OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

NFE-08-01224

Final CRADA Report for

CRADA No. NFE-08-01224
with

Eaton Corporation

Use of High Magnetic Fields to Improve Material Properties for Hydraulics, Automotive and Truck Components

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June 27, 2010

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managed by
UT-BATTELE, LLC
for the
U.S. Department of Energy
under contract DE-AC05-00OR2225

Funding for this project was provided in part by the Department of Energy's Office of Energy Efficiency and Renewable Energy's Technology Commercialization and Deployment Program's Technology Commercialization Fund and by Maturation Funding Avenue under CRADA # NFE-08-01224.

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Abstract

In this CRADA, research and development activities were successfully conducted on magnetic processing effects for the purpose of manipulating microstructure and the application specific performance of three alloys provided by Eaton (alloys provided were: carburized steel, plain low carbon steel and medium carbon spring steel). Three specific industrial/commercial application areas were considered where HMFP can be used to provide significant energy savings and improve materials performance include using HMFP to: 1.)
Produce higher material strengths enabling higher torque bearing capability for drive shafts and other motor components; 2.) Increase the magnetic response in an iron-based material, thereby improving its magnetic permeability resulting in improved magnetic coupling and power density, and 3.) Improve wear resistance. The very promising results achieved in this endeavor include: 1.) a significant increase in tensile strength and a major reduction in volume percent retained austenite for the carburized alloy, and 2.) a substantial improvement in magnetic perm respect to a no-field processed sample (which also represents a significant improvement over the nominal conventional automotive condition of no heat treatment). The successful completion of these activities has resulted in the current 3-year CRADA No. NFE-09-02522 "Prototyping Energy Efficient ThermoMagnetic and Induction Hardening for Heat Treat and Net Shape Forming Applications".

Objectives

In this project the Contractor, UT-Battelle LLC/ORNL, with the Participant, Eaton, a US-based industrial company, focused on investigating the High Magnetic Processing technology to improve the performance for three of their product line components:

- 1.a. A Heavy Duty Drive Train Valve Systems & Components application
- 1.b. A Power Distribution/ Solenoids application.
- 1.c. A truck system requiring wear

<u>FIRST APPLICATION: Shaft for Hydraulic Application</u>

Base material: low carbon carburized steel

Targeted Property Change: Durability/strength

1. Change in carburized microstructure: reduced retained austenite; higher hardness to generate better wear resistant surface. Goal 5% retained austenite by volume.

2. Change in low carbon core microstructure: higher ultimate tensile strength (UTS), based upon quenching under a magnetic field, followed by tempering- Goal: 20% increase in UTS

<u>SECOND APPLICATION: Solenoid Armature Magnetic Permeability</u>

Base material: Plain low carbon Steel

Targeted Property Change – Magnetic permeability

Shift to ferrite microstructure to behave as low carbon/electrical steel. Goal: B-H curve to be similar to spheroidized microstructure. (Coercivity <1.0 Oe at 1.8 T; ref: US steel data sheet, Metals Handbook, Volume 3)

<u>THIRD APPLICATION: Wear Resistant</u>

Base material: Medium carbon spring steel

Targeted Property Change: Durability/strength

Change in microstructure; reduced retained austenite; fine bainitic microstructure. Goal: Improved wear resistance by 50% and maintain UTS

Technical Discussion

The discussion section of this final report is represented by a compilation of summary slides/tables *, that are commented and therefore are explanatory and self-consistent. The salient conclusions are summarized in the final "Conclusion" section of this report.
*Courtesy of A. Ahmad, Eaton Corporation

Hardness and Microstructure Results

Hardness did not increase – that's a good thing
Microstructure improved in low carbon steel (increased ferrite)
Retained austenite decreased in carburized steel

Properties	Plain Low Carbon	Low Carbon Carburized Steel	Carburized Steel	Medium Carburized Steel	Medium Carbon Spring Steel
Microstructures Prior Mag. Field	Pearlite and Ferrite banding	Pearlite and ferrite	Martensite with some austenite	Martensite with some austenite	Pearlite and ferrite with Cr carbides
Microstructure after Mag. Field	Ferrite increased by 40% (good)	N/A	N/A	Retained austenite decreased by 43% (good)	N/A
Hardness	88 Rb	32 HRC	62 HRC	62 HRC	50 HRC
Anneal	78 Rb	None	None	None	None
Mag. Reference	70 Rb	N/A	N/A	None	At ORNL
18 T<T Curie	70 Rb	None	64	62	At ORNL
18T> T Curie	69 Rb	None	63	63	At ORNL

