A COMPARISON OF ANCORDENSE™ PROCESSED MATERIALS WITH MALLEABLE CAST IRON

Arthur J. Rawlings & Francis G. Hanejko
Hoeganaes Corporation
Cinnaminson, New Jersey 08077

ABSTRACT

A study was conducted that compared the mechanical properties of a series of ANCORDENSE prepared materials with malleable cast iron. This paper will present the mechanical properties (TRS, tensile, impact, and fatigue) of various ANCORDENSE prepared premixes in the as sintered condition compared with a malleable cast iron. The objective of this investigation was to demonstrate that an engineered P/M material coupled with ANCORDENSE processing can replace a malleable cast iron component giving equivalent mechanical property performance and potentially equivalent gear performance.

INTRODUCTION

The introduction of warm compaction processing enabled P/M part producers to make single press / single sinter components with sintered densities approaching that of double press / double sinter (DP/DS) components.(1) Displacing existing DP/DS parts proved more difficult than first expected, because of the existence of installed manufacturing capability and the need to recertify the warm compacted replacement component. However, warm compaction to high sintered densities is a proven technique for the economical production of high performance P/M parts to replace wrought steel components.(2) In particular; complex, multi level components made via casting or forging with extensive secondary machining are viewed as prime opportunities.

High strength cast irons are used in applications that require tensile strengths of <150,000 psi (1035 MPa) with minimal elongation and impact toughness requirements. Two methods of producing high strength cast irons are the malleable cast iron process and the ductile cast iron process. Malleable cast iron is initially produced as white cast iron with a lower carbon content, heat treated to covert the carbon containing phase from iron carbide to a nodular form of graphite called temper carbon.(3) The heat treatment cycle for malleable cast irons consists of heating the white cast iron to ~1700°F (925°C) up to 20 hours followed by rapid cooling to ~1400°F (760°C), then subsequent slow cooling to room temperature.(3) Ductile or nodular cast iron contains higher carbon levels and is treated with a nodulizing agent to promote the nodular graphite form in the as cast condition.(4) The process of producing complex gearing via the casting process involves casting the blank, followed by machining, any heat treatment of the gear as required, plus any finish machining after heat treatment. Although the cost of the raw material utilized in castings is low in comparison with P/M materials, the extensive heat treating and machining make these components ideal candidates for P/M technology. P/M processing minimizes the secondary machining giving a near net or net shape component; thus offering a potential cost savings.

The recent interest for greater P/M utilization within the automotive industry posed the question about the suitability of single pressed high density P/M components with complex geometries as replacements in high strength cast iron gearing applications. Shown as Figure 1 are the yield and tensile strengths of several commonly used wrought gearing materials along with two ANCORDENSE processed materials premixed with 0.6 w/o graphite. This preliminary literature review suggested that ANCORDENSE processed materials were potential candidates for the replacement of high strength cast iron gears.

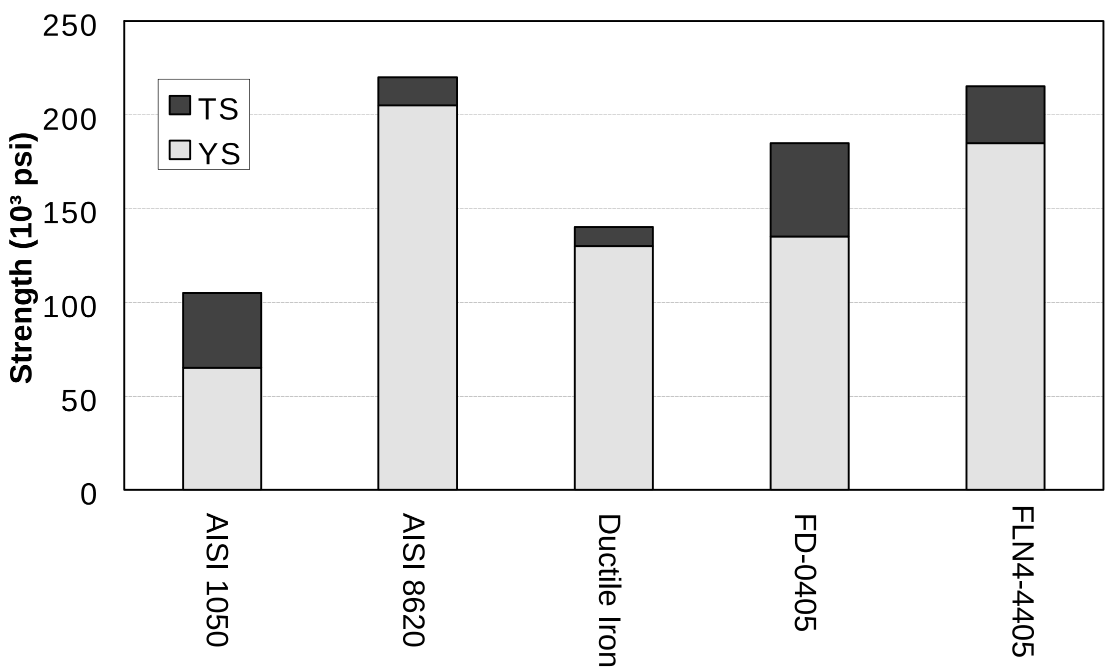

Figure 1: Comparative strength data of various wrought and ANCORDENSE processed materials.

