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Heat Treatment of Iron-Carbon Alloys in a Magnetic Field (Phase 2)



Gerard M. Ludtka

November 9, 2017

**CRADA FINAL REPORT
NFE-14-05181**

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Materials Science and Technology Division
Advanced Manufacturing Office

Heat Treatment of Iron-Carbon Alloys in a Magnetic Field (Phase 2)

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CONTENTS

	Page
CONTENTS	v
LIST OF FIGURES	vi
ACKNOWLEDGEMENTS.....	vii
ABSTRACT	1
1. HEAT TREATMENT OF IRON-CARBON ALLOYS IN A MAGNETIC FIELD (PHASE 2).....	1
1.1 BACKGROUND.....	1
1.2 TECHNICAL RESULTS	3
1.2.1 Idler Gear Application.....	3
1.2.2 Crankshaft Application	7
1.2.3 High Performance Engine Valve Springs.....	7
1.3 IMPACTS	13
1.4 CONCLUSIONS	13
2. CUMMINS BACKGROUND.....	14

LIST OF FIGURES

Figure 1 Improvement in single-tooth bending fatigue life of carburized 8620 idler gears after a 9 T thermomagnetic processing heat treatment.	2
Figure 2 The world’s first commercial prototype thermomagnetic processing system at ORNL that has been used for experimental trials on industrial-scale components.	3
Figure 3 Schematic of an existing induction heating design with integral quench system used in an earlier project was considered to do the idler gear.	4
Figure 4 An enlargement of the sample chamber inside the integral induction heating-quenching insert used in a prior project.	4
Figure 5 Cross-sectional rendering of the sample chamber where the idler gear was initially felt could be thermomagnetically processed.	5
Figure 6 Concept drawing provided by AMI, Inc. for a 9-tesla, cryocooler-based, 15-inch (381 mm) diameter warm-bore superconducting magnet system.....	6
Figure 7 Concept drawing provided by Cryogenic Limited for an 8-tesla, cryogen-free (conduction cooled) 16-inch (400 mm) diameter warm-bore superconducting magnet system.	6
Figure 8 Representative example of a nitrided high performance 9254 alloy steel engine valve spring.	8
Figure 9 The microstructure of this commercially heat treated and nitrided 9254 alloy steel spring is shown fine tempered martensite with a discontinuous nitride layer (thin light gray layer at top of micrograph).	8
Figure 10 ORNL’s 5-inch diameter vertical warm bore, 9-T superconducting magnet system typically used for more fundamental research incorporating a DTA/DSC system.	9
Figure 11 DTA experiment plot summary extracted from the heating and cooling experiments with and without a 9 Tesla magnetic field (summarized in Table 2).	11
Figure 12 DTA plots for the tempering cycles at two separate temperatures with and without a high magnetic field to characterize the completion of the tempering cycle (summarized in Table 3).....	12

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ABSTRACT

Thermomagnetic processing was shown to shift the phase transformation temperatures and therefore microstructural evolution in the high performance engine valve spring 9254 steel alloy by applying a high magnetic field during cooling. These effects would be anticipated to improve performance such as high cycle fatigue as demonstrated in prior projects. Thermomagnetic processing of gears and crank shafts was constrained by the size of the prototype equipment currently available at ORNL. However, the commercial procurement viability of production scale 9-Tesla, 16-inch diameter bore thermomagnetic processing equipment for truck idler gears up to ~11-inch diameter and potential crank shaft applications was shown, as multiple superconducting magnet manufacturing companies (in conjunction with an induction heat treating company, AjaxTOCCO Magnethermic) offered cryogen-free or cryocooler equipment designs to Cummins.

1. HEAT TREATMENT OF IRON-CARBON ALLOYS IN A MAGNETIC FIELD (PHASE 2)

This phase 2 technical collaboration project (MDF-TC-UP-2014-043) was begun on September 16, 2015 and was completed on August 28, 2017. The collaboration partner Cummins, Inc. is a large business. Through these efforts, the commercial viability of production scale thermomagnetic processing equipment (e.g., for truck idler gears up to ~11-inch diameter) was shown as multiple superconducting manufacturing companies (in conjunction with an induction heat treating company, AjaxTOCCO Magnethermic) offered equipment designs to Cummins. In addition, the effect of shifting phase transformation temperatures for a high performance race car engine spring alloy application was shown via differential thermal analysis/differential scanning calorimetry (DTA/DSC) by applying a high magnetic field on cooling the alloy after an austenitization heat treatment.

1.1 BACKGROUND

The purpose of this technical collaboration between Cummins and ORNL was to understand the ability of thermomagnetic heat treatment to significantly alter the physical properties of common engineering alloys to a point where current engine designs can achieve higher power density, better fuel efficiency, and lower carbon emissions. An overarching goal for Cummins was to identify specific current production components, and through processing in ORNL's prototype commercial magnetic processing equipment, identify new processing paradigms resulting in increased component and engine efficiency while economically lowering the carbon footprint of producing current production engines.

In phase 1 of this project, ORNL researchers in partnership with materials scientists from Cummins, Inc. utilized the laboratory's unique experimental capabilities to understand the fundamental scientific principles underlying Fe-C material property improvements resulting from magnetic field processing. The application of a high flux magnetic field as a function of temperature was found via real-time, in-situ neutron diffraction experiments (footnote1) to increase the solubility of carbon in austenite by up to 22%, which leads to improved properties in martensitic steels. This earlier work also provided an experimental explanation for the smaller grain size and finer lath spacing seen in material quenched or solidified in a static magnetic field which leads to increases in physical properties including hardness, ultimate tensile strength, yield strength, and fatigue strength.

