

NEW HIGH PERFORMANCE P/M ALLOYS FOR REPLACING DUCTILE CAST IRONS

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ABSTRACT

Improvements in atomizing technology and binder treatment technology have allowed Hoeganaes to develop unique alloy systems with high strength, ductility, and impact energy. These systems, material MDD (currently experimental) and Ancorloy[®] MDA (commercial product), have been shown to be extremely competitive with numerous ductile cast iron grades. This paper presents the powder, green, and sintered properties of the new materials and compares their performance with existing material systems.

INTRODUCTION

Silicon has been of interest to the P/M community for many years. In addition to its relatively low cost and tendency to increase hardenability, silicon can accelerate sintering in hybrid alloys and substantially impact mechanical properties [1]. However, the use of silicon in P/M can present considerable difficulties. The presence of silicon as ferrosilicon in a P/M compact almost invariably leads to a high degree of shrinkage and possible distortion. If silicon oxide is allowed to form during sintering, it is extremely difficult to reduce and almost always results in an undesirable decline in mechanical properties. Similar problems are experienced in prealloyed powders, where silicon oxide pickup during atomization and/or annealing can lead to lower compressibility and diminished mechanical performance. Not surprisingly, the problems enumerated above can compound to cause extensive processing difficulties.

In an effort to exploit the advantages of silicon while avoiding its pitfalls, a new series of materials have been developed. Through refinements in atomizing, annealing, and binder-treatment technology, these new materials provide exceptional property combinations without large quantities of admixed additions such as nickel, copper, etc. Furthermore, the additional production costs associated with making diffusion-alloyed materials are entirely eliminated.

BACKGROUND

Ductile, or nodular, iron is a cast iron in which eutectic graphite separates from the molten metal during casting and grows as spheres instead of flakes [2]. The presence of such spheres imparts good tensile strength and ductility. Depending on the processing route chosen, ductile iron grades are capable of attaining ferritic, pearlitic, or martensitic microstructures. Typical applications for ductile grades include crankshafts, gears, pinions, slides, and rocker arms.

Given the vast array of possible microstructures, ductile irons can exhibit a varied range of mechanical properties [2]. Tensile strengths have been known to range from 350 to 850 MPa (55,000 to 125,000 psi) with corresponding elongation values of 20 to 2%. As with many other materials, ductile iron grades traditionally lose ductility as higher tensile strengths are achieved. The logical “conversion targets” for the MDA and MDD materials would be medium to medium-high strength ductile iron grades with 2 to 4% elongation. Further enhancements of these new materials may allow for replacement of grades with elevated strength and ductility combinations.

EXPERIMENTAL PROCEDURE

Two new materials, MDA and MDD, were tested as potential replacements for numerous ductile cast iron grades. While material MDA is commercially available from Hoeganaes Corporation under the trade name Ancorloy® MDA, material MDD is still being considered for membership in the Ancorloy family of products. MDA test specimens were produced from a production 4,550 kg (10,000 lb) lot. MDD was obtained from a 230 kg (500 lb) pilot plant lot. In an effort to demonstrate the advantageous interaction between silicon and carbon in determining mechanical properties, a “control” material was produced to mirror the MDA composition but without carbon. This “control” material was strictly experimental in nature.

Compressibility was measured by compacting cylindrical specimens per ASTM B 331 and MPIF Standard 45. Green density, green expansion, sintered density, and dimensional change were determined from the average of five compacted transverse rupture strength (TRS) specimens with a nominal size of 6.35 mm x 12.7 mm x 31.75 mm (0.25 inches x 0.5 inches x 1.25 inches). Tensile tests were conducted on standard dog-bone tensile specimens.