This study was initiated to investigate the mechanical properties of a range of high performance P/M materials single press/single sinter processed warm compaction to achieve maximum part density. The materials chosen were premixes of Ancorsteel 85 HP with various amounts of nickel and copper plus an MPIF FD-0405 diffusion alloyed material. Samples of a malleable cast iron were obtained after the malleable heat treatment process and subsequently machined into tensile, impact, and fatigue specimens.

MATERIALS AND SAMPLE PREPARATION

Several premix compositions were chosen to compare their as sintered properties with those of the cast iron. Each premix composition was produced via the ANCORDENSE premixing process with 0.6 w/o lubricant; the compositions are shown in Table I.

Table I
ANCORDENSE Premix Compositions Evaluated

Premix ID	Base Iron	Ni, (w/o)	Cu, (w/o)	Mo, (w/o)	Graphite (w/o)
A	Ancorsteel 85 HP	4.0	0	0.85*	0.60
B	Ancorsteel 85 HP	3.0	0.75	0.85*	0.60
C	Ancorsteel 85 HP	2.0	1.0	0.85*	0.60
D	FD-0405	4.0	1.50	0.50	0.60

* Prealloyed in base iron

Test specimens were compacted at compacting pressures ranging from 30 to 50 tsi (415 to 690 MPa) utilizing the ANCORDENSE process (a powder preheat of 280°F (138°C) with a die temperature of 300°F (149°C)). Compressibility, sintered density, transverse rupture strength, impact and tensile properties were evaluated. Sintering was performed in a laboratory pusher furnace at either 2050°F (1120°C) or 2300°F (1260°C) in a 75 v/o H_2 / 25 v/o N_2 atmosphere. The sintering time for both sintering temperatures was thirty minutes at temperature..

Tensile, impact and rotating bending fatigue properties, in the pearlitic malleable and heat treated condition, were developed for a pearlitic malleable cast iron, by machining the test specimens from cast "505" tensile specimens. Heat treatment of the malleable cast iron consisted of heating the specimens to 1750°F (954°C) for one hour followed by oil quenching and tempering at 1200°F (677°C) for one hour. The typical composition of the castings used is shown in Table II.

Table II
Typical Chemical Analysis for the Malleable Cast Iron

Carbon (w/o)	Silicon (w/o)	Sulfur (w/o max.)	Manganese (w/o)	Phosphorus (w/o max.)
2.55	1.40	0.12	0.45	0.05

RESULTS

The compressibility of the four P/M materials is shown as Figure 2. The ANCORDENSE FLNX-4405 processed materials demonstrated higher compressibility at lower compaction pressures relative to the FD-0405. At the 50 tsi (690 MPa) compaction pressure all materials gave ~ 7.3 to 7.33 g/cm³ green density, approximately 98% of the pore-free density of these materials. Sintering the four materials at 2050°F (1120°C) produced sintered densities as shown in Figure 3. Material A (FLN4-4405) with the 4 w/o premixed nickel showed the highest sintered density, while those materials with additions of copper exhibited growth during sintering and subsequently lower sintered density. Sintering at 2300°F (1260°C) resulted in higher density relative to sintering at 2050°F (1120°C). The higher sintering temperature produced a uniform microstructure with corresponding increased apparent hardness.

