThermoCALC tool and databases. That ThermoCALC output result, used to generate field dependent phase boundaries, would then provide understanding to the theoretical side, in support of the measured properties of processed materials. Plane wave and multiple scattering-based density functional codes, along with non-collinear magnetism and relativistic treatment, are used in this analysis. Overall, the Fe-C phase diagram showing the effects of the magnetic field on the relevant regions of the diagram (on the α , the $\alpha + \gamma$, and the γ regions) are presented below, along with additional simulation and theoretical analysis involving other metallic species as alloying agents within the Fe matrix.

This modeling effort has contributed to the knowledge base available, to understand and anticipate the effect of magnetic fields on microstructure. In particular, first principles and model calculations were used to explore phase stability in Fe-C and Fe-Ni in the presence of a magnetic field. Thermodynamic expressions for the free energy response to a field were constructed and implemented in files that were used by ThermoCALC to recalculate the FeC and FeNi phase diagram for a series of field strengths. A nonlinear behavior of the free energy was proposed to understand the increase in saturation moment as Ni is added to Fe. The magnetic states in Cementite were investigated. The saturation moment of a series of metastable FeC phases were calculated. Together with the Curie temperature, annealing strategies were developed to promote the survival of metastable precipitates upon cooling from the Austenite phase. The effects of alloy additions on the local magnetization were calculated for a series of additions in order to understand the effect of alloy additions on phase stability. The magnetic structure surrounding C, at interstitial positions and along the diffusion path between the tetrahedral and octahedral interstitial positions, was calculated. It was found that a magnetic field inhibits diffusion; this behavior was correlated with observed finer grain structure in samples processed in the 9T field.

Initial DFT (Density Functional Theory) calculations were performed for substitutional and interstitial impurities in bcc Fe. The influence of alloying elements on magnetic moments was calculated. These magnetic moments were used to construct thermodynamic data to input into CALPHAD (e.g., ThermoCalc) databases to predict field-dependent phase diagrams. The primary goal was to investigate the effect of an applied magnetic field on the phase equilibria of Fe-base alloys relevant to this research. To accomplish the goal, the team employed the modern computational thermodynamic tool Thermo-Calc software system^{[1]Ref} and calculated Fe-C phase diagram at applied magnetic fields of 10, 20, 30, 40 and 50 Tesla. This was achieved by adding a field dependent magnetization free energy term to the Gibbs energy of pure Fe in bcc (ferrite) and fcc (austenite) phases, and to the Gibbs energy of cementite phase in the critically assessed thermodynamic database in Thermo-Calc. The results show increases in bcc/fcc equilibrium temperature, C solubility in bcc, eutectoid temperature and eutectoid C composition with increasing magnetic field.

The magnetization energies of α -Fe (taken from Ref. 2 and 3) and γ -Fe (Ref. 4) are added to the Gibbs energy of pure Fe in ThermoCALC database.^[1] This is due to the fact that magnetization energies of bcc and fcc phases as a function of C-content are not available. In other words, an implicit assumption is that C (in solution) simply acts as a diluent. In the case of cementite, the magnetization free energy (Ref. 5) is added to the molar Gibbs energy of the phase.

Figure 21 below shows the calculated Fe-C phase diagram at 0, 10, 30, and 50 Tesla. Several important features of calculated phase diagram are listed in the Tables below (**Table 8** and **Table 9**).

