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

Material Fatigue Life Enhancement of Grey Cast Iron Using Magnetic Processing[1]

Cummins, Inc.

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Company Size: Large business, 46,000 employees worldwide

Summary
ORNL and Cummins, Inc. collaborated to evaluate the benefit of high magnetic field processing on cast iron properties with the ultimate goal of achieving wrought-like mechanical properties and microstructures in a cast product. The project was initially focused to quantify the magnetoplasticity effect on high cycle fatigue life. However, samples provided had superior surface finishes with no accumulated deformation damage from exposure to the application environment; therefore, no impact on fatigue life was measureable. Further experimentation indicated that thermomagnetic processing heat treatment followed by quenching of a cast iron can under some conditions result in an ~100% improvement in ultimate tensile strength for a quenched and tempered pearlitic ductile iron. Additional experimentation is now needed to provide data over a broader thermomagnetic processing parameter space to optimize this effect and provide the guidance necessary for commercial adoption of this technology.

Background
The defect structure/deformation response of materials has been shown to respond to high magnetic fields (magnetoplasticity) potentially enabling high and low cycle fatigue damage mitigation and component life extension. Significant commercial benefits would result if the magnetoplasticity effect could be exploited to increase the fatigue life of commercial grades of cast iron. This study initially aimed to do a proof of concept experiment on a typical grey cast iron, by measuring the fatigue life on a statistically significant sample via rolling bending fatigue testing after exposure to a high magnetic field prior to insertion into its intended application. Since the test samples had been precision machined, had superior surface finishes and had no accumulated deformation damage from prior exposure to the application environment, no impact on fatigue life was measured since the magnetoplasticity effect had no accumulated damage to

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eliminate or repair. Therefore this study was redirected towards another critical application directed at improving the heat treatment response of a typical cast iron through thermomagnetic processing in a 9 Tesla field.

This effort then examined the impact of an austenitization and quench heat-treatment in field and no-field conditions of a pearlitic ductile iron to produce a starting material with a significantly enhanced (>30%) quenched ultimate tensile strength prior to tempering. Achieving this goal would open up major applications of industrial interest such as cast iron crank shafts replacing forged steel crank shafts in high performance diesel engines.

Technical Results

Precision machined test coupons with no prior deformation damage accumulation indicated no fatigue life enhancement by near ambient temperature magnetic processing as shown in Table 1 for the initial magnetoplasticity study. Published data indicated treating the cast iron in a high magnetic field after some fatigue damage was present increased fatigue life. However, treating a component after some fatigue damage is present does not constitute a viable commercial process. The researchers were attempting to see if initial processing had the same effect. It did not. The study then considered another critical thrust for Cummins of more commercial interest.

Table 1 Magnetoplasticity Reversed Bending Fatigue Testing Experimental Results for Magnetically Processed Samples (200-X notations) were not statistically different from unprocessed (base) samples

BAR I.D.	Type	Loc	HBW	Mach	Test Date	Min. Dia.	Stress Target	Test Cycles	Stress Actual	Operator / Comments
R-31	base	4-2	207	224	2-05-13	0.3002	14,000	1,542,200	13.980	TJT / LE
R-41	base	4-26	197	225	2-06-13	0.3010	15,000	190,400	14,990	LE
R-33	base	4-30	207	225	2-07-13	0.3004	13,000	206,000	13,010	1.8 mm cells
R-39	base	4-18	207	225	2-07-13	0.3005	13,000	857,700	13,000	TJT / LE
R-43	base	4-17	207	224	2-07-13	0.3008	16,000	710,100	16,000	TJT / LE
R-35	base	4-14	207	225	2-08-13	0.3004	16,000	141,800	16,020	TJT / LE
R-22	200-3	4-22	207	224	2-06-13	0.3004	14,000	338,700	14,000	TJT / LE
R-24	200-5	4-19	207	225	2-06-13	0.3005	15,000	233,600	15.020	LE /TJT
R-20	200-1	4-12	207	225	2-07-13	0.3005	13,000	332,500	13,000	TJT / LE
R-28	200-9	4-16	207	224	2-07-13	0.3006	16,000	3,015,700	15,990	TJT / LE
R-26	200-7	4-24	207	225	2-08-13	0.3003	16,000	125,200	15,990	TJT / LE