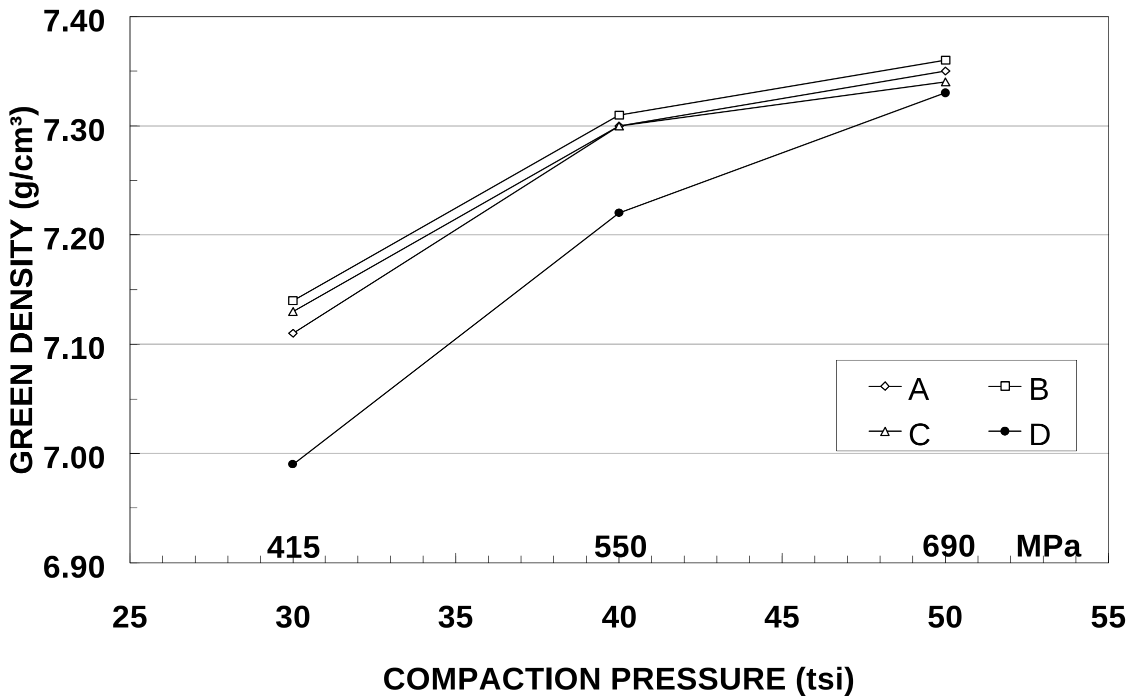

Figure 2: Compressibility of the four materials evaluated.

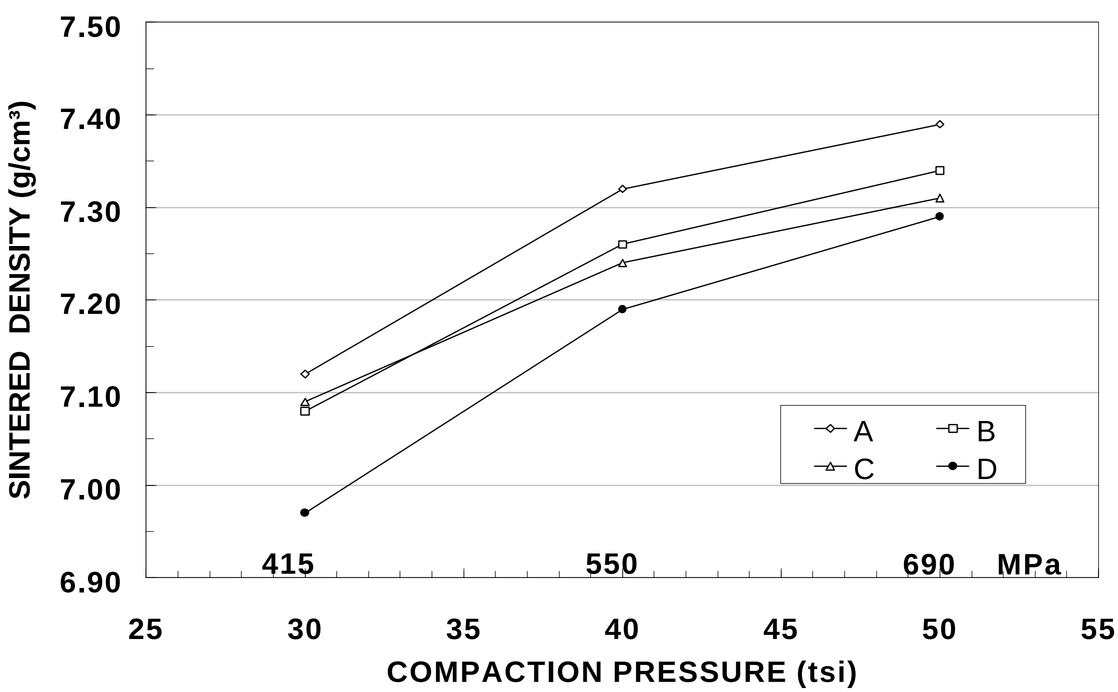

Figure 3: Sintered density of the materials tested with 2050°F (1120°C) sintering in a 75v/o hydrogen and 25v/o nitrogen atmosphere.

