

Opportunities for Conversion of Powertrain Components from Malleable/Ductile Cast Irons to Powder Metallurgy

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ABSTRACT

Malleable and ductile cast irons are used extensively in gearing and high strength applications within automotive power train applications. Advantages of malleable and ductile cast irons are low material cost with mechanical properties that meet or exceed the requirements of the intended application(s). One disadvantage of the malleable cast iron is the extensive heat treating required to obtain the proper microstructure and mechanical properties. Both malleable and ductile iron components require extensive machining to produce the finished component. The combination of heat treating and extensive machining often results in a component that is costly to manufacture. Recent advances in the Powder Metallurgy (P/M) process including high strength material systems and high density processing have achieved mechanical properties that meet or exceed the level achieved with the current malleable and ductile cast iron materials.

This paper will present an evaluation and comparison of the mechanical properties of malleable cast iron with selected P/M material systems and processing parameters. This property discussion will

demonstrate the suitability of the P/M process in replacing these cast and machined components. Examples of specific parts will be cited and discussed.

INTRODUCTION

Cast irons used in the automotive industry consist of gray iron, malleable cast iron, and ductile cast iron. Gray cast irons have an acicular graphite flake morphology resulting in mechanical property levels with a maximum of 50,000 psi tensile strength with less than 2% tensile elongation. Automotive applications for gray cast irons include cylinder blocks, clutch plates, oil pump bodies, carriers, and main bearing caps.(1) Powder Metallurgy (P/M) has proven successful in converting gray cast iron components that have the shape and size suitable for P/M processing. Iron copper steels have mechanical properties that are equivalent or superior to the mechanical properties of gray cast irons. One potential limitation in P/M steels is the reduced Modulus of Elasticity. Gray cast irons have a Modulus of Elasticity of 20×10^6 to 24×10^6 psi; to achieve this level, P/M steels require a minimum part density of $\sim 7.2 \text{ g/cm}^3$.

Both malleable and ductile cast irons have significantly higher levels of mechanical properties compared to gray iron, with maximum tensile strengths approaching 150,000 psi. Malleable cast iron is initially cast as a white iron; which is subsequently heat treated (malleabilized) to transform the iron carbide phase to a nodular graphite called temper carbon.(2) The heat treatment cycle for malleable cast irons consists of heating the white iron to ~1700°F (925°C) up to 20 hours followed by rapid cooling to ~1400°F (760°C), then subsequently slow cooling to room temperature.(2) Ductile or nodular cast iron contains higher carbon and silicon levels and is treated with a nodulizing agent to promote the spherical graphite in the as cast condition.(3) The process of producing net shape components via the casting process necessitates machining of the casting in addition to heat treatment and any finish machining as required.

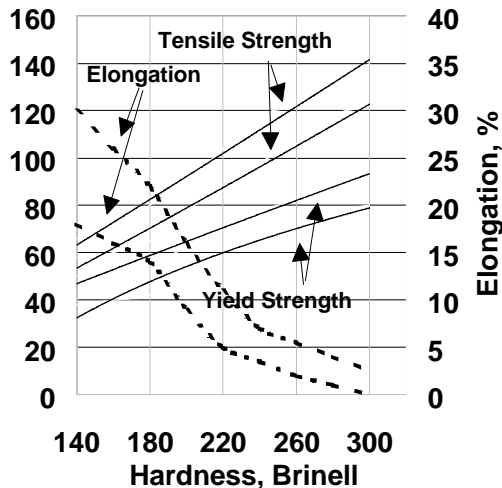


Figure 1: Strength and elongation vs. hardness in ductile cast iron (Ref.3).