All test pieces were sintered in a Hayes laboratory, high temperature sintering pusher furnace. The sintering cycle used for specimens was as follows:

Sintering Temperature:	1260 °C (2300 °F)
Atmosphere:	75 v/o H ₂ , 25 v/o N ₂ (Synthetic DA)
Time at Temperature:	30 minutes
Cooling:	Standard Water-Jacketed Section

Apparent hardness measurements were performed on the surface of the specimens using a Rockwell hardness tester. All measurements were conducted on the Rockwell A scale (HRA) for ease of comparison. Transverse rupture strength and dimensional change from die size were measured according to ASTM B 528 and B 610. Tensile testing was performed on a 267 kN (60,000 pound) Tinius Olsen universal testing machine at a crosshead speed of 0.635 millimeters/minute (0.025 inches/minute). Elongation values were determined by utilizing an extensometer with a range of 0 to 20%. The extensometer was left on until failure. All specimens were tested in the as-sintered condition.

Metallographic evaluation was performed on MDA and MDD sections prepared from dog-bone tensile bars. Photomicrographs of typical microstructures were taken following a 2% nital / 4% picral etch at an original magnification of 500X. The relative microstructural constituent content was estimated by observing numerous representative fields.

RESULTS AND DISCUSSIONS

Powder Properties and Green Strength

Particular attention was paid to key powder properties as well as green strength. The powder properties investigated were apparent density, flow, chemical composition, and compressibility. Chemical composition, apparent density, and flow for the materials grades tested in this paper are presented in Table I. While Figure 1 presents compressibility curves for MDA and MDD, Figure 2 contains green strength curves for both materials. The flow, apparent density, compressibility, and green strength of both MDA and MDD do not represent a significant departure from similar “high” performance materials.

Table I: Chemical Compositions, Apparent Density, and Hall Flow for Material Grades Tested

Grade	AD (g/cm ³)	Flow (s/50g)	Fe (w/o)	Si (w/o)	Mo (w/o)	Ni (w/o)	C (w/o)	Cr (w/o)	Mn (w/o)
MDA*	3.12	30	Bal.	0.68	0.03	0.05	0.91	0.03	0.16
“Control”	3.06	31	Bal.	0.68	0.03	0.05	0.04	0.03	0.16
MDD	3.08	28	Bal.	0.71	0.87	2.07	0.32	0.05	0.19

*MDA is commercially available from Hoeganaes Corporation as Ancorloy MDA

Sintered Properties

The sintered data collected are presented in two parts – TRS and impact properties (Table II) and tensile properties (Table III). All data represents performance in the as-sintered condition with no secondary processing.

Once again, the “control” material was chosen in order to demonstrate the desirable interaction between silicon and carbon in the iron-silicon-carbon system. While the “control” exhibited a comparatively low strength, it was coupled with an unusually high elongation of 11.5% at a density of only 7.06 g/cm³. Through modifications of the “control”, the compositions for MDA and MDD were attained. As seen in Table III and Figure 3, such modifications served to increase strength levels by as much as 250% while retaining as much as 36% of the ductility seen in the original “control” material. Although differences were also observed in dimensional change characteristics and apparent hardness values, the data in these areas would not be classified as atypical for many P/M materials.

As is the case in nearly any other P/M material system, mechanical performance and apparent hardness increased with density / compaction pressure. However, unlike many other material systems, the exceptional combination of tensile properties was achieved in lighter-weight parts. In an effort to further enhance properties and density levels, a rigorous investigation of ANCORDERSE[®] (warm compaction) processing of these materials has been initiated.