The dimensional change of the four materials after sintering at both 2050°F (1120°C) and 2300°F (1260°C) is presented in Table 3. Material A with the 4 w/o premixed nickel gave a 0% dimensional change after sintering at 2050°F (1120°C) and a -0.16% dimensional change after sintering at 2300°F (1260°C). Consequently, this material produced the highest as sintered density of the four P/M materials evaluated. Material B showed a -0.01% dimensional change after sintering at 2300°F (1260°C).

Table 3
Sintered Dimensional Change (from Die) for the Premix Compositions compacted at 50 tsi (690 MPa)

Material	2050°F (1120°C)	2300°F (1260°C)
A	0.00%	-0.16%
B	+0.17%	-0.01%
C	+0.23%	+0.10%
D	+0.26%	+0.07%

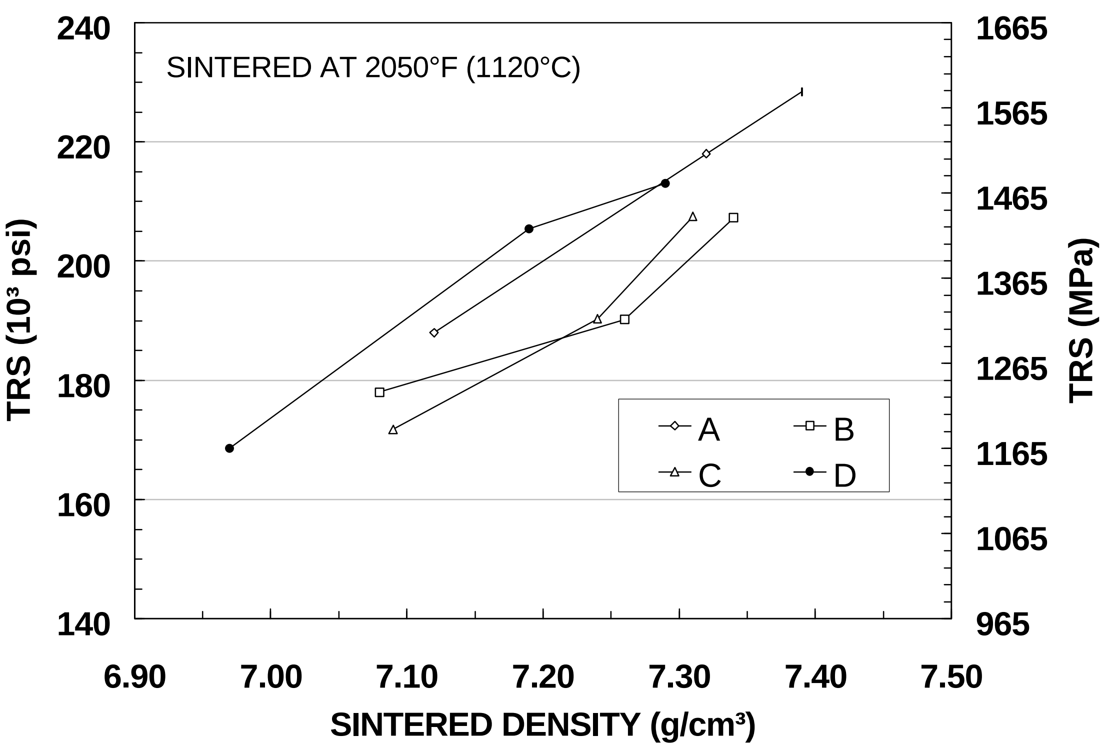

Figure 4: Sintered transverse rupture strength of the 4 ANCORDENSE materials sintered at 2050°F (1120°C).

Sintered transverse rupture strength test results are presented in Figure 4. Testing of the ANCORDENSE prepared material was done in the as sintered condition and the results are shown as a function of the sintered density. No TRS testing was done on the malleable cast iron because the tensile elongation of this material exceeded 3%.(5) The maximum TRS strength obtained from the P/M material was the Ancorsteel 85 HP material premixed with 4 w/o added nickel in the as sintered condition; a value of > 220,000 psi (1515 MPa) was achieved. The FLN4-4405 produced nearly identical TRS strengths as the FD-0405 material at the lower sintered densities. However, the FLN4-4405 sintered to a higher density resulting in higher TRS strength at the 50 tsi (690 MPa) compaction pressure. Ancorsteel 85 HP with nickel and copper additions showed a lower sintered TRS than the FD-0405.