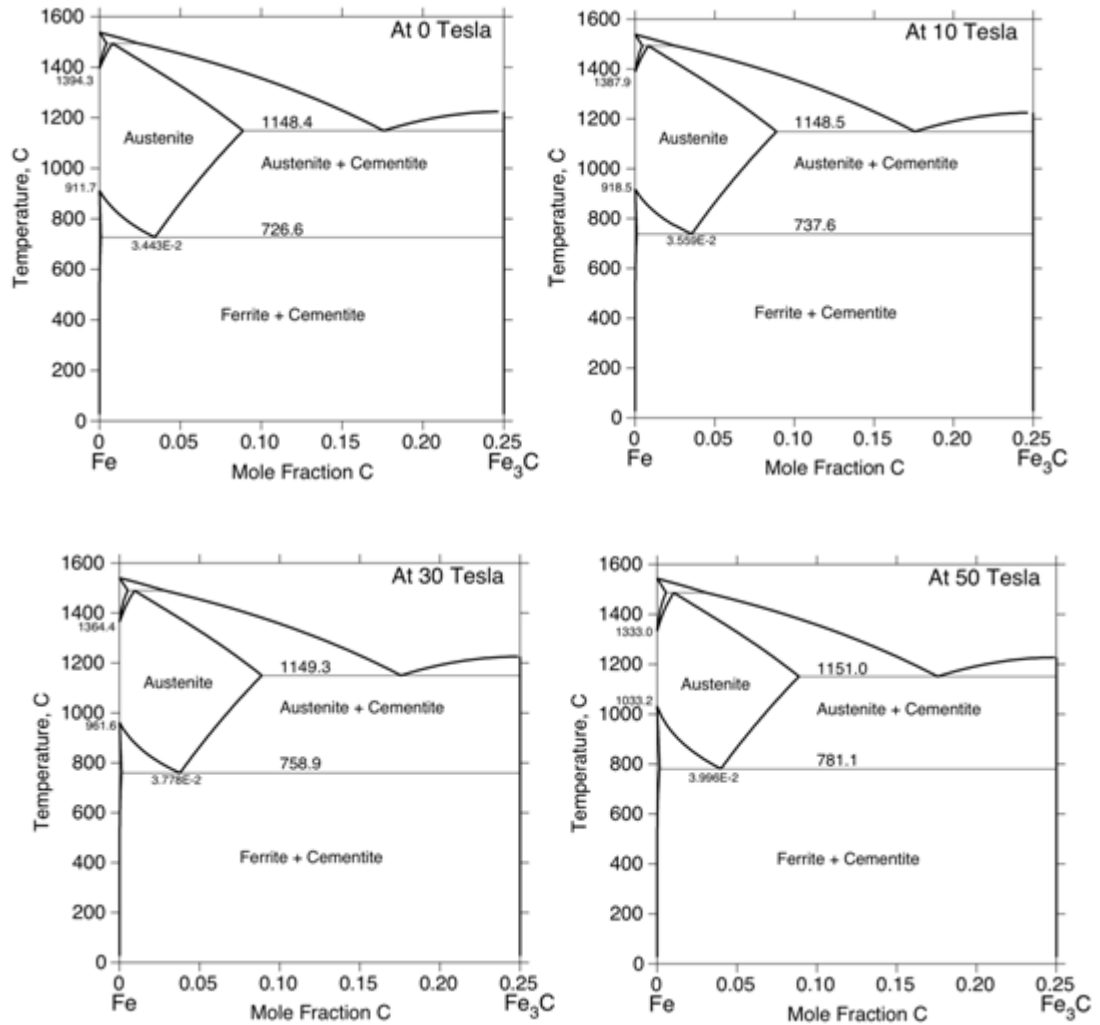


Figure 21: Calculated Fe-C Phase Diagram

Table 8: Calculated bcc/fcc transition temperature of pure Fe as a function of magnetic field strength.

Field strength (Tesla)	Temp, °C ($\alpha \rightarrow \gamma$)	Temp., °C ($\gamma \rightarrow \delta$)
0	911.7	1394.3
10	918.5	1387.9
20	936.2	1376.4
30	961.6	1364.4
40	993.7	1350.4
50	1033.2	1333.0

Table 9: Calculated eutectoid temperature (fcc \rightarrow bcc + cementite), eutectoid composition and C solubility in bcc phase at the eutectoid temperature as a function of magnetic field strength.

Field strength (Tesla)	Eutectoid temp, °C	Eutectoid composition at. fr. C (wt. fr. C)	C-solubility in bcc at. fr. C (wt. fr. C)
0	726.6	3.443E-2 (7.608E-3)	8.848E-4 (1.904E-4)
10	737.6	3.559E-2 (7.874E-3)	1.002E-3 (2.157E-4)
20	746.6	3.652E-2 (8.086E-3)	1.107E-3 (2.383E-4)
30	758.9	3.778E-2 (8.374E-3)	1.264E-3 (2.721E-4)
40	769.0	3.878E-2 (8.602E-3)	1.404E-3 (3.023E-4)
50	781.1	3.996E-2 (8.872E-3)	1.587E-3 (3.417E-4)

Table 8 lists the values of $\alpha \rightarrow \gamma$ and $\gamma \rightarrow \delta$ transition temperatures of pure Fe as a function of applied field strength. As expected, the trend is due to enhanced stability of α -Fe in the presence of magnetic field. In **Table 9** the increases in eutectoid (fcc \rightarrow bcc + cementite) temperature, the eutectoid composition, and the C solubility in bcc at the eutectoid temperature may be noted. These results are in good agreement with previous reports.^[2,3,5,6]