Microstructures

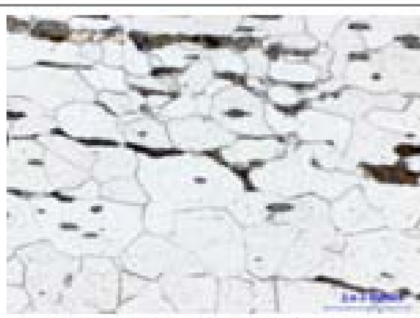
Plain low Carbon Steel Hot roll structure @100x

Plain low Carbon Steel reference @100x 15% ferrite increased

Plain low Carbon Steel 18T < T Curie @100X 40% ferrite formed with an applied 18T

Plain low Carbon Steel 18T >T Curie @100X 30% ferrite formed with an applied 18T

Microstructures cont.



Plain low carbon steel Hot roll structure @ 500x (no field)

Plain low carbon steel Reference @ 500x (15% ferrite increased)

Plain low carbon steel 18T < T Curie @ 500X (40% ferrite increased)

Plain low carbon steel 18T >T Curie @500X (30% ferrite increased)

Microstructures cont.

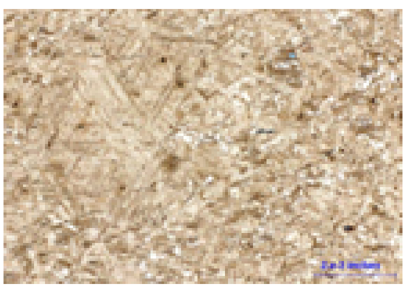
Carburized Steel Hot roll structure @ 500x Baseline

Carburized Steel (c 0.41)carburized @ 500x (conventional process) typical microstructure

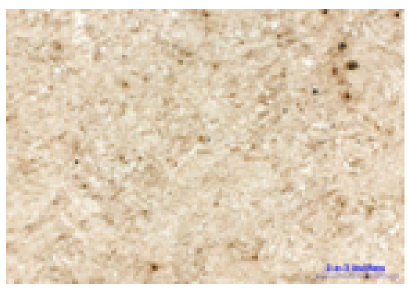
Carburized Steel(C0.47) carburized @ 500x (conventional process)

Medium Carbon Steel hot roll @ 500x (conventional process)

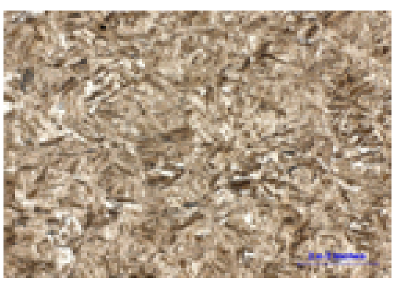
Microstructures changing after applying Magnetic field



Carburized Steel 0.47)Magnetic 18T<T Curie @ 500x less retained austenite due to low carbon content



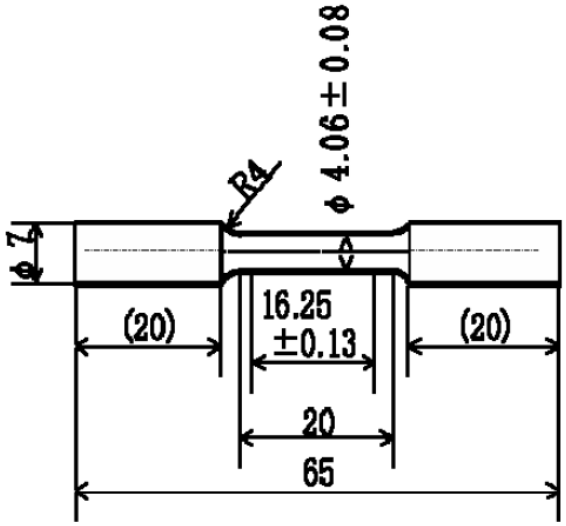
Carburized Steel (0.47) Magnetic 18T>T Curie @ 500x less retained austenite due to the low carbon content