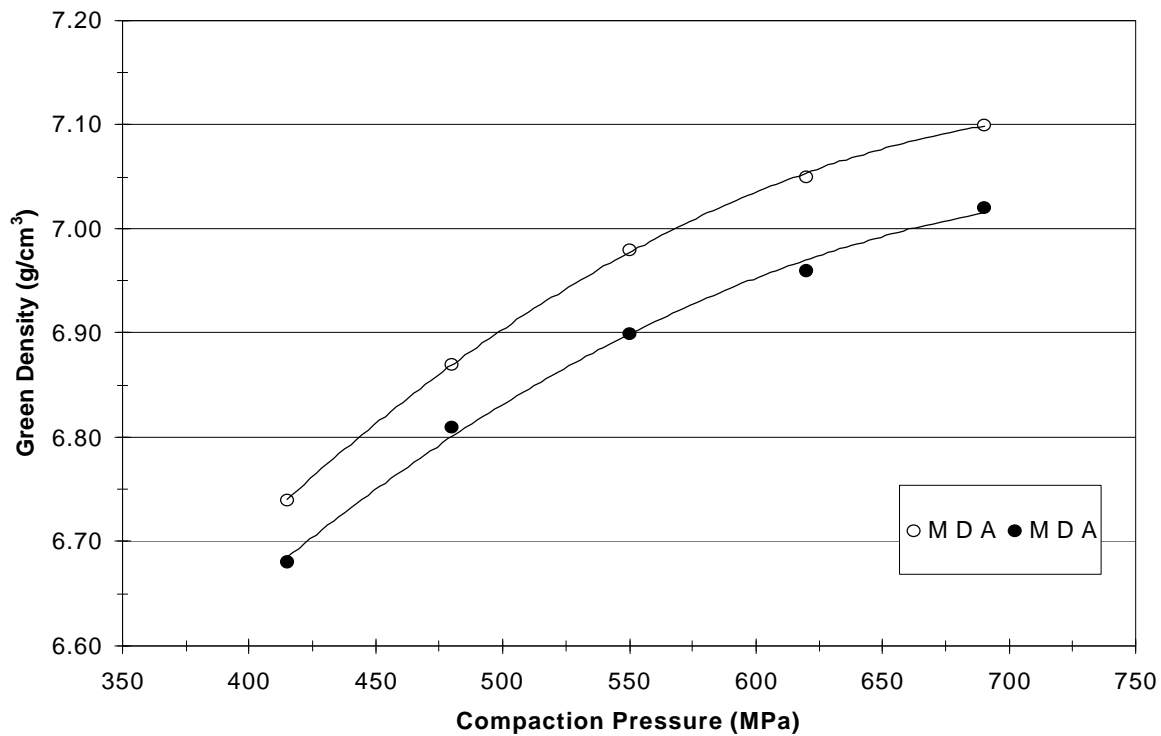


Figure 1: Compressibility Curves for MDA and MDD Using Standard Cylindrical Specimens with 0.75 w/o Acrawax.