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1. "Phase Transformation in a High Flux Magnetic Field," R. England, G. M. Ludtka, et al, Conference Proceedings of the TMS 2015 144th Annual Meeting & Exhibition, 2015, p.1345-1351.

Two types of components were proposed to be examined in phase 2. In the first year, carburized 8620 gears for a critical Cummins' application were planned to be tested in one of ORNL's current thermomagnetic processing systems for the effects of magnetic processing on the quench and tempering. These experiments were intended verify results achieved with Eaton Corp. as shown in Figure 1 (footnote 2) where thermomagnetically processed (indicated as ITMP for induction thermomagnetic processing versus "Baseline" that were induction heat treated only), carburized 8620 idler gears achieved statistically significant fatigue life improvements ranging from 250 to 500% over baseline gears.

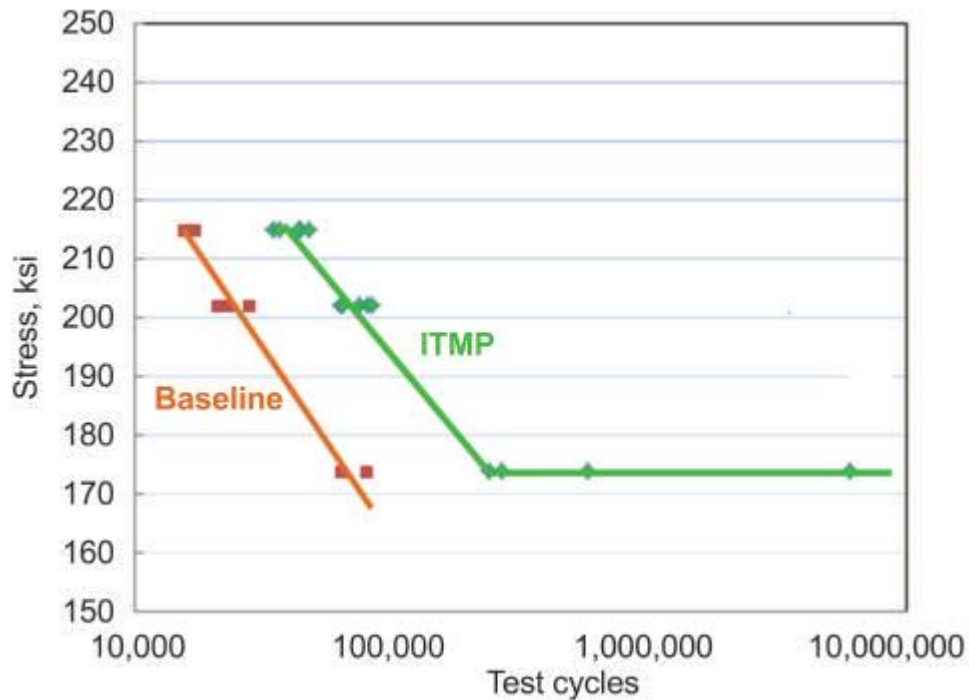


Figure 1 Improvement in single-tooth bending fatigue life of carburized 8620 idler gears after a 9 T thermomagnetic processing heat treatment.

Next, a less expensive and more easily processed alloy would be investigated via similar testing as an alternative to alloy 8620. AISE 4340 steel is less expensive and requires and less expensive heat treatment processing since no carburizing is not needed. The move to AISI 4340 could significantly lower energy consumption during processing (since no carburization required), and also lower base material cost. The improvements of magnetic processing were hoped to be sufficient to lower these processes and still exceed required strength.

In the second year of the project camshafts and camshaft roller followers were planned to be tested in a similar manner. The move to higher ramp rates on camshafts can increase engine volumetric efficiency, and the reduction of spalling incidences in the tribological interface between the camshaft and the roller follower can increase oil drain intervals on heavy duty engines, lowering the consumption of oil and decreasing environmental impact.

2. "Induction Coupled Thermomagnetic Processing: A Disruptive Technology," Aquil Ahmad, George Pfaffmann, Gail Mackiewicz Ludtka, and Gerard. M. Ludtka, Advanced Materials and Processes, 2016, v.174, issue 6, p.35-37.

Components initially targeted in this study were gears, camshafts, and camshaft roller followers. These are specific components where enhancement of physical properties can directly affect the efficiency of the engine. The work was intended to be accomplished with actual components that would be identified as critical applications for Cummins and that could be integrated into ORNL's ~8-inch diameter, warm bore commercial thermomagnetic processing system with integrated induction heating and quench capability (Figure 2). Those tested samples were then to be tested on engines using Cummins engine testing capabilities.



Figure 2 The world's first commercial prototype thermomagnetic processing system at ORNL that has been used for experimental trials on industrial-scale components.

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

1.2 TECHNICAL RESULTS

1.2.1 Idler Gear Application

Idler gears experience severe engine loading conditions due to the reversed bending loading the gear teeth receive while in operation that may lead to high stress, high cycle fatigue failures and so currently their design mandates a conservative approach that can reduce the effective power density achievable in an engine. The idler teeth are loaded first in one direction by the driving gear, then in the opposite direction (with the same force) by the driven gear. Putting this in perspective, at 4600 input RPM, it takes only 36 hours for the driving gear to reach 10 million fatigue cycles. Therefore some of the most significant overall engine performance improvements can be made if the gear material's fatigue resistance can be enhanced through higher cost alloys or by implementation of a breakthrough material processing technology, such as thermomagnetic processing, which can sufficiently alter microstructure to improve fatigue life in current used alloys or potential future lower cost ones. The ideal idler gear for processing for Cummins to improve power density and overall performance in one of their largest engine systems would have been for a ~280-mm (~11-inch) gear but currently no TMP systems exist worldwide. A brief discussion of viable, commercially-robust systems proposed by commercial superconducting magnet manufacturers to Cummins

that could handle that gear size will be discussed later in this report.