For the study of the impact of the magnetic field on an austenitization and quench heat-treatment phase of the project, a series of thermomagnetic processing heat treatments were employed during various aspects of the austenitization, quench, and tempering cycle at various tempering times, temperatures and field strengths (9T or No Field) to provide a first approximation of successful processing conditions (Table 2). Ultimate tensile strengths (UTS) in ksi for processed samples and the baseline as-received condition (AR) are shown in Figure 1.

Table 2 Processing conditions and testing results for austenitization and quench heat-treated samples

Label	Solution Time (Min)	Solution Field (Tesla)	Aging Time	Aging field	Mod (Msi)	U.T.S. (ksi)	0.2%YS (ksi)	Elong. (%)a	RA (%)	Processing
ID 1	60	0	10	0	(b)	98.5	(d)	0.2	0.3(c)	900C/60min 500C/10min
ID 2	60	9	0	0	23.4	72	54.5	5	17	900C/60min
ID 3	60	0	10	9	24.4	88	(d)	0.4	0.2(c)	900C/60min 500C/10min
ID 4	60	9	10	9	23.9	72	55.5	5	18	900C/60min 500C/10min
ID 5	120	9	10	9	24.7	82	82	0.2	0.2(c)	900C/120min 500C/10min
ID 6	120	9	10	0	22.4	70.5	52	7	14	900C/120min 500C/10min
ID 7	120	0	10	9	23	208	185	1	1.8	900C/120min 500C/10min
ID 8	120	9	10	9	23.2	70	52.5	6	18	900C/120min 500C/10min
ID 9-1	10	9	0	0	22.7	39.7	(d)	0	0..0(e)	1100C/10min
ID 9-2	10	9	0	0	21.8	54.5	(d)	0	0..0(e)	1100C/10min
ID 10	10	0	0	0	21.1	49.2	(d)	0	0..0(e)	1100C/10min
ID 10-2	10	0	0	0	21.1	54	(d)	0	0..0(e)	1100C/10min
ID 11	1	9	0	0	22.3	54.5	(d)	0	0..0(e)	1100C/1min
ID 11-2	1	9	0	0	23.6	65	(d)	0	0..0(e)	1100C/1min
ID 12	30	9	0	0	22.2	48.9	(d)	0	0..0(e)	1100C/30min
ID 12-2	30	9	0	0	24.3	42.3	(d)	0	0..0(e)	1100C/30min
ID 12-3	30	9	0	0	21.5	39.2	(d)	0	0..0(e)	1100C/30min
AR	AR	AR	AR	0	23.7	92	57	7	6.0(c)	AR
Notes	(a) Value based on overall length measurements.									
	(b) Computer malfunctioned when specimen failed; Digital test data was lost.									
	(c) Specimen failed at/in the radius.									
	(d) Specimen failed before 0.2% yield was obtained.									
	(e) Specimen failed in the threads.									