Ductile and malleable cast irons can be heat treated to a wide range of strengths. Figure 1 shows the relationship between yield strength, tensile strength, and elongation for ductile cast iron. It is obvious that high ductility can be achieved; however, the strength is substantially reduced. As the yield strength is raised to 80,000 / 100,000 psi, the elongation

decreases to less than 5%. A similar trend occurs in malleable cast irons. Thus, ductile and malleable cast irons used in high strength applications will have tensile elongation less than 5% and more typically in the range of 2% to 3%. The Modulus of Elasticity of these materials ranges from 23×10^6 to 27×10^6 psi. Figure 2 shows the relationship between the tensile strength and the fatigue endurance ratio. At the 100,000 psi tensile strength level, the fatigue endurance ratio is approximately 0.4 implying a 40,000 psi fatigue endurance limit.

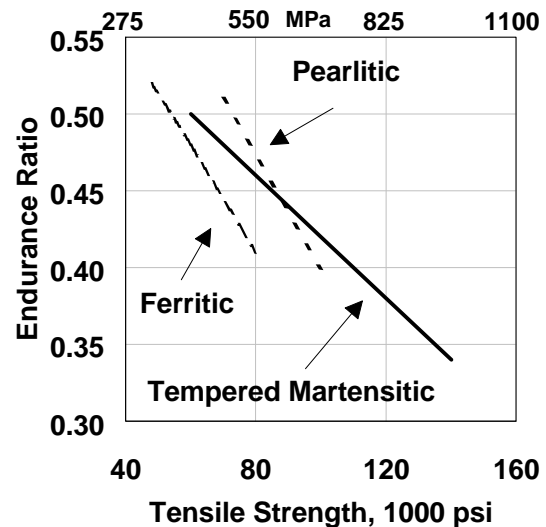


Figure 2: Fatigue properties of ductile cast iron (Ref. 3).

Although the cost of the raw materials utilized in castings is low relative to P/M materials; the extensive heat treating and machining make these components' candidates for P/M technology. P/M processing minimizes secondary machining giving a net or near net shape component; thus offering potential cost savings. The combination of strength and ductility inherent in malleable and ductile cast irons imposes upon the P/M industry a unique set of challenges. Traditional compaction of P/M materials makes possible matching of the yield and tensile strengths of the high performance cast irons. However, attaining the level of ductility or impact energy

toughness can be achieved with higher sintered densities through the traditional method of double press and double sinter (DP/DS). However, the DP/DS process adds additional manufacturing costs and is often impractical in the manufacture of complex parts or helical gearing.

The introduction of warm compaction processing enabled P/M part producers to manufacture single press / single sinter components with sintered densities approaching that of DP/DS components.(4) 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 technology for the economical production of high performance P/M parts to replace wrought steel components.(5) In particular; complex, multi level components made via casting or forging with extensive secondary machining are viewed as excellent conversion opportunities.

The recent interest for greater P/M utilization within the automotive industry questioned the viability of single pressed high density P/M components with complex geometry's such as high strength cast iron applications. Shown as Figure 3 is the yield and tensile strengths of several commonly used wrought gearing materials along with two ANCORDERSE processed materials premixed with 0.6 w/o graphite. It should be noted that AISI 8620 is a carburizing grade of steel most commonly used in high performance gear applications. The data presented in Figure 3 shows the heat treated strengths of FD-0405 and the FLN4-4405 in relation to the heat treated yield and tensile strength of ductile cast iron and an AISI 8620 steel.

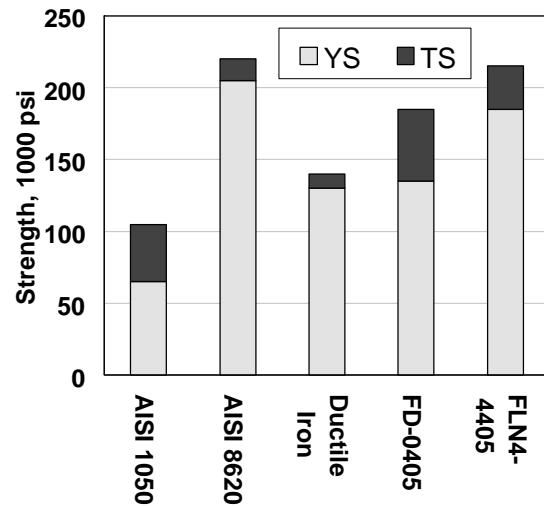


Figure 3: Comparative strength of ANCORDERSE materials.