For the idler gear application, a nominally 6-inch diameter (155.9 mm) gear was initially considered for processing in ORNL's ~8-inch diameter bore, commercial prototype system. An existing insert that was designed and built for an earlier project and that had an ID slightly larger than the gear OD. As can be seen in Figures 3 through 5, a relatively large chamber volume seemed viable to accommodate the idler gear although it would have been tight, and would have required modification of the sample holding component. However, electromagnetic coupling simulations by staff at AjaxTOCCO (who designed and built that insert) showed that the idler gear could not be successfully processed in this insert. In addition, the ~8-inch diameter magnet bore was determined not sufficiently large enough to facilitate a new, alternate insert design to process the idler gear without possible danger of inductively coupling to the magnet bore itself (because of the extremely close proximity of the inductor coil to the magnet ID) which would cause catastrophic failure of the superconducting solenoid magnet coil. Unfortunately at this time too, the cryocooler system components for the commercial prototype had reached their design limit (exceeded their life cycle for maintenance replacement) and were becoming inefficient at maintaining the superconducting magnet coil at the required near liquid helium temperatures. So, that magnet system was sent back to the manufacturer for cryocooler replacement mandating that one of ORNL's smaller (5-inch diameter warm-bore) superconducting magnet systems be considered for smaller component processing for the project duration.

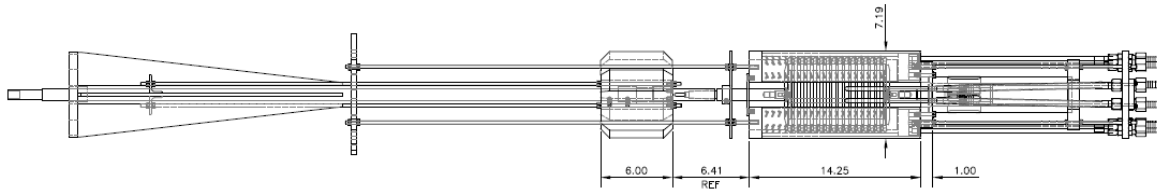


Figure 3 Schematic of an existing induction heating design with integral quench system used in an earlier project was considered to do the idler gear.

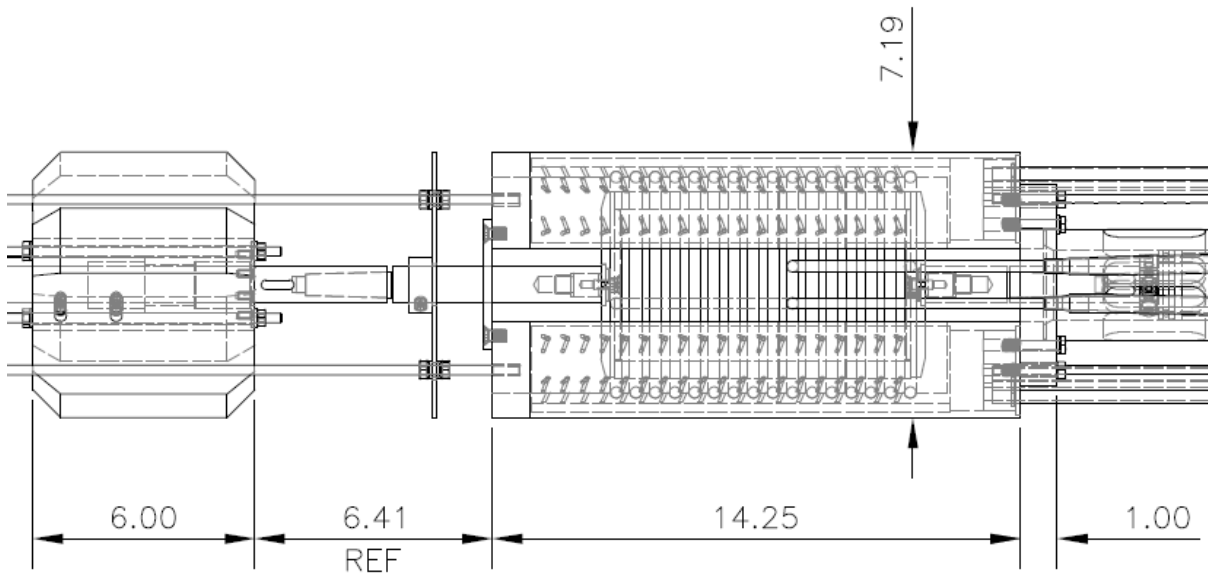


Figure 4 An enlargement of the sample chamber inside the integral induction heating-quenching insert used in a prior project.