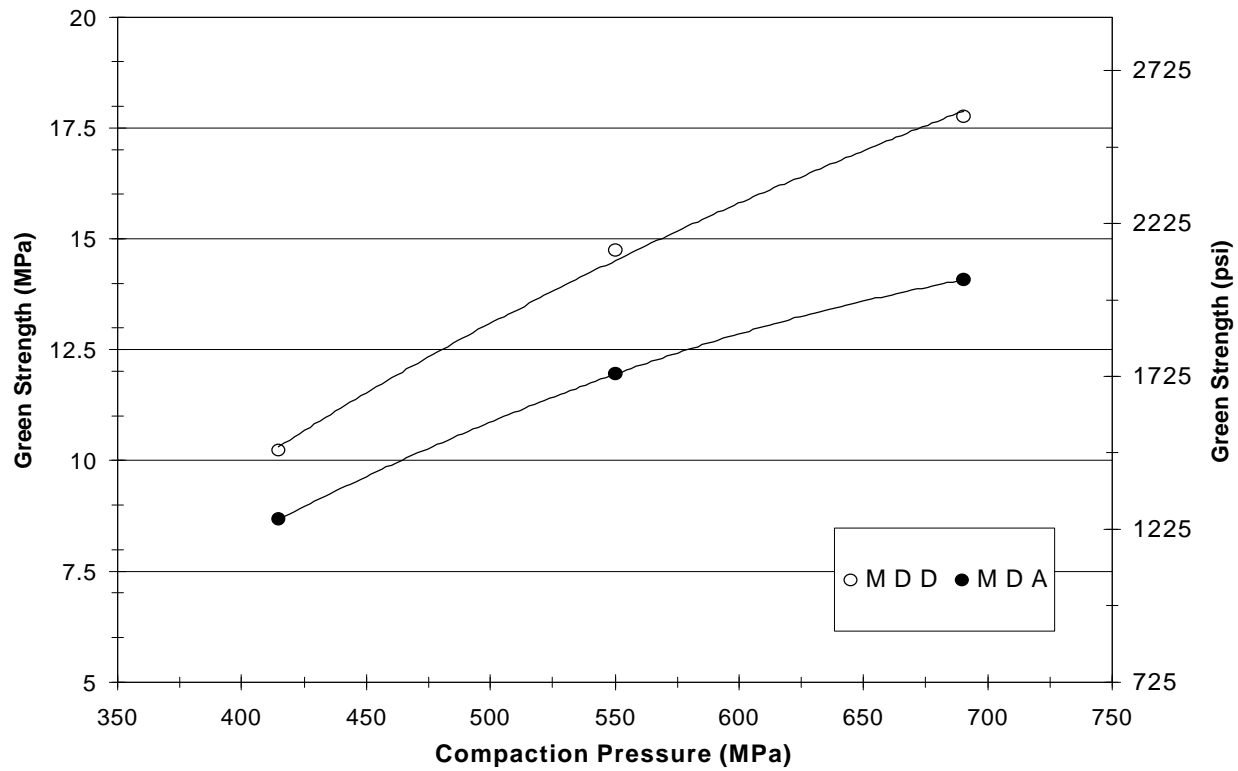


Figure 2: Green Strength Curves for MDA and MDD Using Standard Green Strength Bars with 0.75 w/o Acrawax.

Table II: As-Sintered TRS and Impact Properties for Three Material Grades

Grade	Comp. Press. (MPa / tsi)	Green Density (g/cm ³)	Green Exp. (%)	Sintered Density (g/cm ³)	D.C. (%)	Apparent Hardness (HRA)	TRS (MPa / 10 ³ psi)	Impact Energy (J / ft.lbf)
MDA	415 / 30	6.66	0.13	6.66	-0.15	45	915 / 133	12 / 9
	550 / 40	6.88	0.16	6.89	-0.12	47	1030 / 150	17 / 13
	690 / 50	6.99	0.18	7.01	-0.10	50	1200 / 175	21 / 15
"Control"	415 / 30	6.59	0.12	6.61	-0.27	10	415 / 60	--
	550 / 40	6.86	0.16	6.88	-0.23	18	530 / 77	--
	690 / 50	7.01	0.20	7.05	-0.21	22	605 / 88	--
MDD	415 / 30	6.73	0.16	6.75	-0.28	50	1130 / 164	16 / 12
	550 / 40	6.97	0.19	6.98	-0.26	54	1345 / 195	19 / 14
	690 / 50	7.10	0.21	7.12	-0.23	55	1490 / 216	26 / 19

Table III: As-Sintered Tensile Properties for Three Material Grades

Grade	Comp. Press. (MPa / tsi)	Sintered Density (g/cm ³)	UTS (MPa / 10 ³ psi)	YS (MPa / 10 ³ psi)	Elong. (%)	Apparent Hardness (HRA)
MDA	415 / 30	6.66	490 / 71	325 / 47	2.6	46
	550 / 40	6.91	580 / 84	360 / 52	3.6	50
	690 / 50	7.04	650 / 94	400 / 58	3.8	52
"Control"	415 / 30	6.60	185 / 27	120 / 17	8.3	13
	550 / 40	6.88	220 / 32	130 / 19	10.0	16
	690 / 50	7.06	255 / 37	150 / 22	11.5	17
MDD	415 / 30	6.76	570 / 83	400 / 58	2.1	49
	550 / 40	7.00	695 / 101	455 / 66	2.9	52
	690 / 50	7.14	755 / 109	480 / 70	3.6	56

Although specimens in this work have been sintered exclusively at 1260 °C (2300 °F), preliminary trials have suggested that appealing mechanical properties can be achieved at temperatures as low as 1120 °C (2050 °F). It has also been observed that longer sintering times at low temperatures can approach high temperature sintered performance levels. Further testing in these arenas has been initiated in production environments under a wide range of sintering conditions and atmospheres.

Metallography

No useful photomicrograph could be obtained for the MDA material as its structure was nearly all fine pearlite. Although some small areas could be resolved at 1000X, most of the extremely fine pearlite colonies were indiscernible. Therefore, it was believed that the inclusion of its microstructure would serve little purpose. However, the fine nature of the pearlite was thought to be partially responsible for the good tensile properties despite the elimination of copper and nickel in the material.