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 P/M steels 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 these cast samples were 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 a malleable cast iron. The premix compositions were produced via the ANCORDERSE premixing process with 0.6 w/o lubricant; the compositions are shown in Table I.

Table 1
ANCORDENSE Premix Compositions

ID	Iron	Ni, w/o	Cu, w/o	Mo, w/o	Gr, w/o
A	A85HP	4.0	0	0.85 *	0.60
B	A85HP	3.0	0.75	0.85 *	0.60
C	A85HP	2.0	1.00	0.85 *	0.60
D	FD0405	4.0	1.50	0.50	0.60

A85HP is Ancorsteel 85HP™

* Moly is prealloyed in base iron

Mechanical property specimens were compacted at pressures from 30 to 50 tsi (415 to 690 MPa) utilizing the ANCORDENSE processing (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 H₂ / 25 v/o N₂ atmosphere. The sintering time for both sintering temperatures was maintained at thirty minutes at temperature.

Mechanical property test specimens were prepared from the pearlitic malleable cast iron via machining from cast "505" tensile specimens. During the investigation, the hardness and strength of the cast specimens were below that of the specific minimums and additional samples were prepared from heat treated test coupons. Heat treatment of the malleable cast iron consisted of austenitizing at 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 2.

Table 2
Chemical Analysis of Malleable Cast Iron

Carbon, (w/o)	Si, (w/o)	S, (w/o)	Mn, (w/o)	P, (w/o)
2.55	1.40	0.12*	0.45	0.05*

* Max.

RESULTS

The compressibility of the four P/M materials is shown as Figure 4. The ANCORDENSE FLNX-4405 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 5. 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 a corresponding increase in apparent hardness.

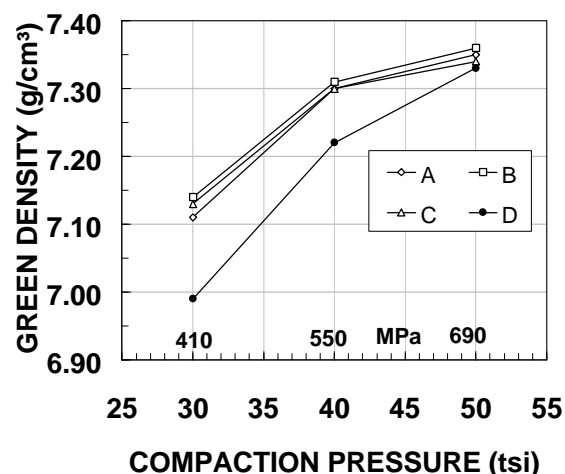


Figure 4: Compressibility of 4 P/M steels evaluated, powder temperature of 270°F (132°C) and die temperature of 300°F (150°C).

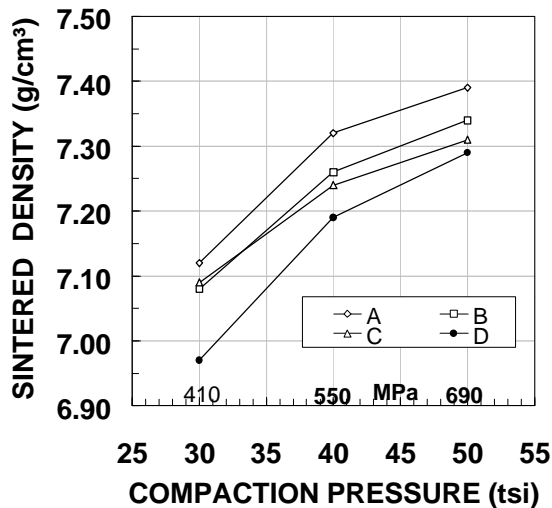


Figure 5: Sintered density of 4 P/M steels, sintered at 2050°F in 75v/o hydrogen and 25v/o nitrogen.