Yield and tensile strengths of the four P/M materials plus the malleable cast iron are presented in Figure 5 (sintered at 2050°F (1120°C)) and Figure 6 (sintered at 2300°F (1260°C)). The cast iron values were evaluated in both the pearlitic malleable condition plus the heat treated condition. Heat treating was done to raise both the hardness and tensile properties of the cast iron to the levels commonly specified for this material. The specification for this cast iron is a minimum yield strength of 80,000 psi with a minimum tensile strength of 100,000 psi (690 MPa). In the as cast condition the hardness was approximately 20 HRC; in the heat treated condition, the hardness was raised to approximately 28 HRC (mid range of the specification). All the P/M tensile values in Figures 5 and 6 are in the as sintered condition after compaction at 50 tsi
(690 MPa). Tensile properties for Material C were not measured for a sintering temperature of 2300°F (1260°C). This data shows that the materials chosen gave equal or better tensile performance than the cast iron in the pearlitic malleable condition.

Heat treating the cast iron raised the yield strength to ~100,000 psi (690 MPa) and the tensile strength to ~130,000 psi (896 MPa). The P/M materials sintered at 2050°F (1120°C) exhibited lower yield and tensile strengths compared with the heat treated cast iron. Sintering at 2300°F (1260°C) increased the yield and tensile strengths of the P/M materials to the extent that Material A is nearly identical to the heat treated cast iron. Higher tensile properties could be obtained if the P/M materials were given an accelerated cooling after the sintering cycle.

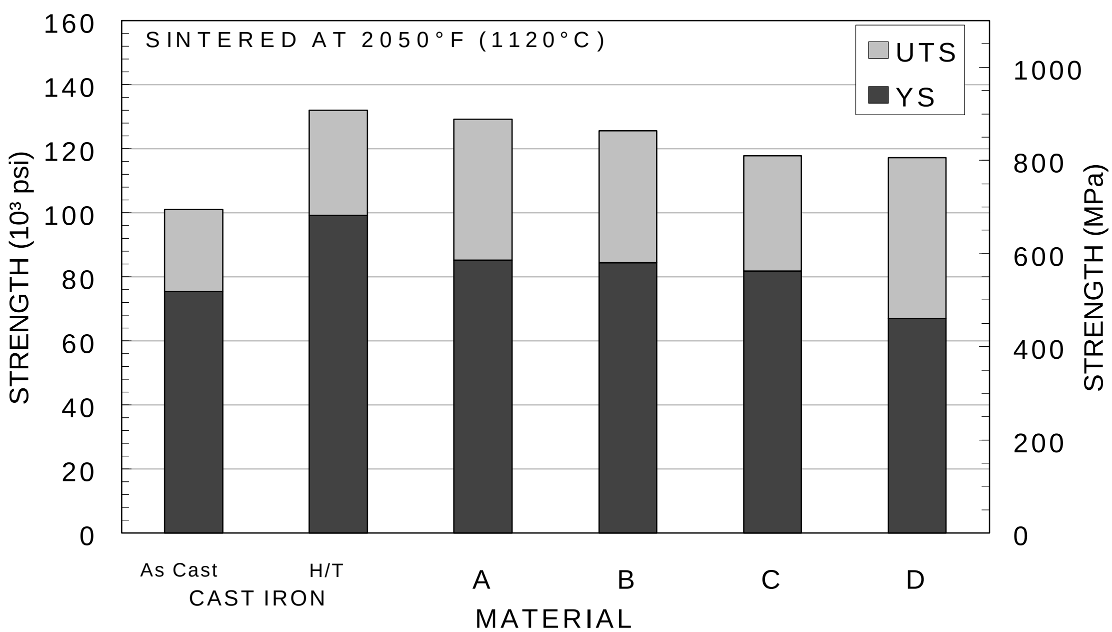

Figure 5: Yield and tensile strengths of the cast iron material and ANCORDENSE processed materials with a 2050°F (1120°C) sintering condition.