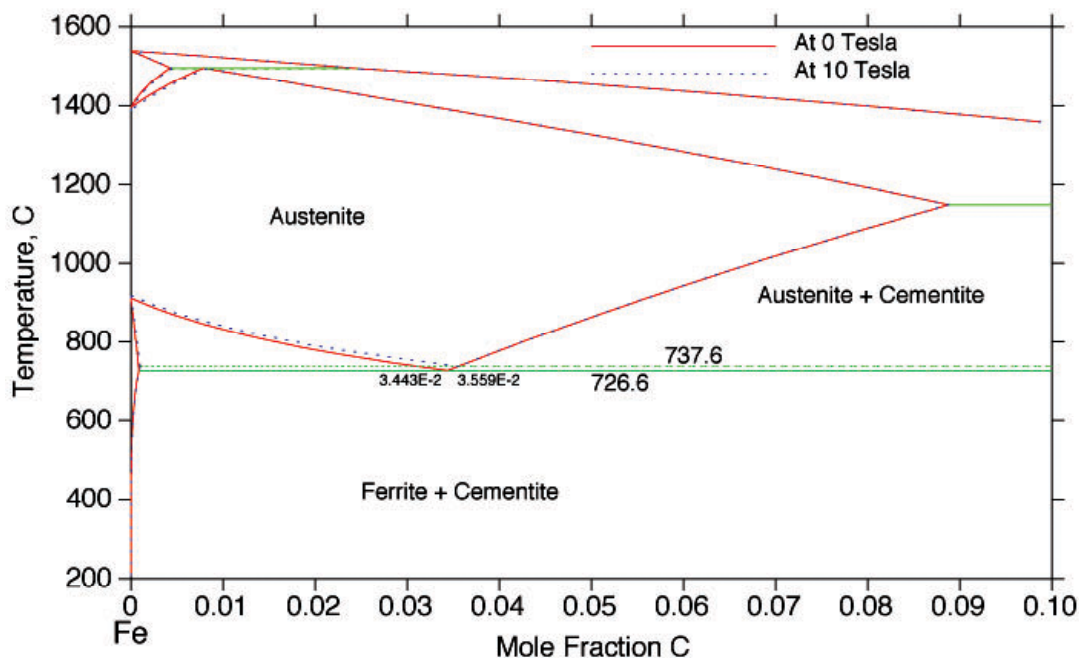


Figure 22: Enlarged Fe-C Phase Diagram

Figure 22 above is an enlarged part of Fe-C phase diagram where calculated phase boundaries, without and with a magnetic field of 10 Tesla, are superimposed for the sake of comparison. It is seen that with decreasing temperature the applied magnetic field exerts strongest influence on the α/γ phase boundary. In contrast, the δ/γ phase boundary shows only a minimal change and the γ /cementite phase boundary remains virtually unchanged.

The same approach was then applied to calculate the phase equilibria of SAE1045, SAE4150 and SAE 4350 (see **Table 10**). The effect, that a substitutional 3d transition metal solute atom has on the magnetic state of ferromagnetic bcc Fe (see **Figure 23** and **Figure 24** below), was studied. DFT calculations were run with a 54 atom supercell containing 53 Fe atoms and a single solute atom. A supercell, containing 54 Fe atoms, was also run to provide a baseline with which to compare. When a 3d transition metal solute atom is placed in bcc Fe the total magnetic moment decreases between 1 and 3 μ_B . There are two exceptions (Co and Ni) that cause the total magnetic moment to increase by about 1 μ_B . The total change in the magnetic moment can be broken down into the following categories:

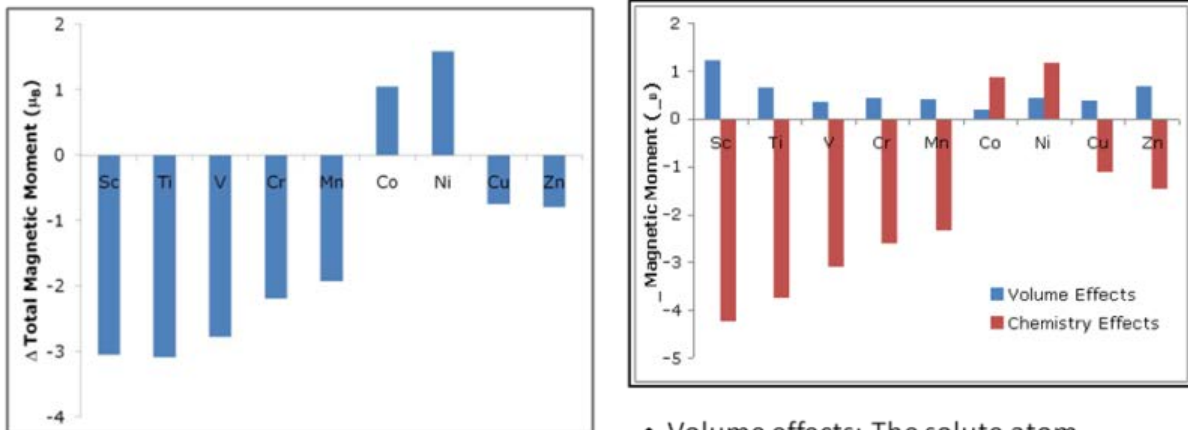
- Volume effects: The change in the magnetic moment due to volume change.
- Chemistry effects: The change in the magnetic moment due solely to solute atom.