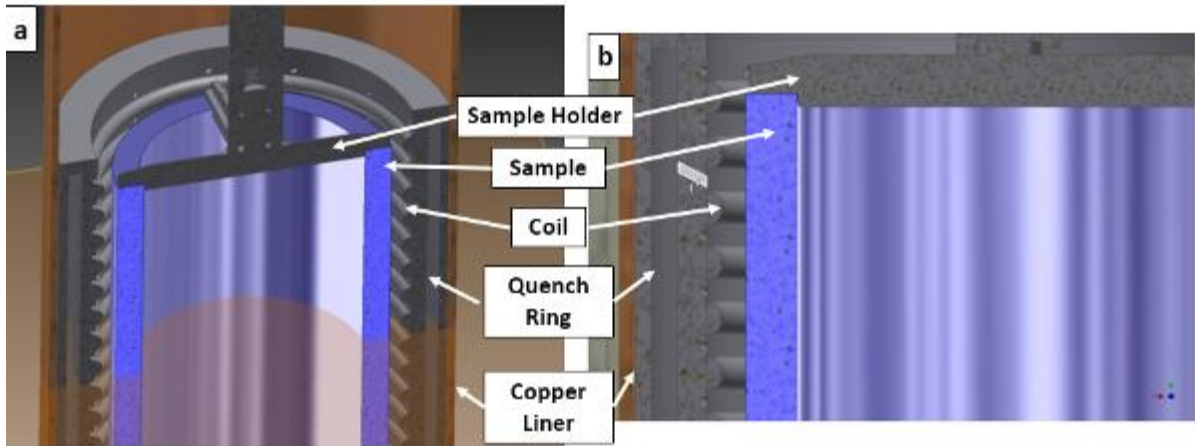


Figure 5 Cross-sectional rendering of the sample chamber where the idler gear was initially felt could be thermomagnetically processed.

Since thermomagnetic processing would initially have the biggest impact on some of the larger idler gears as mentioned earlier an ~9-inch (~230 mm) gear was considered. The project team of Cummins, ORNL, and AjaxTOCCO (informal partner) started pursuing potential procurement opportunities of possible industrially robust, commercial-scale superconducting magnet systems available in the marketplace that would be suitable for this thermomagnetic processing application.

Very favorable responses were obtained by AjaxTOCCO from three technology leaders in the superconducting magnet manufacture field: American Magnetics, Inc. (AMI), Cryogenics Limited, and Cryomagnetics Inc. Figure 6 shows the design suggested by AMI, Inc. for a cryocooler-based (requires 3 cryocoolers), 9-T, 15-inch (381 mm) diameter warm-bore superconducting system. This design is very similar to the ~8-inch, 9-T commercial prototype system currently at ORNL that was built by AMI. The design suggested by Cryogenics Limited is shown in Figure 7 and is for an 8-T, 16-inch (400 mm) diameter warm-bore system and has the added advantage that it is cryogen-free. The system is conduction cooled and will not require liquid helium cryogenics for operation. From a lower operational cost and liquid helium availability issue this feature is extremely advantageous over other approaches (even cryocooler systems that constantly recondense the initial liquid helium supply and therefore does not require refilling with liquid helium after the initial amount) to keep superconducting coils at their required cryogenic temperatures. The Cryomagnetics Inc. system proposed was a 16-inch diameter warm-bore, 8-T cryocooler-based superconducting system. The first two designs were for shielded magnets to dramatically reduce the stray magnetic fields surrounding the magnet system which is essential for more ease of operation and worker safety. The Cryomagnetics system was proposed as non-shielded.

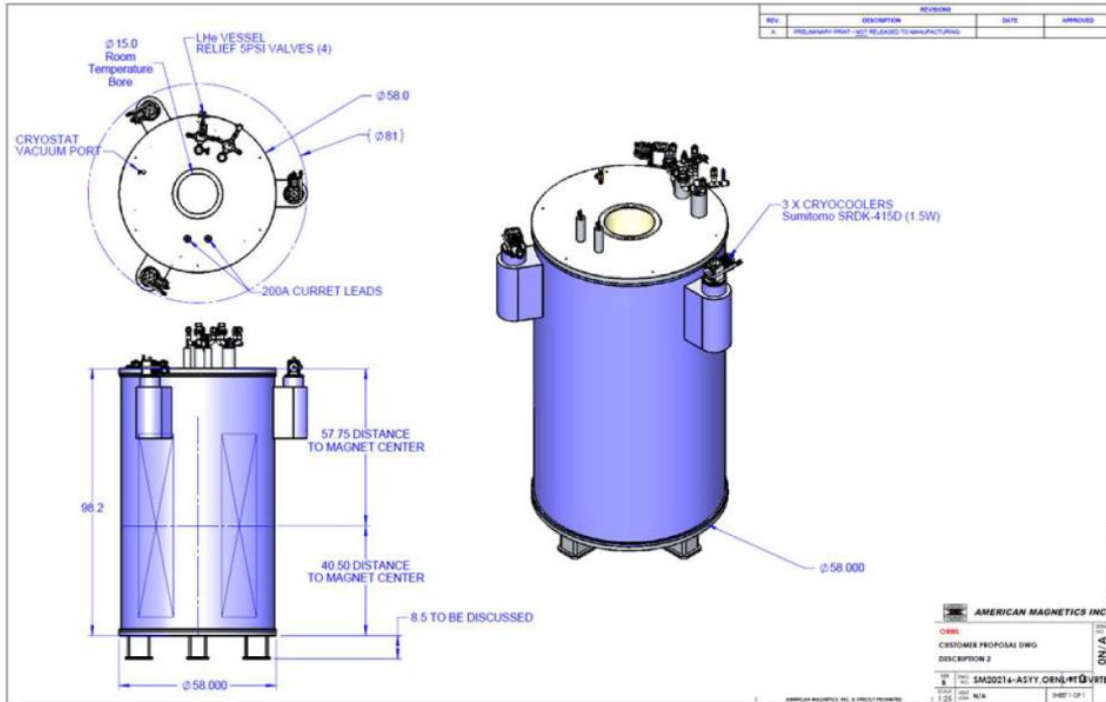


Figure 6 Concept drawing provided by AMI, Inc. for a 9-tesla, cryocooler-based, 15-inch (381 mm) diameter warm-bore superconducting magnet system.