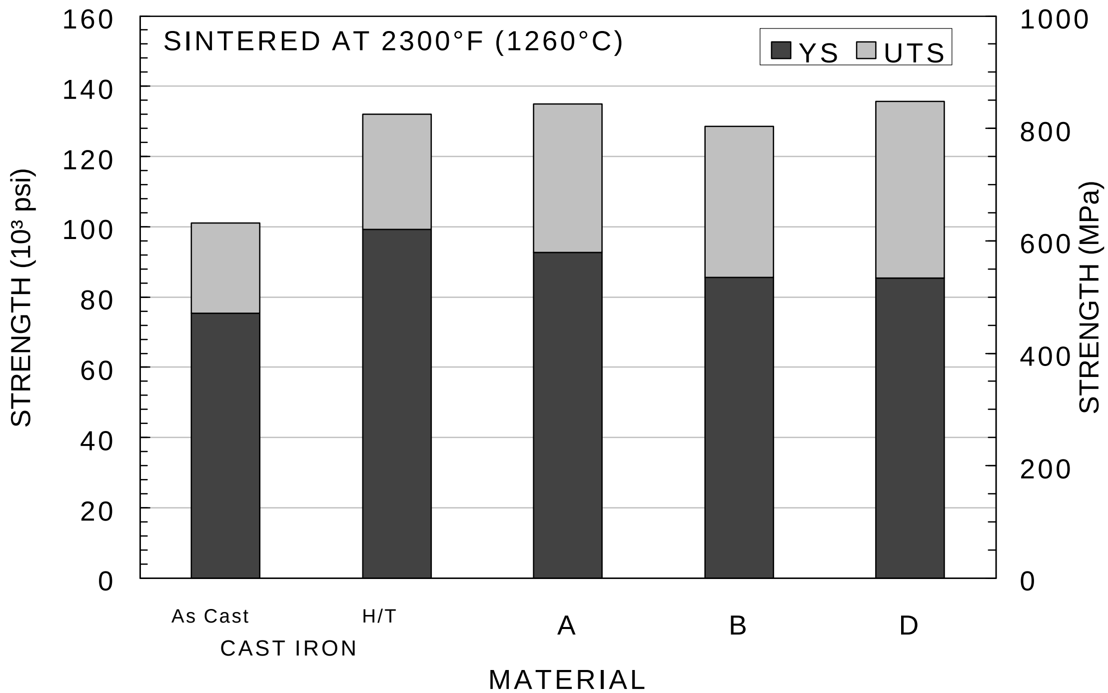

Figure 6: Yield and tensile strengths of the cast iron material and ANCORDENSE processed materials with a 2300°F (1260°C) sintering condition.

Tensile elongation values of the cast iron plus the four candidate P/M materials are presented in Figure 7. Each of the P/M materials exhibited a tensile elongation of >2% after sintering at 2050°F (1120°C). Raising the sintering temperature to 2300°F (1260°C) generally lowered the tensile elongation. This lower elongation is a result of the greater homogeneity of the alloying additions and subsequently higher sintered apparent hardness (Table 4). The as received cast iron gave ~8% tensile elongation but heat treating to increase the yield strength lowered the tensile elongation to ~4%. Elongation values of the P/M materials are below that of the cast iron in both the as cast and heat treated condition. The only way to raise the elongation while maintaining the strength is to increase the density of the P/M part. Experimental work is underway to address this issue; it does require either lowering of the lubricant level or lowering the graphite level to raise the pore-free density of the material.

Table 4
Sintered Hardness Results for Tensile Properties compacted at 50 tsi (690 MPa)

	Hardness		
Material	**Cast Iron**	**2050°F (1120°C)**	**2300°F (1260°C)**
As Cast	20 HRC		
Heat Treated	28 HRC		
A		25 HRC	27 HRC
B		25 HRC	26 HRC
C		21 HRC	
D		97 HRB	30 HRC

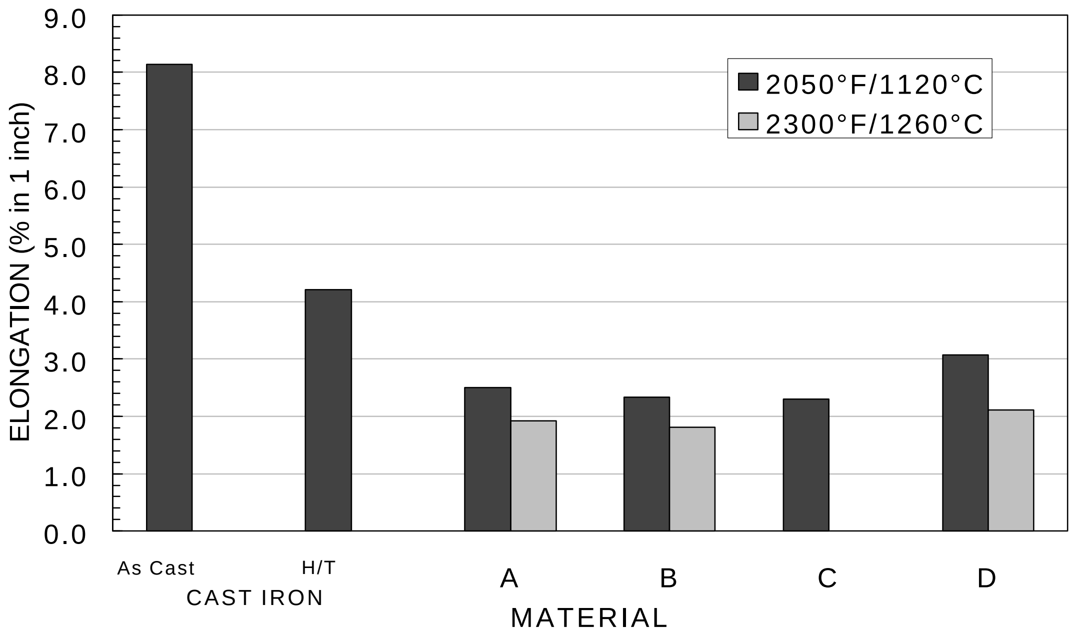

Figure 7: Tensile elongation of the cast iron and P/M materials is the as-sintered condition.