Carburized Steel Magnetic (C 0.47) before magnetic field

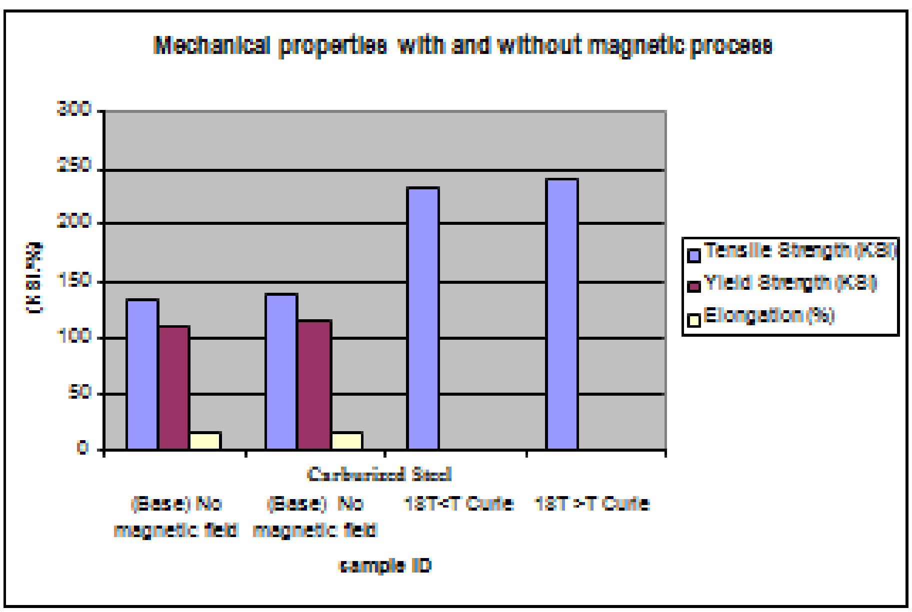
Change in microstructure by applying magnetic field

Tensile Testing- ASTM E8 - 04



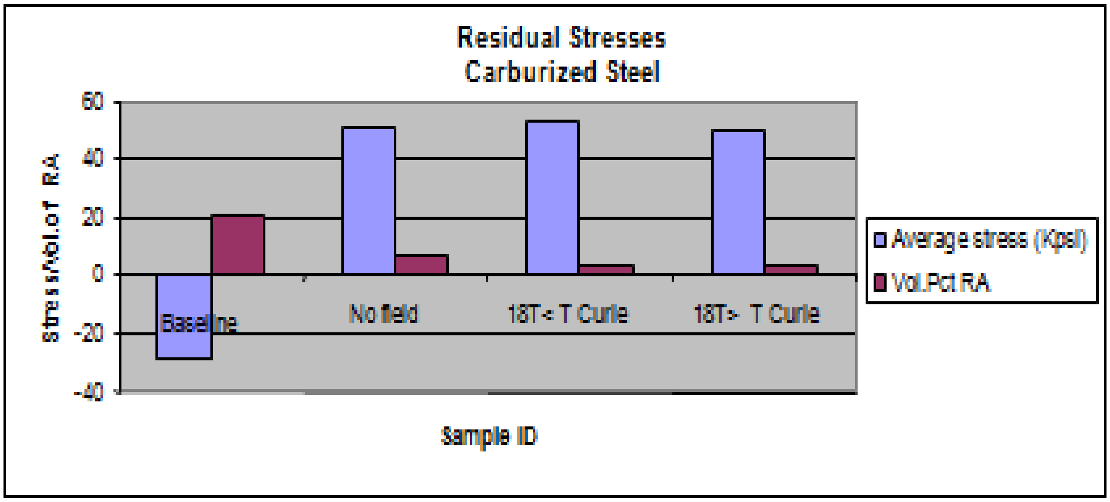
Dimensions are in mm (the 4.06 mm corresponds to the 0.160-inch diameter gage length in the following ASTM E-8 specification sketch)

Mechanical properties Cont.



Apply the magnetic field improved the tensile strength by 85%
(Carbon content is 0.47)

Residual Stresses Cont.