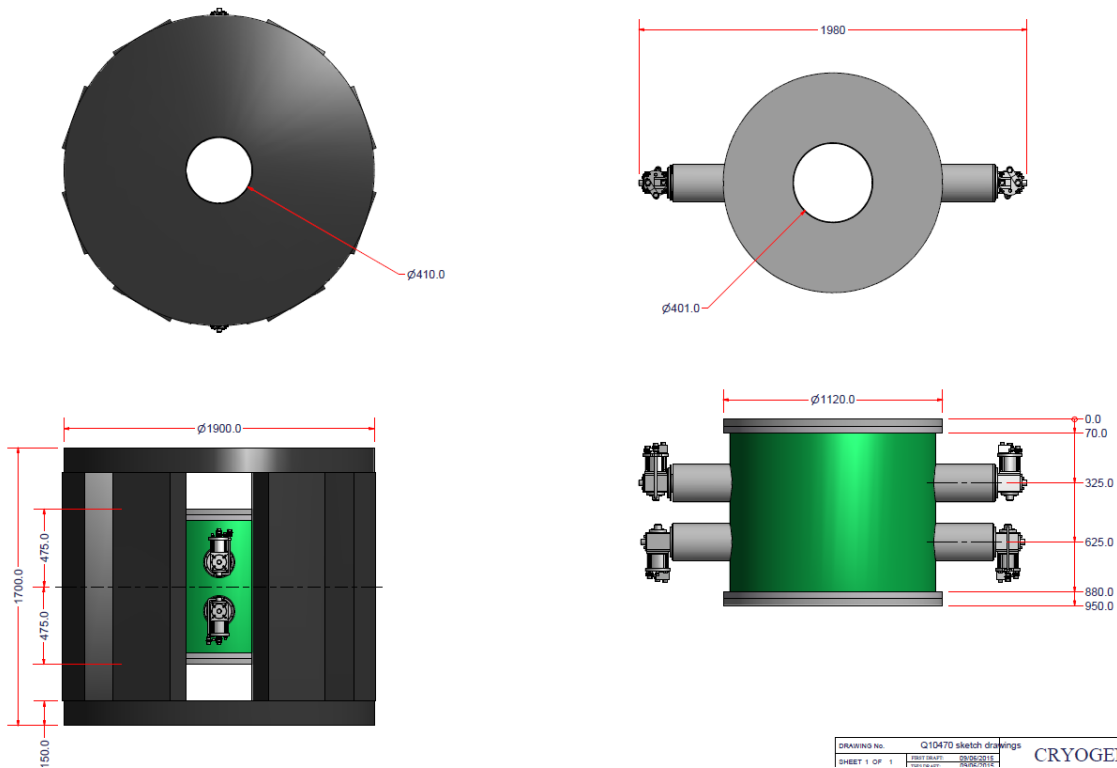


Figure 7 Concept drawing provided by Cryogenic Limited for an 8-tesla, cryogen-free (conduction cooled) 16-inch (400 mm) diameter warm-bore superconducting magnet system.

1.2.2 Crankshaft Application

As was mentioned earlier, improving the performance of crankshafts through thermomagnetic processing would decrease the mass of the crankshaft, which would have a positive input on acceleration, requiring less energy in transient operations, which would improve fuel economy as well. Also, the amount of energy consumed in production of the crankshaft would also decrease with the reduction in mass, decreasing energy requirements by melting, forging, heat treating and machining less material.

Therefore, several crankshafts were considered for this study and two candidates were evaluated. The first was for a nominal 5.2-inch “cylinder diameter” crankshaft that a partial segment would have been machined from it so as to fit in the 9-inch uniform field zone of the ORNL magnet system and be processed and subsequently bending fatigue tested in one of Cummins’ test beds. A 2.8 L engine crankshaft where main-pin-main sections could be processed were also considered. For these parts to fit into an insert and into the magnet bore, the counterweights would have to be cut-off. Although the 8-inch commercial prototype magnet system was at the manufacturer for maintenance (replacement of cryocoolers) and repair (replacement of a superconducting solenoid coil protection circuit diode), that system is the only one at ORNL that has an integral quench capability which would be required for the thermomagnetic heat treatment to be successful. The intent was to develop a suitable crankshaft sample, design and fabricate a custom induction heating/quenching insert and thermomagnetically process these samples once the magnet came online again.

Several issues prevented pursuing this task to a successful completion. First, even with removing the counterweights, the effective crankshaft segment diameters would have been too large to fit inside a custom-designed insert that would be able to integrate into the 8-inch bore magnet. Second, the experts at AjaxTOCCO, who would have designed and built a custom induction heating and quenching insert, stated that the prior conventional approach of using an encircling induction heating coil (for axisymmetric parts) would not work to harden the fillets. They stated that it must be a 180-degree coil that requires the crankshaft to rotate during the hardening process. They further commented that to harden an eccentric crankshaft pin would require a rotary current connection within the bore of the magnet and that would not have been economically feasible for the project. Third, those experts further commented that the ORNL 200 KW induction heating power supply system was not sufficient to surface harden a 5-inch diameter camshaft but perhaps a smaller 3-inch diameter part would be viable. This project thrust could not proceed forward based on those considerations plus the issue that the ORNL 8-inch commercial prototype is not scheduled for return from the manufacturer after the maintenance and repair operations are completed until the end of September 2017. That magnet is anticipated to be operational by the end of October 2017 once it goes through the two-week cryogen filling procedure to get to the steady state superconducting operational condition. The potential commercial systems with warm-bore diameters of >15-inches discussed earlier are anticipated to be able to handle these applications provided the magnet system was sufficiently designed to have the required uniform magnetic field length zone to encompass the entire crankshaft.