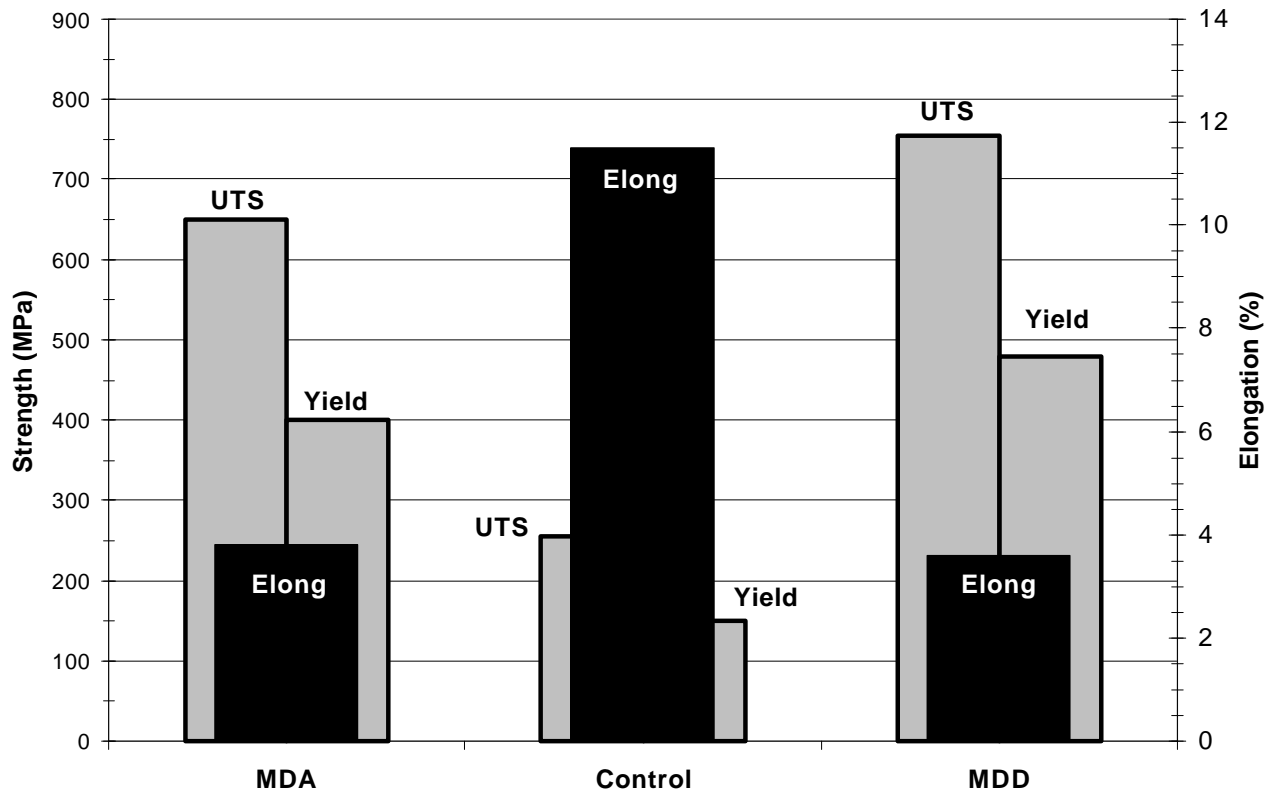


Figure 3: A Comparison of Tensile Properties for Three Different Materials Compacted at 690 MPa (50 tsi) Illustrating the Beneficial Interaction between Silicon and Carbon.

The microstructure of MDD was much easier to resolve than that of MDA and is presented in Figure 4. Microstructural constituents included divorced pearlite and martensite. The presence of martensite suggested that this material might benefit from tempering. Such a stress relief might be expected to increase UTS, yield strength, and ductility. However, work has only begun to quantify the benefits of tempering.