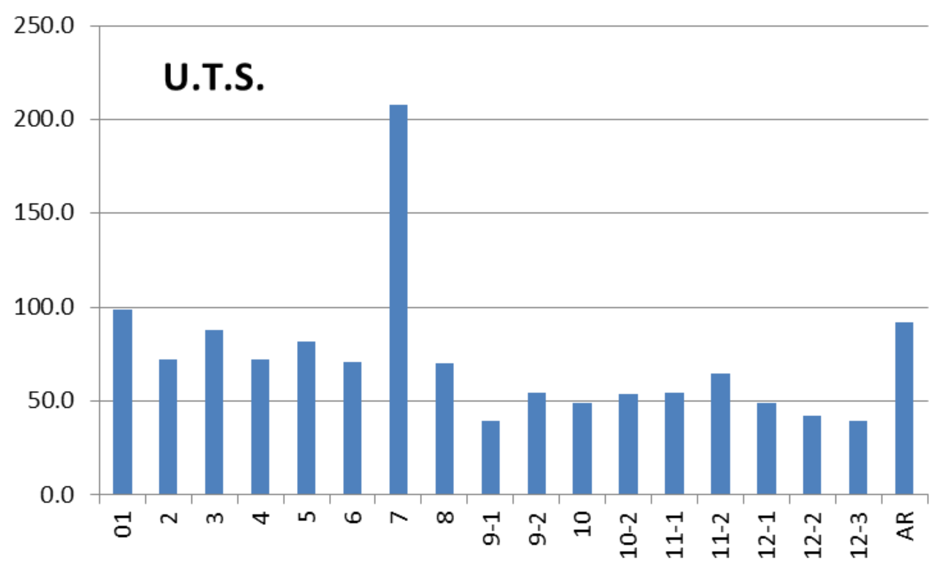

Figure 1. Ultimate tensile strength for various samples of a pearlitic cast iron with and without high magnetic field processing during various sequences of the austenitization, quench, and tempering process.

Of the samples processed, #7 exhibited the most significant improvement due to thermomagnetic processing. Samples #5 and #7 received the same thermal processing cycle of 900°C for 120 minutes followed by a water quench and then tempered at 500°C for 10 minutes, but the tempering cycle for sample #7 was done in a 9 Tesla field environment using the ORNL 8" diameter vertical bore magnet. Sample #7 achieved an ultimate tensile strength (UTS) of 208 ksi (and a yield strength of 185 ksi with 1% elongation) compared to the no-field case (#5) that exhibited only an ~82ksi UTS (and a YS of nominally the same 82 ksi since it only had 0.2% elongation). The AR material had a 92 ksi UTS and 57 ksi YS with a 7% elongation. So, a high magnetic field environment during tempering was able to achieve >100% increase in UTS over the AR condition.

Also of interest is the fact that sample #7 drifted to a higher temperature during the austenitization process than sample #5, which might be indicative of more carbon dissolution in the austenite phase (induced by the high magnetic field enhanced solubility effect and the higher temperature combination) that would result in higher strength after the remainder of the heat treatment cycle. Thermomagnetic field processing has been shown in the literature for steel to appreciably change the carbon diffusivity in austenite in one temperature range while it has minimal impact at higher temperatures for the same alloy (Hao and Ohtsuka, 2005). This has been hypothesized that it might be due to possible change in ratio of ferromagnetic to antiferromagnetic quantum states in the austenite phase under these conditions. This earlier published result and the limited results of this collaboration both indicate that high magnetic field processing of cast irons has the potential for significant property improvements, opening up many industrial applications to the use of cast iron in replacement of more expensive steel components. [i]

The optical micrograph in Figure 2 shows new graphite formation along the grain boundaries as a result of the particular magnetic processing treatment (Sample 4: 900°C for 60 minutes in 9 Tesla, water quenched, tempered at 500°C for 10 minutes at 9 Tesla). Typically the graphite morphology in cast irons is established during the solidification process and so this is a new finding for cast irons.