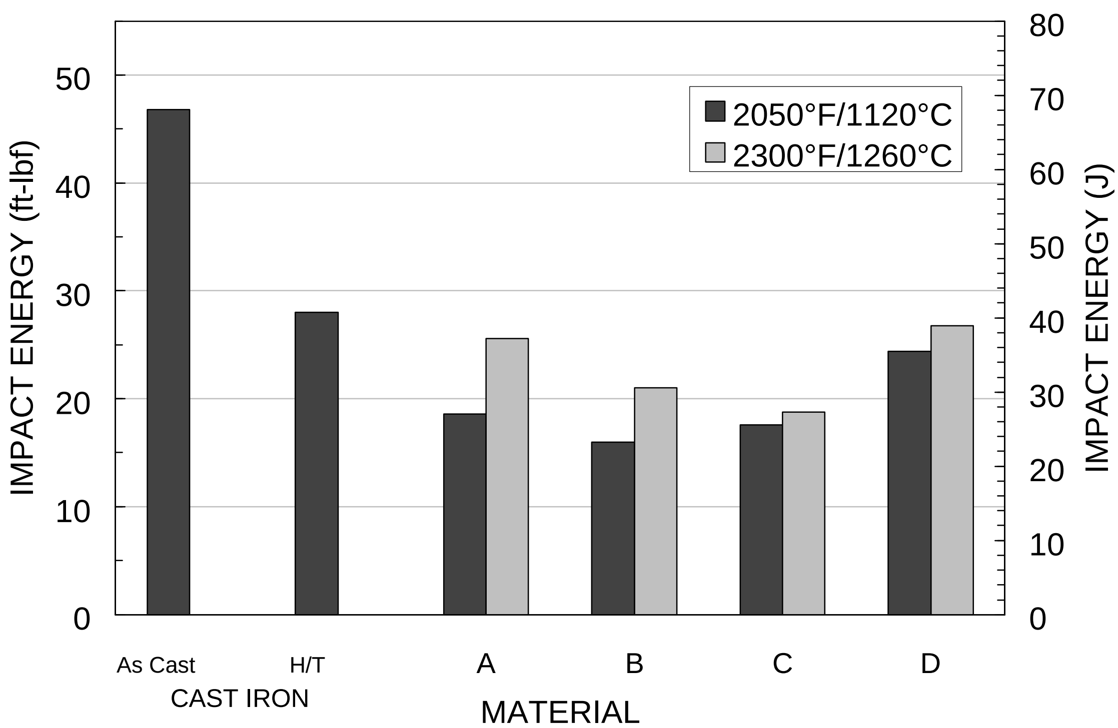

Figure 8: As sintered impact energy of the cast iron and the 4 candidate P/M materials.

Room temperature unnotched Charpy impact testing was performed on all materials, the results are shown in Figure 8. The as-received malleable cast iron had impact energy of ~47 ft.lbf
(63 J); however, heat treating to raise the tensile strength lowered the impact energy to ~28 ft.lbf (38 J). All the P/M materials sintered at 2050°F (1120°C) exhibited lower impact energies relative to the cast iron. Sintering at 2300°F (1260°C) raised the impact toughness sufficiently that Material A and Material D had nearly identical impact toughness as the heat treated cast iron. The cast iron is a fully dense material with ~2% graphitic flakes in the microstructure. The P/M materials contain ~ 6% porosity thus the lower impact energy of the P/M materials is a direct result of the higher void volume of the P/M materials compared with the cast iron. It is doubtful that a P/M material sintered at 2050°F (1120°C) with densities under
7.5 g/cm³ will ever provide the level of impact toughness achievable with the fully dense cast iron. However, high temperature sintering can give the required toughness values with sintered densities below the 7.5 g/cm³ level.

DISCUSSION

The objective of this investigation was to find a suitable P/M material(s) that could be single pressed / single sintered to potentially displace a high strength malleable cast iron. Materials were chosen that could be processed either at conventional sintering temperatures or via high temperature sintering for enhanced mechanical properties. To achieve the level of mechanical properties required, it was necessary to process the materials via warm compaction.