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). As such, 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 Size) of P/M Steels 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%

Sintered transverse rupture strength test results are presented in Figure 4. Testing of the ANCORDERSE prepared material was done in the as sintered condition and

the results are shown based on sintered density. TRS testing was not performed on the malleable cast iron (the elongation of this material exceeded 3%)(6). The FLN4-4405 achieved the highest sintered density and the highest sintered TRS achieving a strength in excess of 220,000 psi (1515 MPa). At lowered sintered densities, the FLN4-4405 produced nearly equivalent TRS strengths to the FD-0405 material. Ancorsteel 85HP premixed with nickel and copper demonstrated lower sintered densities at the same compaction pressures and lower sintered TRS values.

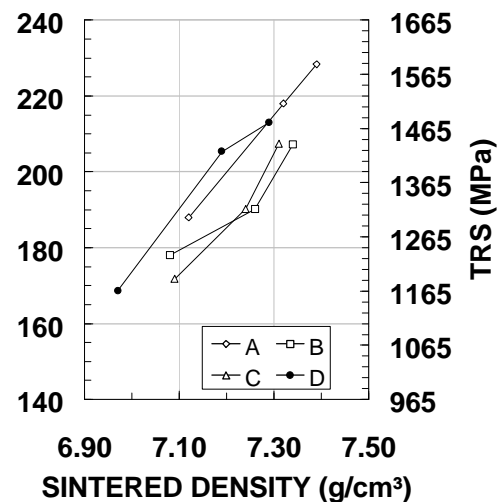


Figure 6: Sintered TRS of 4 P/M steels sintered at 2050°F

Yield and tensile strengths of the four P/M materials plus the malleable cast iron are presented in Figure 7 (sintered at 2050°F (1120°C)) and Figure 8 (sintered at 2300°F (1260°C)). The malleable cast iron was evaluated in both the pearlitic malleable condition plus the heat treated condition. 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; heat treating raised the hardness to approximately 28 HRC (mid range of the specification). All the P/M tensile values in Figures 7 and 8 are in the as sintered condition after compaction at 50 tsi

(690 MPa). The data presented in Figures 7 and 8 indicates that the P/M materials chosen (except for the FD0405) gave equal or better tensile strength to the cast iron in the pearlitic malleable condition.

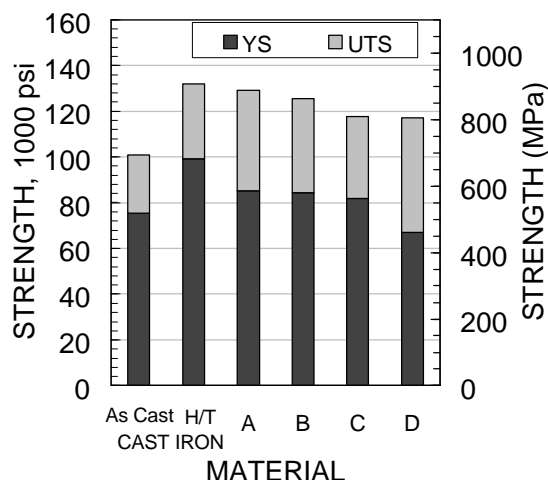


Figure 7: Tensile properties of P/M steels sintered at 2050°F (1120°C)

The heat treatment of 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 accelerated cooled after the sintering cycle.

Table 4
Sintered Hardness of P/M Steels
Compacted at 50 tsi

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

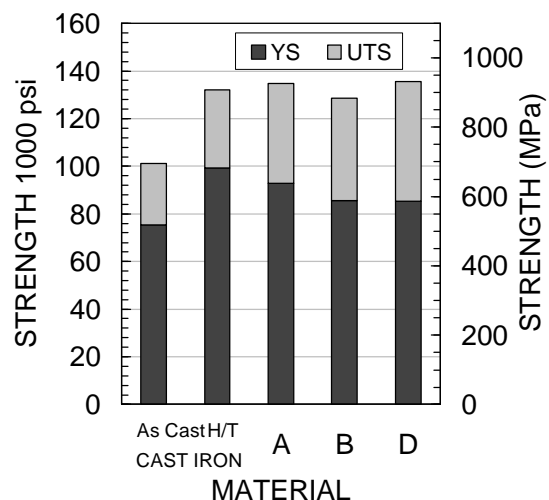


Figure 8: Tensile properties of P/M steels sintered at 2300°F (1260°F)