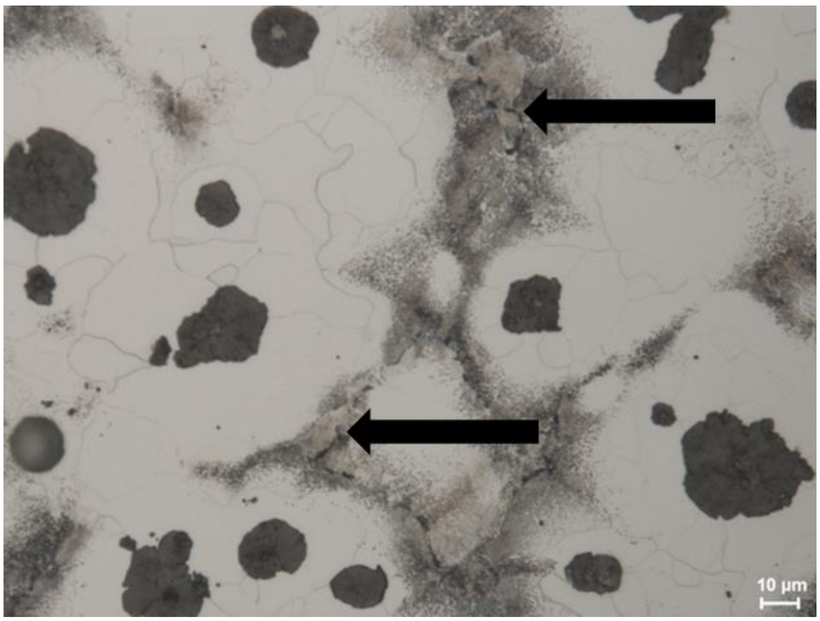

Figure 2. Evidence of new graphite formation (arrows) along grain boundaries is evident as a result of this thermomagnetic processing sequence.

Impacts

Adoption of this technology could lead to cost reductions and energy savings in the use of cast vs. forged parts. Crankshafts currently used in high performance diesel engines are made from an energy intensive process using forged steels whose properties are optimized for strength, ductility, and with minimum defects for high reliability. A less energy intensive alternative to forged crankshafts are components that are cast into the right shape with minimum machining. However, cast crankshafts made of ductile cast irons available today do not possess the required performance metrics. Ductile iron crankshafts will become an attractive alternative if the limitations of strength and reliability can be overcome using alternate processing techniques.

This MDF collaboration indicates the possibility of overcoming these limitations by synergistically coupling high magnetic fields with traditional heat-treatments to modify either the matrix microstructure or the nodule content (or both) for a given composition that is designed to produce pearlitic ductile iron. If proven to be feasible, then cast iron microstructures can be manipulated to obtain the optimum combination of castability, strength, ductility, and reliability at lower cost, thus allowing their use to manufacture lower-cost, high performance, cast crankshafts. This initial discovery, supported by additional data, could significantly contribute to improved manufacturing competitiveness for the U.S. in the light and heavy-duty automotive market.

Conclusions

The goal of this collaboration was successfully achieved by obtaining at least a 30% improvement in UTS over the as-received condition for a pearlitic cast iron material, as one thermomagnetic processing test yielded a >100% increase in UTS. In addition, limited microstructural evaluation indicates that high magnetic fields alter the as-cast microstructure in that new graphite formation along grain boundaries was observed which may reflect enhanced carbon dissolution during the austenitization cycle under a 9 Tesla magnetic field.

These preliminary results are based on a very limited number of experiments, but indicate that further work is needed to provide statistically significant data, and to cover a much broader processing parameter space of temperature, magnetic field strength, and time (to quantify the heat treatment kinetics acceleration). Also, since this study suggests current predictive models underestimate the shift in transformation temperatures that can be achieved in ferromagnetic materials such as cast iron, the phase transformation temperature prediction model needs to be improved.

Commercial viability and cost-effectiveness of implementing thermomagnetic processing of cast irons to replace wrought steel for higher performance applications such as crankshafts needs further quantitative evaluation for technology adoption.

About the Company

Cummins Inc., headquartered in Columbus, Indiana, is a global leader in the power industry that designs, manufactures, distributes and services engines and related technologies.

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[i] Hao, X., and Ohtsuka, H. (2005). “Phase transformation and diffusion in Fe-C alloys in a high magnetic field”. Electromagnetics in Materials Processing, Materials Science and Technology 2005 Conference and Exhibition: pages 127-134