The volume and chemistry effects were separated by taking the relaxed supercell containing Fe atoms and a single solute and replacing the solute atom with a Fe atom and calculating its total magnetic moment. In this calculation, the volume of the supercell and the position of the atoms were fixed to match those in the Fe-solute supercell. The volume effect is the difference between the total magnetic moment of this “distorted” 54 Fe atom supercell and a completely relaxed 54 Fe atom supercell. The chemistry effect is the difference between the total magnetic moment of the Fe+solute supercell and the “distorted” 54 Fe atom supercell.

The local magnetic moment on each solute atom varies. The first five transition metals align themselves antiferromagnetically to the surrounding Fe atoms. As the number of d electrons increases, the magnitude of the magnetic moment also increases. The last five transition metals align themselves ferromagnetically to the surrounding Fe atoms. In this case as the number of d electrons increases, the magnitude of the local magnetic moment decreases.

The solute atom disturbs the magnetic moment on the surrounding Fe atoms. For most solutes, the first nearest neighbors (1NN) show the largest change and the effect decays the larger Fe – solute atom separation distance increases. Generally speaking, solute atoms that align themselves antiferromagnetically to the surrounding Fe atoms decrease the magnetic moment on the surrounding Fe atoms. Similarly, solute atoms that align themselves ferromagnetically to the surrounding Fe atoms increase the magnetic moment on the surrounding Fe atoms. There are two exceptions (Cr and Mn) to both of the aforementioned trends. These two solutes have little effect on the first and second nearest neighbors. The largest effect is felt at the third nearest neighbor. Also, these two solutes align themselves antiferromagnetically to the surrounding Fe atoms but they increase the magnetic moment in the surrounding Fe atoms.

Change in the Magnetic Moment of FeX Relative to Fe



- Most 3d transition metals reduce the overall magnetic moment
- Two exceptions: Co and Ni

- Volume effects: The solute atom causes an increase in the volume, which the magnetic moment of bcc Fe to increase.
- Chemistry effects: The change in the magnetic moment caused by solute atom