Tensile elongation of the cast iron plus the four candidate P/M materials is presented in Figure 9. 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 pearlitic malleable had ~8% tensile elongation but heat treating to increase both the strength and hardness to the specification range lowered the tensile elongation to ~4%. Tensile elongation for the P/M materials are below that of the cast iron in both the as cast and heat treated condition. If greater than 4% tensile elongation is necessary, it will be necessary 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 materials.

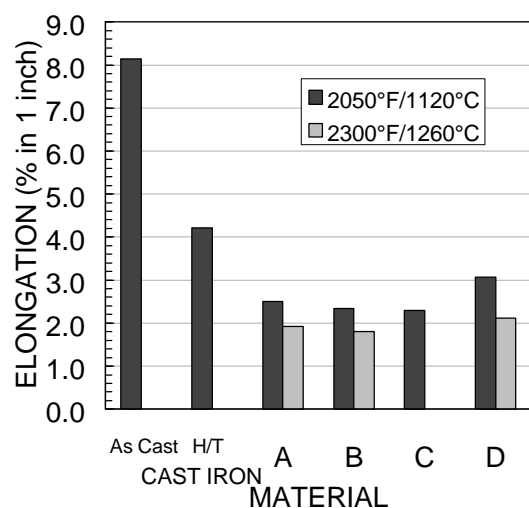


Figure 9: Tensile Elongation of Cast iron and P/M steels

Room temperature unnotched Charpy impact testing was performed on all materials, the results are shown in Figure 10. The as-received malleable cast iron had impact energy of ~47 ft.lbf (63 J); however, heat treating 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% nodular graphite 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 below 7.5 g/cm³ will ever provide the level of impact toughness attainable 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.

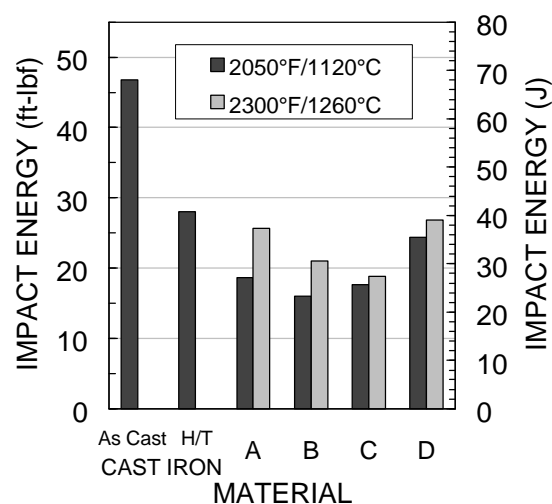


Figure 10: Room temperature Impact energy of materials evaluated

DISCUSSION

The objective of this investigation was to find a suitable P/M material(s) that could be single pressed / single sintered to displace a high strength malleable or ductile cast irons. Materials were chosen that could be processed 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.

The four P/M material systems investigated had equal yield and tensile strengths compared with the non- heat treated malleable cast iron. 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 will be necessary or utilizing high temperature sintering of Material A or Material B. The Modulus of Elasticity for the cast iron is ~26 x 10⁶ psi; the P/M materials evaluated at the 7.3 to 7.4 g/cm³ density exhibited a Modulus of Elasticity of ~25 x 10⁶ psi. Tensile elongation values of the P/M systems are

below the cast irons and it is doubtful that any P/M material under 7.5 g/cm^3 sintered density will achieve the 4% 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 all materials evaluated showed adequate performance in this regard.