1.2.3 High Performance Engine Valve Springs

Given the equipment constraints described above, Cummins suggested evaluating a high performance engine valve spring application (Figure 8) for thermomagnetic processing to improve high cycle fatigue life in the nitrided 9254 alloy steel component. This component is given a custom heat treatment and receives a final nitriding processing cycle to provide an extremely hard surface. Cummins staff performed metallography on one of these springs and Figure 9 depicts a microstructure of fine tempered martensite. The nitrided layer (thin light gray layer on top of micrograph) on this one example was discontinuous rather than the desired continuous condition. The nominal chemistry of this alloy is given in Table 1. To

determine the relative impact of thermomagnetic processing on the microstructure evolution, and therefore subsequent performance for this spring application, the path forward on this application was to do fundamental phase transformation characterization experiments both with and without a high magnetic field in the ORNL 5-inch diameter, vertical warm bore 9-T superconducting magnet with its DTA/DSC (differential thermal analysis/differential scanning calorimetry) insert. Figure 10 shows that magnet system as viewed from the top working platform. The goal of these experiments was to evaluate DTA plots to determine any path optimization using different processing temperatures with high magnetic fields.



Figure 8 Representative example of a nitrided high performance 9254 alloy steel engine valve spring



Figure 9 The microstructure of this commercially heat treated and nitrided 9254 alloy steel spring is shown fine tempered martensite with a discontinuous nitride layer (thin light gray layer at top of micrograph).

Table 1 Nominal Chemistry (in weight percent) for the 9254 Steel Alloy (balance Fe)

C	Si	Mn	Cr
0.51-0.59	1.2-1.6	0.6-0.9	0.6-0.8



Figure 10 ORNL's 5-inch diameter vertical warm bore, 9-T superconducting magnet system typically used for more fundamental research incorporating a DTA/DSC system.

The experimental plan for the thermomagnetic processing DTA experiments, the current complete heat treatment and nitriding cycle used for these high performance valve springs is shown here:

High Performance Valve Spring Heat Treatment Procedure:

Austenitization Temperature: 923°C

Cool to 176C (they do a salt bath to salt bath quench from 923°C to 126°C)

Raise temperature to Temper: 316°C

Tempering time: 30 minutes

Nitriding temperature: 374°C

Nitriding time: 48 hours

The DTA experiments were conducted with the following experimental procedure. First, 9254 alloy steel cylinders 5 mm diam. X 5 mm high were weighed and inserted into platinum crucibles. The steel specimens were mass balanced using another platinum crucible filled with pure Alumina. The sample and reference were placed on the DTA holder. The work head and DTA sensor were lowered into the magnet insert which contains the susceptor and is sealed on both ends with gas inlet/outlet ports. A vacuum was pulled to below 100 mTorr and the insert was then backfilled with Argon, which continually flowed throughout each experiment. For the field cases, the magnet was ramped to 9 Tesla prior to heating. The induction furnace was ramped at 50C/minute up to 923°C and held for 5 minutes. The samples were then quenched using He gas at a regulator pressure of 10 psi. A helium gas quench was used rather than water

quenched since the DTA apparatus and sensors are extremely fragile and attempting to do a water quench would have been catastrophic to the DTA system itself. Also, the 5-inch vertical bore magnet system is not setup to do water quenches as the 8-inch vertical magnet is capable of doing with an appropriate insert. Selected helium quenched samples were reheated to either 316°C or 374°C and held for 30 minutes, then allowed to furnace cool to room temperature.

The following results summary in Figure 11 and Table 2 definitely indicates that the high magnetic field shifted the phase transformation peaks in the 9254 alloy steel to lower temperatures upon heating and higher temperatures upon cooling which is consistent with the trend noted in footnote 1. Less conclusive information is reflected in Figure 12 and Table 3 for the subsequent tempering experiments with and without a high magnetic field applied. Prior experiments (footnote 3) on other alloy systems show that high magnetic fields can dramatically reduce tempering times from 120 minutes to 10 minutes or less while achieving superior performance to conventionally processed components. One possible explanation for the inconsistency in the current tempering data is that the samples received a prior helium gas quenched before the tempering experiments which was not sufficient to completely transform the as-quenched microstructure to martensite as achievable in water or oil quenched components.

These results indicate that using a high magnetic field during the austenitization and quench heat treatment cycle impacts the martensite phase transformation start temperature. Prior research (footnote 4) shows that when this is accomplished the martensite lathes are finer and upon subsequent tempering in a high magnetic field results in a finer and more copious carbide distribution with increased yield and ultimate tensile strength without loss of ductility. If the 8-inch vertical magnet were available for validation experiments on actual springs, this potential for performance improvement could be validated and subsequent fatigue testing experiments could be conducted to get actual fatigue life data. Before those fatigue experiments would be conducted the quench and tempered springs would need to receive their final standard nitriding heat treatment cycle. Of potential benefit for that final operation, prior research at ORNL has shown through the Zeeman effect that high magnetic fields dramatically make nitrogen-based gaseous environments more chemically reactive (footnote 5) and would be anticipated to have a beneficial impact on the nitriding process as it did in the accelerated synthesis of Fe₁₆N₂ iron nitride from elemental iron powders and a nitrogen purge while at temperature while in a high magnetic field environment.

3 “Prototyping Energy Efficient Thermo-Magnetic & Induction Hardening for Heat Treat & Net Shape Forming Applications”, Eaton project final technical report for Award DE-FG36-08GO18131, July 30, 2013, Eaton principal investigator Aquil Ahmad, Report file designation: “GO 18131 Eaton Final Technical Report”.