Figure 23: Magnetic Moments – First Principles

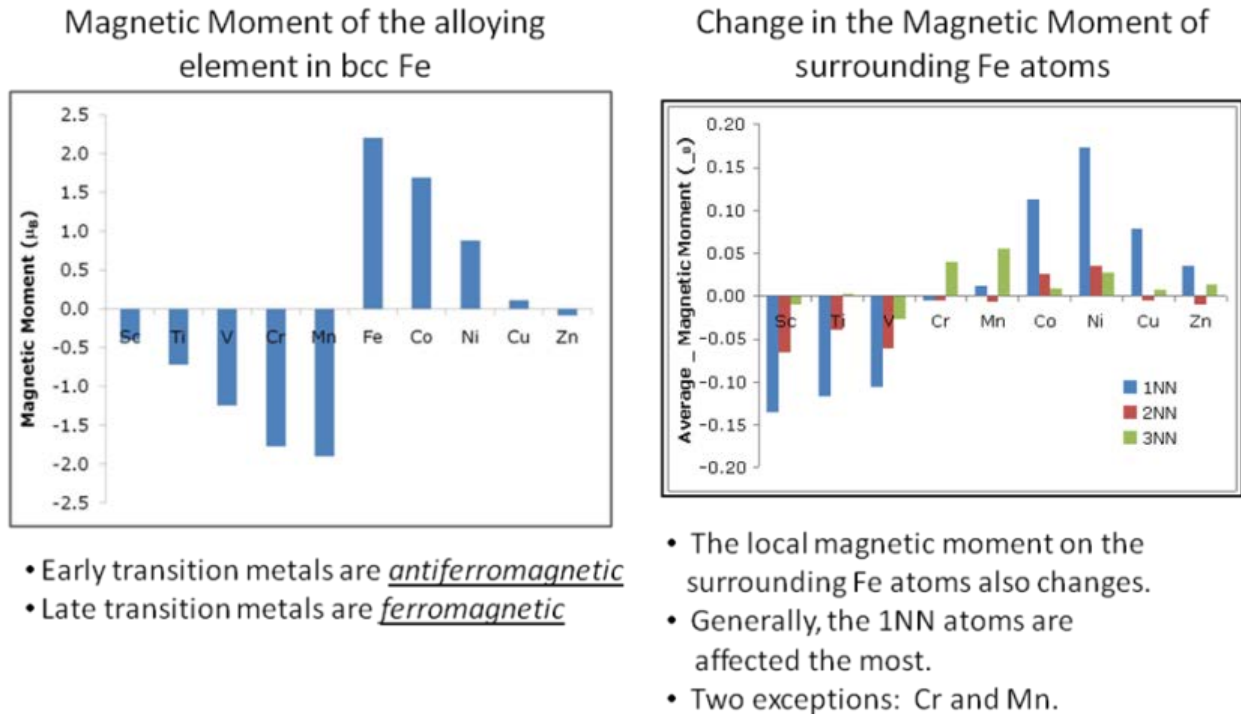


Figure 24: Magnetic Moment Results

As described above, the approach using Gibbs energies of three phases (bcc, fcc and cementite) are modified by adding a field dependent magnetization free energy term. The same approach is applied to calculate the phase equilibria of SAE1045, SAE4150, SAE4350 and SAE8620. The alloy compositions used in this study are summarized in **Table 10**.

Table 10: Composition (in mass%) of SAE alloys used in this study

Element	SAE1045	SAE 4150	SAE4350	SAE8620
C	0.46	0.52	0.54	0.22
Cr	0.02	1.02	0.90	0.54
Cu	----	0.03	0.18	----
Mn	0.75	0.95	0.69	0.85
Mo	0.004	0.2	0.21	0.20
N	0.005	0.007	----	----
Nb	0.001	0.001	----	----
Ni	----	0.04	1.91	0.43
Si	0.26	0.18	0.30	0.22
V	0.022	0.004	----	----
Fe	balance	balance	balance	balance

Presently, similar experimental data (i.e. the paramagnetic susceptibility), for the alloys of interest, is not available, although the composition dependence of average magnetic moment (at zero temperature) is available in ThermoCALC database. A fundamental assumption in present calculations is that the alloying elements in SAE alloys (i.e. in solid solutions) simply act as diluent as far as paramagnetic susceptibility is concerned. This is referred to as the zeroth-order approximation.

The calculated results are summarized in **Table 11** and **Table 12**. We find that all alloys are fully austenitic, without or with magnetic field, at the heat treatment temperature 843 °C (1550 F) currently used.

Table 11: Effect of an applied 10 Tesla magnetic field on selected transformation temperatures during cooling.

Steel	Transformation	Temperature, °C	
		Without field	With 10 T field
SAE1045	Ferrite start	767	779
	Ferrite finish	707	720
	Cementite start	724	736
SAE 4150	Ferrite start	747	762
	Ferrite finish	703	718
	Cementite start	733	743
SAE4350	Ferrite start	724	737
	Ferrite finish	648	667
	Cementite start	717	729
SAE8620	Ferrite start	803	813
	Ferrite finish	703	717
	Cementite start	721	733

Table 12: Effect of magnetic aging (due to an applied 10 tesla field) on the phase fraction at 177 °C (350 F).

Steel	Phase	Mole fraction	
		Without field	With 10 T field
SAE1045	Ferrite	0.9158	0.9158
	Cementite	0.0836	0.0836
	MC ((V,Nb)(C,N))	0.000485	0.000485
	M ₂ C ((Mn,Cr,Mo) ₂ C)	0.0000803	0.0000773
SAE 4150	Ferrite	0.9176	0.9181
	Cementite	0.0533	0.0478
	MC ((Cr,V)(C,N))	0.000704	0.000701
	M ₂ C ((Mn,Cr,Mo) ₂ C)	0.00594	-----
	M ₃ C ₂ (Cr ₃ C ₂)	0.0158	0.0164
	M ₇ C ₃ ((Mn,Fe,Cr) ₇ C ₃)	0.00663	0.0169
SAE4350	Ferrite	0.9127	0.9126
	Cementite	0.0624	0.0627
	M ₃ C ₂ (Cr ₃ C ₂)	0.0150	0.0149
	M ₇ C ₃ ((Mn,Fe,Cr) ₇ C ₃)	0.00995	0.00969
SAE8620	Ferrite	0.9692	0.9692
	M ₃ C ₂ (Cr ₃ C ₂)	0.00889	0.00886
	M ₇ C ₃ ((Mn,Fe,Cr) ₇ C ₃)	0.0219	0.0219

Table 11 compares important transformation temperatures, with and without a field of 10 Tesla, when the alloys are cooled from fully austenitic state. As noted in the binary Fe-C system, an applied field of 10 Tesla increases the ferrite transformation temperature by 10 to 15 °C. Similarly, ferrite finish temperature is also increase by about 10 to 15 °C. Similar to an increase in ferrite transformation temperature, an applied field of 10 Tesla also increases the cementite precipitation

temperature by about 10 °C. **Table 12** compares predicted equilibrium phase fractions at the aging temperature of 177 °C (350 F) without and with an applied field of 10 Tesla. As seen, the phase fractions are nearly identical. With the exception SAE8620, the predominant carbide is cementite.