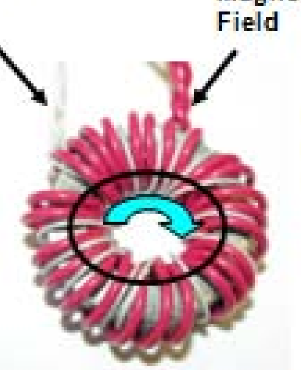


Magnetic Permeability Low Carbon Steel

Walker LDJ AMH-5,15,25
Hysteresisgraph

Read Magnetic Flux

Apply Magnetic Field



Calculate reluctance of sample

Calculate B-H Curves of material

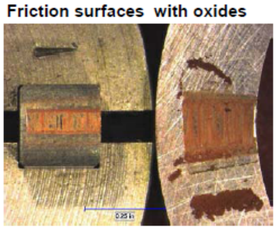
Magnetic Permeability Cont.

Sample Identification	Magnetic Permeability (%)
Low carbon steel Hot Roll (baseline) (Nominal Automotive Condition)	0
Low carbon steel Anneal	+3%
Low carbon steel reference	+7%
Low carbon steel (18T<T Curie)	+11.3%
Low carbon steel (18T>T Curie)	+11.5%

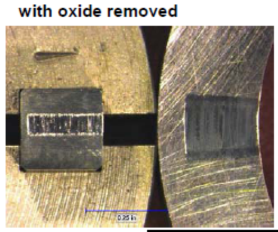
Increase in permeability by significant amount

Medium Carbon Steel
Truck Application Requiring Wear Resistance

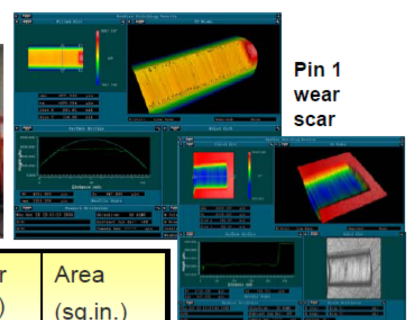
Friction surfaces with oxides



with oxide removed



2 hour test; 5Hz; 100 lb load; dry



Pin 1 wear scar

Preliminary Test Findings (Falex):

- **18% reduction in worn area**
- **40% reduction in scar depth**

Batch #	Wear Scar Depth (in.)	Area (sq.in.)
Baseline 1	0.00235	0.0161
Baseline 2	0.00273	0.0167
Batch “B” Pins	0.00135	0.0132
Batch “C” Pins	0.00170	0.0136

Sideways view after test

Conclusions from HMFL – Florida Process Runs

- The microstructure of carburized steel (Carbon 0.47) decreased in retained austenite by a significant amount.
- The ferrite in microstructure of plain low carbon steel increased by 40% when applying a magnetic field compared to the reference heat treated ORNL sample coupon
- The magnetic permeability improved by 64% by applying the magnetic field compared to the reference heat treat ORNL sample coupon
- The tensile strength improved by 85% after applying the magnetic field

Subject Inventions

No new intellectual property was generated under this CRADA.

Commercialization Possibilities

The results of this preliminary investigation indicated that the thermomagnetic processing technology has major potential commercialization applications from process energy efficiency improvement perspectives as well as making major improvements in component performance metrics (properties) for a broad range of applications. Future collaborations (next section) with Eaton and potential equipment suppliers (AjaxTOCCO [induction heating equipment] and American Magnetics Inc [superconducting magnet technology]) will pursue those possibilities.

Plans for Future Collaborations

The positive results obtained in this initial CRADA resulted in a winning proposal being submitted to and selected for funding via the EERE EIP Industry-led Project Program. This has resulted in the current multimillion dollar, 3-year CRADA No. NFE-09-02522 "Prototyping Energy Efficient ThermoMagnetic and Induction Hardening for Heat Treat and Net Shape Forming Applications" whose collaboration objectives include:

- 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 the new innovative 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 reduced 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.

Conclusions

Thermomagnetic processing was shown to make significant improvements in microstructure and strength and other performance metrics when compared to the no-field references cases (indicated as "reference ORNL sample coupon). These improvements include:

1.) The microstructure of carburized medium carbon steel alloy steel decreased in retained austenite by 43% provided a major reduction in retained austenite.
2.) The ferrite in the microstructure of plain low carbon steel alloy steel increased significantly when applying a magnetic field compared to the reference heat treated ORNL sample coupon.
3.) The magnetic permeability of the plain low carbon steel improved significantly by applying the magnetic field compared to the reference heat treated ORNL sample coupon.
4.) The tensile strength improved significantly in low carbon carburized steel sample after applying the magnetic field.