All four of the material systems chosen showed equal yield and tensile strengths compared with the malleable cast iron sintered at either 2050°F (1120°C) or 2300°F (1260°C). The tensile properties of the cast iron in the heat treated condition were a yield strength of ~100,000 psi (690 MPa) with a tensile strength of ~ 130,000 psi (896 MPa). To achieve this level of strength with the P/M materials, either heat treatment of the materials is necessary or using high temperature sintering of Material A and Material B. Modulus of elasticity for the cast iron is
~26 x 10^6 psi, the P/M materials evaluated at the 7.3 to 7.4 g/cm³ density exhibited a Modulus of elasticity of ~25 x 10^6 psi. Tensile elongation values of the P/M systems are below the cast irons and it is doubtful that any P/M material under a 7.5 g/cm³ density will achieve a 4% minimum level of elongation. However, it is noted that the specification for this material is 2% minimum tensile elongation. Considering this specification, Material A and Material B meet the specification requirements for yield and tensile strengths, elongation and Modulus of elasticity.

Impact toughness values of the P/M materials are nearly equivalent to the heat treated malleable cast iron. High temperature sintering (at 2300°F (1260°C)) provides a significant increase in the P/M materials. Most applications using this cast iron material will not be subjected to high Impact loading. Thus the materials chosen show adequate performance in this regard.

Actual gear testing of the P/M materials relative to the cast iron was not performed. Important considerations in gear testing are the AGMA gear classification of the as sintered gear, bending fatigue, and the resistance to rolling contact fatigue. The quality of the as sintered or heat treated P/M gear is dependent upon the uniformity of the density throughout the part and the sintered dimensional change. ANCORDENSE processed materials have demonstrated more uniform density distribution with potentially higher gear tolerance capability.

Experimental work reported by Chmelar, et al., demonstrated uniform part density in a helical gear warm compacted and sintered to ~7.35 g/cm³ plus density.(6) Rotating bending fatigue of the malleable cast iron was measured in both the malleable and heat treated conditions. In the as-malleable condition, the cast iron had a 99% fatigue endurance limit of 45,000 psi (310 MPa); in the heat treated condition, the fatigue endurance limit was 50,000 psi (345 MPa). Fatigue testing of the four materials chosen has not been completed. Results published by Rutz et al, demonstrated that the FD-0405 and alloys of Ancorsteel 85 HP are capable of achieving 99% fatigue strength ~ 50,000 psi (345 MPa) when the materials are heat treated to tensile strengths of ~ 160,000 psi (1100 MPa) to 180,000 psi (1240 MPa).(7) Additional fatigue testing of Material A and Material B is necessary to verify the suitability of these materials for rotating bending fatigue life.

Rolling contact fatigue of P/M materials is dependent upon the sintered density. At sintered densities of ~7.4 g/cm³, P/M materials have shown a 50% confidence rolling contact fatigue resistance ranging from 200,000 to 230,000 psi, Hertzian stress. Similar testing of wrought steel has produced a range of 280,000 to 310,000 psi, Hertzian stress.(8&9) These two studies demonstrated a linear relationship between density and RCF life. Although the exact RCF life of the cast iron is not known at this time, it is expected that the cast iron will have a rolling contact fatigue strength below that of the steel. It will be necessary for the design engineer to review the available data on rolling contact fatigue resistance in direct comparison with the expected RCF life of the malleable cast iron to determine if a 7.3 to 7.4 g/cm³ P/M part will provide adequate RCF life. Additional testing is required to fully evaluate the cast iron material plus Material A and Material B for resistance to rolling contact fatigue.

CONCLUSIONS

1.) The four candidate P/M materials warm compacted at 50 tsi, showed equivalent yield and tensile strengths in the as sintered condition to the malleable cast. When the cast iron was heat treated to ~28 HRC, Material A and Material B high temperature sintered showed equivalent yield and tensile strengths. The tensile elongation of the P/M materials were lower than the cast iron.

2.) Impact toughness values of the ANCORDENSE materials sintered at 2300°F (1260°C) were nearly identical to the heat treated malleable cast iron.

3.) Rotating bending fatigue of P/M materials in the heat treated condition can equal that of the cast iron.

4.) ANCORDENSE processed P/M materials in particular Material A and Material B are good candidate materials to replace malleable cast iron gearing components. Actual gear testing of these materials is needed to verify the suitability of these materials in these applications.

SUGGESTIONS FOR FUTURE WORK

To fully understand the potential to replace a malleable cast iron, additional testing work is necessary. This work includes:

1.) Develop the RCF life of the malleable cast iron in the hardened condition.

2.) Complete the rotating bending fatigue of Material A and Material B for both the 2050°F (1120°C) and 2300°F (1260°C) sintering condition.

3.) Perform actual gear testing of the candidate P/M materials.

4.) Pursue opportunities for higher sintered densities via the P/M process for Material A and Material B.

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