3.5 Task 4 –ThermoMagnetic Processing Equipment Generation 2 Design

This task addresses the following topics which were completed under the project:

- Develop an equipment design for an industrial scale prototype system for magnetic processing, integrating induction with thermomagnetic processing, along with a conceptual design for component handling system. The magnet design includes the superconducting coil hardware, the electronic control system hardware/software for the industrial environment (as opposed to an academic setting), and the cryostat design.
- Install and operate the 9 Tesla 8 inch bore commercial prototype processing system (including supporting systems for part indexing and handling, inductive heating, and liquid/polymer quench mechanisms).

Several challenges to achieve the superconducting 9T 8” ITMP system were overcome during the course of this project. Because of the unknowns in going to the large 8” bore size with the 9T field strength, the decision to build an intermediate magnet was taken; AMI built a 10T; 4” bore, room temperature solenoid magnet. The manufacturing of this solenoid addressed issues associated with increased bore size of both the NbTi outer diameter winding and the Nb3Sn inner diameter winding. Nb3Sn material from different vendors was qualified, such that the Nb3Sn insert could be built for completion of the large 8” bore 9T solenoid.

Regarding the cryostat design, the cryogenic engineering team at AMI worked on a design of the 9 Tesla 8 inch room temperature bore superconducting magnet system to address the project requirements. The cryostat is capable of handling a 2000 pound extraction force and uses re-condensing technology to minimize operational costs and human servicing. The cryostat design was further modified to facilitate the integration of the induction heating apparatus.

AjaxTocco installed a higher power induction heating system (200KW power level). Induction coil was designed to provide ability to distribute the thermal energy along the geometry of the sample.

Upon receipt of the AMI 9T 8” magnet design, AjaxTocco reviewed and launched a structured analysis of the mechanical handling hardware and system construction requirements to utilize the full capabilities of induction heating in multiple combinations with ITMP. This study acknowledged the substantial magnet bore part entry attraction force and extraction force of 2000 pounds along with the requirements of precise axial and radial positioning, including the required rotation of the part for uniformity of heating and quenching. Also considered was the reactive torsional force to the rotational requirement. Additionally there were a number of space design issues in the integrating of the induction heating/quenching process within the magnet bore confines. It was also important to incorporate features to allow extensive process flexibility to evaluate a wide range of combinations of processing conditions (pre and post ITMP processing). The “on board” flexible computerized programmable controls to properly implement these different process agendas and collect accurate processing data to duplicate industrial operating conditions were included in the design concept. Some of the applications considered were shafts and gears, where precise heating is required to generate a good surface hardened case.

At one point, the elevated high power level of the induction coil was found to induce voltage excursions with the internal windings of the magnet. The concern was with the rate of change (i.e. dv/dt) of these excursions, in that they should not peak (spike) and result in causing a voltage breakdown in the magnet winding. The tests regarding this effect, thus far, indicate that these issues are manageable.

A second electrical operational issue was with the amplification factor when coupling induction heating with high level (Tesla) magnetic fields. This combination can potentially generate a high level of acoustical energy which is proportional to the applied power level of induction heating and inversely proportional to the applied frequency used for induction heating. The tests were programmed to operate at frequencies in the range of 30kHz until the team developed a more comprehensive understanding of the severity of this effect.

Ultimately AMI and AjaxTocco, with support from the project team, completed the 9T 8" room temperature bore magnet system for ITMP processing. The AMI ReCon™ cryostat has been in continuous operation for several months with no noted helium losses. ORNL has successfully processed the test shafts to validate the ITMP system. All ITMP systems appear to be in good shape.

The ITMP-process validation using the 9T 8 inch magnet was completed using industrial test shafts to show the completion and capability of the new ORNL 9T 8 inch thermomagnetic processing system deliverable. The new system has been exercised throughout the 0T to 8.5T magnetic field range under a variety of applied induction power settings and quench scenarios. The test shafts, due to shorter time at the austenitizing temperature did not show significant surface oxidation, which is desired. The heating time at temperature was 20 seconds, as opposed to 20 minutes in the earlier studies; the fast rate (20 seconds) has reduced the oxidation of the component surface. The residual stress was high compressive (~100ksi) and the volume percent retained austenite was very low (~<4%). Hardness was very uniform indicating uniform heating and quenching of the components.