Actual gear testing of the P/M materials was not performed. Important considerations in gear testing are the AGMA gear classification, 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. ANCORDERSE processed materials have demonstrated greater uniformity of density distribution with potentially higher gear tolerance capability. Experimental work reported by Timelier, et al., demonstrated uniform part density in a helical gear warm compacted and sintered to $\sim 7.35 \text{ g/cm}^3$ plus density.(7)

Rotating bending fatigue of the malleable cast iron was measured in both the malleable and heat treated conditions. In the malleable condition, the cast iron had a 99% fatigue endurance limit of $\sim 45,000 \text{ psi}$ (310 MPa); in the heat treated condition, the fatigue endurance limit was $\sim 50,000 \text{ psi}$ (345 MPa). Fatigue testing of the four P/M 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 $\sim 50,000 \text{ psi}$ (345 MPa) when the materials are heat treated to tensile strengths of $\sim 160,000 \text{ psi}$ (1100 MPa) to $180,000 \text{ psi}$ (1240 MPa). (8) 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 (RCF) of P/M materials is dependent upon the sintered density. Figure 11 is data developed by the Center for Powder Metallurgy Technology. It shows that sintered densities of $\sim 7.4 \text{ g/cm}^3$, P/M materials have rolling contact fatigue resistance ranging from $200,000 \text{ psi}$ to $220,000 \text{ psi}$, Hertzian stress. Similar testing of wrought steel has produced $\sim 285,000 \text{ psi}$ Hertzian stress. (9&10) Figure 11 shows the a linear relationship between density and RCF life. Actual RCF testing of the cast iron was not performed. However, cast irons have a density of approximately 7.5 g/cm^3 and assuming that the cast iron will perform the same as the P/M quench and tempered. Thus, the RCF life of the cast iron can be estimated to be approximately $215,000 \text{ psi}$ Hertzian stress. An RCF life of $210,000 \text{ psi}$ can be achieved in P/M materials at a density of $\sim 7.3 \text{ g/cm}^3$ provided that the component is carburized. This area of rolling contact fatigue is receiving considerable attention within the P/M industry. What is necessary is to confirm the RCF life of the high performance cast irons.

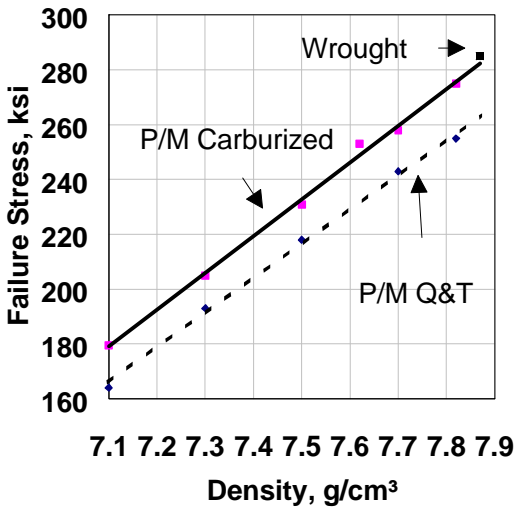


Figure 11: Rolling contact fatigue characteristics of P/M materials (Ref. 10)

POTENTIAL AUTOMOTIVE CONVERSIONS

Any discussion of conversion opportunities assumes that the component can be produced by the P/M process. Additionally, the high densities achieved with the test samples can be achieved in the critical stress regions of the actual part. Opportunities for high density P/M parts within automotive powertrains include:

- 1.) Ductile iron connecting rods. Traditionally, cast iron connecting rods have a flexure fatigue limit of ~30,000 psi. The four materials discussed will provide that level of fatigue endurance.
- 2.) Malleable iron ring gears and pinion gears. These components are used in the induction hardened condition. High density P/M processing will give identical tensile strengths at a reduced level of ductility. Secondary processing after sintering may be required to meet the gear tolerance.

CONCLUSIONS

1.) The four candidates 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.) Perform actual gear testing of the candidate P/M materials via compaction of actual component.
- 3.) Pursue opportunities for higher sintered densities via the P/M process for Material A and Material B via die spray and reduced powder lubricant levels.

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