4 “Magnetic Field Processing – A Heat Free Heat Treating Method,” G. M. Ludtka, et al, ORNL Tech. memo, ORNL/TM-2012/78, August 8, 2012, www.osti.gov/servlets/purl/1049805/.

5 “APPLIED MAGNETIC FIELD SYNTHESIS AND PROCESSING OF IRON NITRIDE MAGNETIC MATERIALS”, M. Brady, et al, USPTO published patent application number 20150380158.

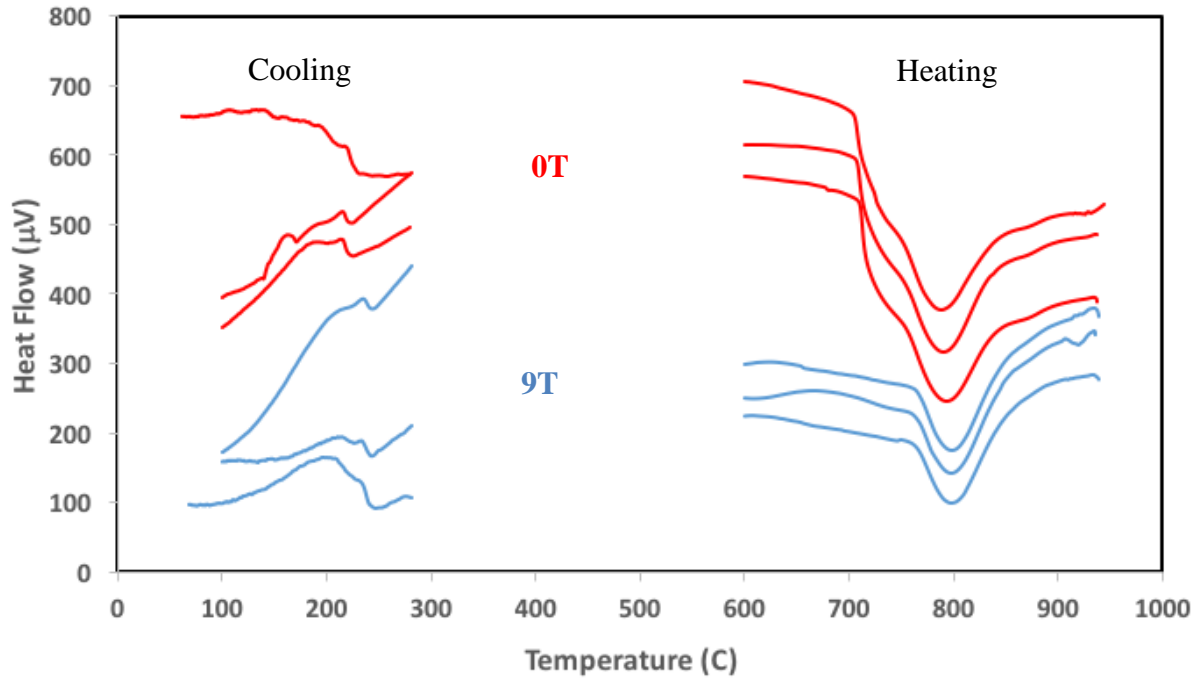


Figure 11 DTA experiment plot summary extracted from the heating and cooling experiments with and without a 9 Tesla magnetic field (summarized in Table 2).

Table 2 Summary of the transformation start temperatures upon heating (austenite start) and cooling (martensite start) with and without a 9 Tesla magnetic field for the 3 replicate runs.

	0T	9T
Austenite Start (Celcius)	704	764
	706	765
	708	763
Martensite Start (Celcius)	230	244
	224	243
	223	246

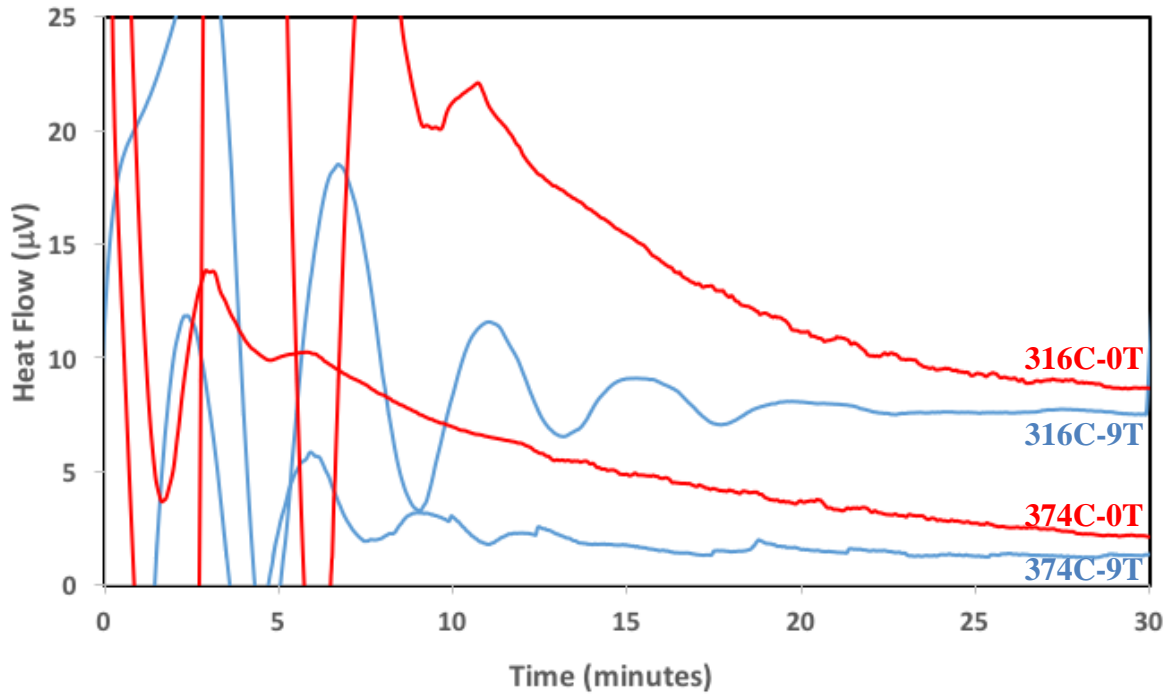


Figure 12 DTA plots for the tempering cycles at two separate temperatures with and without a high magnetic field to characterize the completion of the tempering cycle (summarized in Table 3).