Figure 25: World's First Prototype Commercial Magnet

Figure 25 shows how the design was converted to a reality in the form of a vertical 8" diameter bore, 9" long uniform magnetic field zone that is capable of providing 0 to 9Tesla magnetic field with induction heating capable of providing 0 to 1600C temperatures in process.

With the initial validation success of the 9T 8" system using the industrial test parts, the next step was validation of the ITMP process using the commercially available Reverse Idler Gears. The fixturing for the reverse idler gear is shown in **Figure 26**. This fixturing enabled the reverse idler gear (see **Figure 27**) to be inserted into the 8" dia superconducting magnet at a rate of 4 inches per second. The gear was heated by a dual frequency 200kW induction heating power supply. The part was rotated at 30rpm in the magnet during heating and quenching to maintain uniform case depth.

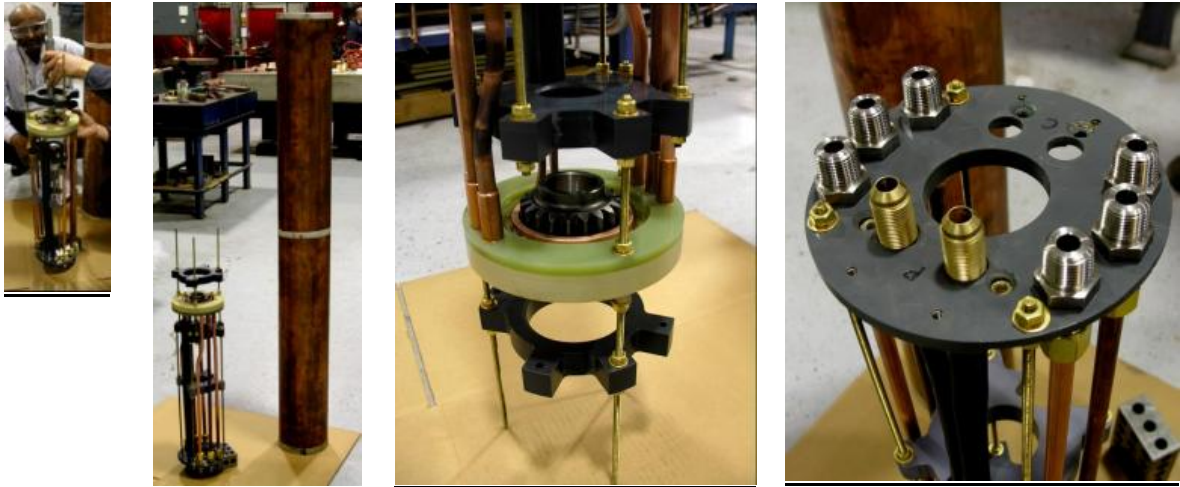


Figure 26: Fixture for Reverse Idler Gear

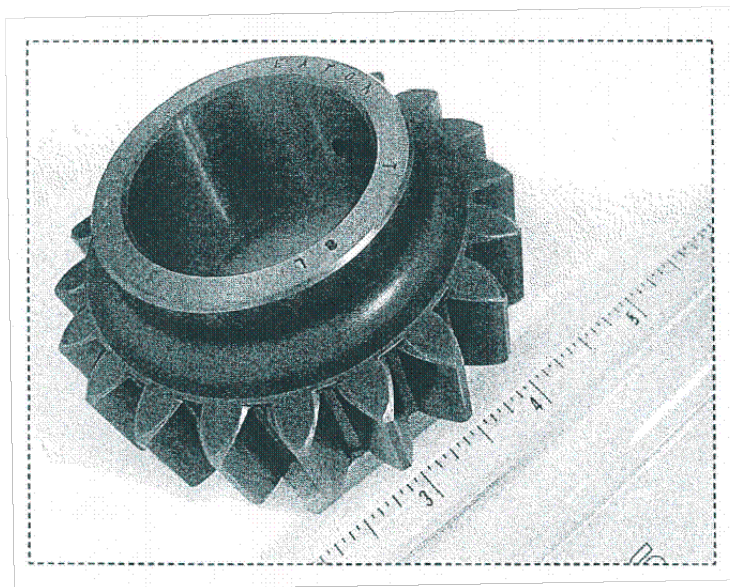


Figure 27: Reverse Idler Gear

4.0 BENEFITS ASSESSMENT

The work done under the ITMP project clearly demonstrates the energy savings, with a corresponding reduction in the carbon dioxide gas emission. The induction heat treat process replaces the large carburizing and tempering furnaces as well as gas generating ancillary equipment, such as large exhaust and environmental control apparatus. The productivity is greatly improved with “just-in-time” response and an in-line manufacturing approach, resulting in reduced inventory with a smaller manufacturing footprint.

Besides the energy savings, thermo-magnetic processing has opened the door to greatly improved material properties, enabling lower cost materials substitution in place of more exotic alloys. This will also result in reduced dependence upon strategic and expensive alloying elements through achieving similar or improved properties using less expensive and more readily available materials.

5.0 COMMERCIALIZATION

The world's first prototype for a commercialization unit has been developed under the current program, using the new component handling mechanical system, placed and tested at ORNL. The commercialization for Eaton applications, utilizing this technology in manufacturing as a substitution for steels is being pursued.

Energy savings is demonstrated in the section of energy calculations particularly as a substitute for carburization; which further lends credibility to industrialization of the ITMP. This is a major step in sustainability.

6.0 ACCOMPLISHMENTS

The following accomplishments through the Induction Thermo-Magnetic Processing (ITMP) are noteworthy:

- Demonstration and development of the first commercial prototype superconducting magnet, component handling system and in-situ quench for product applications; processing times were designed to meet the conventional productivity of gears and other industrial component parts. This paves the way for the next generation of commercial production using superconducting magnets.
- Demonstration of the use of lower cost materials using ITMP to replace the conventional carburized low carbon steels; improvements shown in mechanical properties, fatigue properties and formability, through application of the concept to Eaton components, including gears, orbital drives and forged valves.
- Demonstration of “First Principles” modeling to the iron-carbon phase diagram with the associated influence of the alloying elements; leading to future tailoring of the ITMP-enabled alloys.
- Utilized the DEFORM models and simulations for forging and forming operations for improvement in product; resulted in significant energy savings and waste reduction (in Eaton manufacturing operations).
- Achieved validated energy savings that are significantly greater than targeted levels; demonstrated savings of 86% compared to baselines.
- Achieved energy savings in terms of reducing the tempering time of heat treated components; from two hours (for traditional carburized) to only ten minutes (using the magnetic field). Similar demonstration of reduction in tempering times was shown when applied to tool steels.

7.0 CONCLUSIONS

ITMP is a breakthrough game-changing technology with tremendous commercial viability and potential for energy savings and reduction in carbon foot print. The present project has demonstrated not only energy savings, but has opened the way to utilization of more economical alloys and improved manufacturing practices. Through the ITMP process, in-line manufacturing is a real possibility, with less material handling, smaller manufacturing foot-print (less square footage) and a resulting cleaner environment.

The ITMP process is beneficial not only for materials that are carburized or heat treated, but in areas like the electrical applications, modifying low cost magnetic steel to one with superior properties, changing the microstructures to affect improvement in the properties. The change in microstructures and the effective improvement in ductility can be used for formability, net forming and improved performance, with less machining and a reduction in manufacturing time and energy. The benefits from this technology are many; this is an industrial game changer.

Specifically, the through carburized SAE8620 alloy samples (effectively a 8671 alloy), the 9T ITMP processed samples exhibited 30% improvement in ultimate tensile strength over no-field processed specimens exceeding the project's goals of at least a 20% improvement in UTS.

In high strength steel SAE4350 steel alloy, the 9T ITMP processed samples exhibited 10% improvement in yield strength, 90% improvement in elongation over the no field processed specimens.

For wear applications, SAE9254 steel alloy, the 9T ITMP processed samples exhibited a 40% improvement in wear over the no field processed specimens.

Orbital drive torque testing experiments indicated a ~100% improvement in ductility for the 9T ITMP processed orbital drives over the baseline samples without the ITMP processing.

The H10 tool steel extrude die inserts processed using the 9T ITMP required only 1 high temperature tempering cycle to essentially eliminate all retained austenite issues, whereas normally two high temperature tempering cycles, sometimes with an intermediate cryogenic step, are required to mitigate potential retained austenite issues.

For the tempering of carburized SAE8620 alloy, the 9T ITMP processed samples exhibited a reduction in time from two hours to ten minutes in comparison to the no field processed specimens. The hardness was uniform.

8.0 RECOMMENDATIONS

The ITMP project has demonstrated a game changing technology. The following recommendations are suggested for near term deployment:

- Implement Induction Thermo-Magnetic-Processing in the industry to maximize the benefits in terms of energy savings and improvement in material properties.
- Proceed with the commercialization of an 8 to 10 inch diameter, 8 to 9 Tesla superconducting ITMP system to process industrial components such as gears, shafts, orbital drives and other ferrous based material parts.
- More research is required in superconducting coil wire materials for magnets that can provide up to higher than 10T levels. Some of the work conducted in this study shows that higher magnetic field levels can generate even better physical properties than that achieved by 9T. At present there is a global shortage of Nb₃Sn wire.

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