Table 3 Tempering results for completion of the tempering process at two separate temperatures with and without a high magnetic field applied.

	0T	9T
316C Heat Treatment	Approximately 17 minutes into the 30 minute hold	Approximately 20 minutes into the 30 minute hold (unclear)
374C Heat Treatment	Approximately 12 minutes into the 30 minute hold	Approximately 10 minutes into the 30 minute hold

1.3 IMPACTS

During the execution of the tasks of this CRADA, the project team, along with informal partner, AjaxTOCCO Magnethermic, learned that there are multiple commercial superconducting magnet manufacturers who have the technology to design and deliver industrially robust thermomagnetic processing equipment with magnet bores up to 16-inch diameter and magnetic fields up to 9 Tesla. Prior successful EERE-sponsored thermomagnetic processing projects (see footnotes 3 and 4) had demonstrated the great potential for thermomagnetic processing. The availability of magnet manufacturers determined in this project indicates commercial viability for the technology for gears up to ~11-inch diameter and crankshafts. Perhaps the findings of this report that a commercial system is viable will help spawn a mechanism (perhaps involving multiple industrial partners who each share in the capital investment) to get this technology from its current TRL level of ~7 to the first commercial demonstration of this breakthrough energy-savings and green technology.

1.4 CONCLUSIONS

- 1.) Thermomagnetic processing was shown to shift the phase transformation temperatures and therefore microstructural evolution in the high performance engine valve spring 9254 steel alloy by applying a high magnetic field during cooling which would be anticipated to improve performance such as high cycle fatigue as demonstrated in prior projects.
- 2.) Along with the evaluated component sizes being too large for ORNL's commercial prototype ~8-inch diameter vertical warm-bore superconducting magnet system with integral induction heating and quench capability, the system unavailability due to that equipment's cryocooler maintenance requirement during this time frame prevented the demonstration of this technology on Cummins' gears and crankshafts.
- 3.) The commercial procurement viability of production scale thermomagnetic processing equipment for truck idler gears up to ~11-inch diameter and potential crank shaft applications was shown as multiple superconducting magnet manufacturing companies (in conjunction with an induction heat treating company, AjaxTOCCO Magnethermic) offered cryogen-free equipment designs to Cummins.

2. CUMMINS BACKGROUND

Cummins Inc. designs, manufactures, sells and services diesel and alternative fuel engines from 2.8 to 95 liters, diesel and alternative-fueled electrical generator sets from 2.5 to 3,500 kW, as well as related components and technology. Cummins serves customers through their network of 600 company-owned and independent distributor facilities and more than 7,400 dealer locations in more than 190 countries and territories. Cummins Inc. is organized into four distinct but complementary business segments:

Engine Segment

The Engine Segment designs and manufactures state-of-the-art diesel and natural gas powered engines for on-highway and off-highway use. The business also offers new parts and remanufactured parts and engines.

Power Systems Segment

The Power Systems Segment is a global provider of high-speed high-horsepower engines and power generation equipment, including standby and prime power generator sets, alternators, switchgear and other components. Power Systems offers engines, power generation systems, components and services, and alternative-fuel electrical generators for use in residential standby, commercial industrial, mining, marine, oil and gas, defense, data centers, telecom and healthcare applications and industries.

Components Segment

The Components Segment consists of four businesses with key technologies for delivering integrated solutions:

Cummins Filtration

Cummins Filtration designs, manufactures and distributes heavy-duty air, fuel, hydraulic and lube filtration, chemicals and exhaust system technology products for diesel and gas-powered equipment. For more information, visit the Cummins Filtration website.

Cummins Turbo Technologies

Cummins Turbo Technologies designs and manufactures turbochargers and related products, on a global scale, for diesel engines above three liters. For more information, visit the Cummins Turbo Technologies website.

Cummins Emission Solutions

Cummins Emission Solutions develops and produces various emission solutions designed to meet the highest emissions standards worldwide. For more information, visit the Cummins Emission Solutions website.

Cummins Electronics and Fuel Systems

Cummins Electronics and Fuel Systems consists of two separate product lines. The electronics product line develops engine control modules and electronics control units, software, sensors and tools. The fuel system product line designs, develops, manufactures and remanufactures both unit injector and common rail systems. For more information, visit the Cummins Fuel Systems page.

Distribution Segment

The Distribution Segment drives a comprehensive global distribution strategy and channel management. This business provides sales, service and support to our customers around the world

through the largest number of certified service and support locations of any engine manufacturer. Cummins has the technical expertise and experience to deliver fast, high-quality repairs, planned maintenance and upgrade solutions. Our local distributor locations offer a complete range of Cummins products and Cummins genuine parts – supporting parts availability and the custom engineering requirements necessary to keep customers operating 24/7. No matter where a customer's equipment operates, they will have access to one of the most capable support networks.