Comparisons with Other Materials

Following the development and subsequent testing of the two new products, comparisons were made with existing P/M materials. Iron-carbon, iron-copper, iron-nickel, and diffusion-alloyed systems at near equivalent density levels were selected [3,4]. The tensile strength and ductility properties of the various material systems are compared with those of MDA and MDD in Figure 5. As can be seen, the upper right corner of Figure 5 represents more desirable combinations of ductility and strength.

As evidenced in Figure 5, the properties of the two new materials were found to easily exceed the tensile properties possible in conventionally processed iron-carbon, iron-copper-carbon, and iron-nickel-carbon materials. Interestingly enough, both materials exhibited tensile strength and elongation combinations that met or exceeded the property combination of a commercially available diffusion-alloyed material containing 0.5 w/o graphite sintered at 1250 °C (2280 °F) for 30 minutes [4]. However, in the case of MDA and MDD, the added cost of diffusion alloying has been entirely eliminated. Hence, a comparison of “properties per unit cost” would likely favor the two new materials.

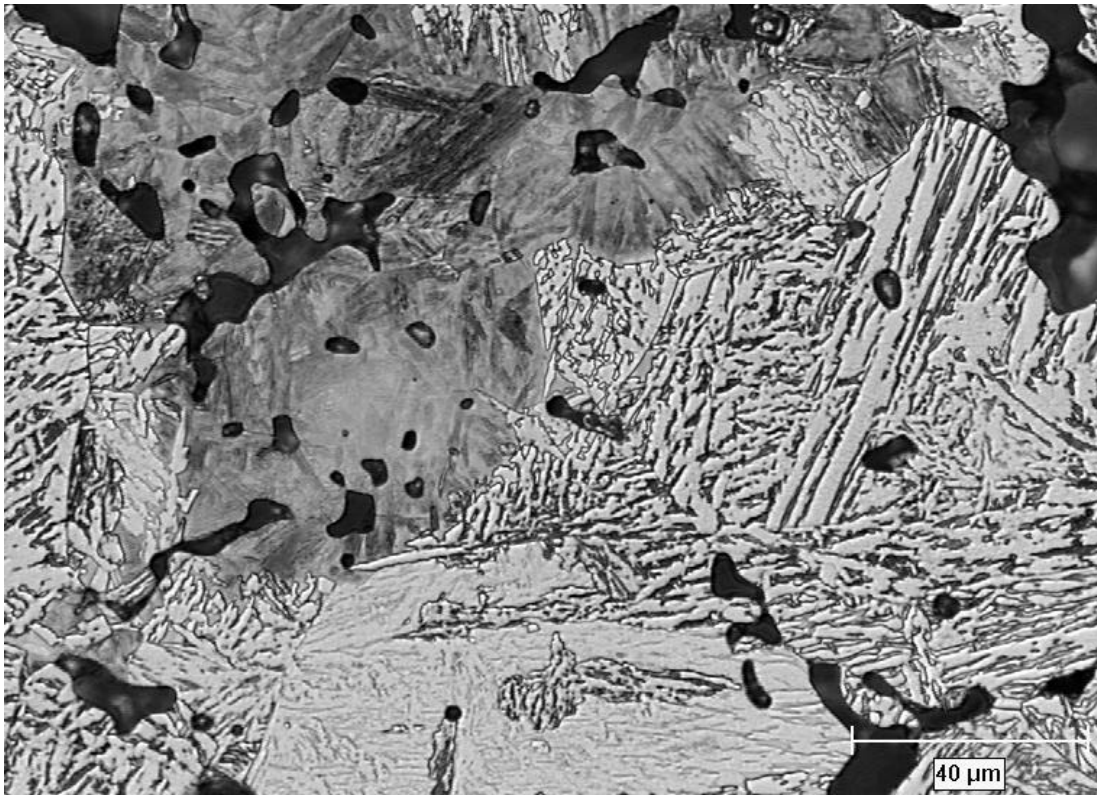


Figure 4: Photomicrograph of Material MDD Sintered at 1260 °C (2300 °F) in Synthetic DA. Etched with 2% nital / 4% picral. Original Magnification 500X.

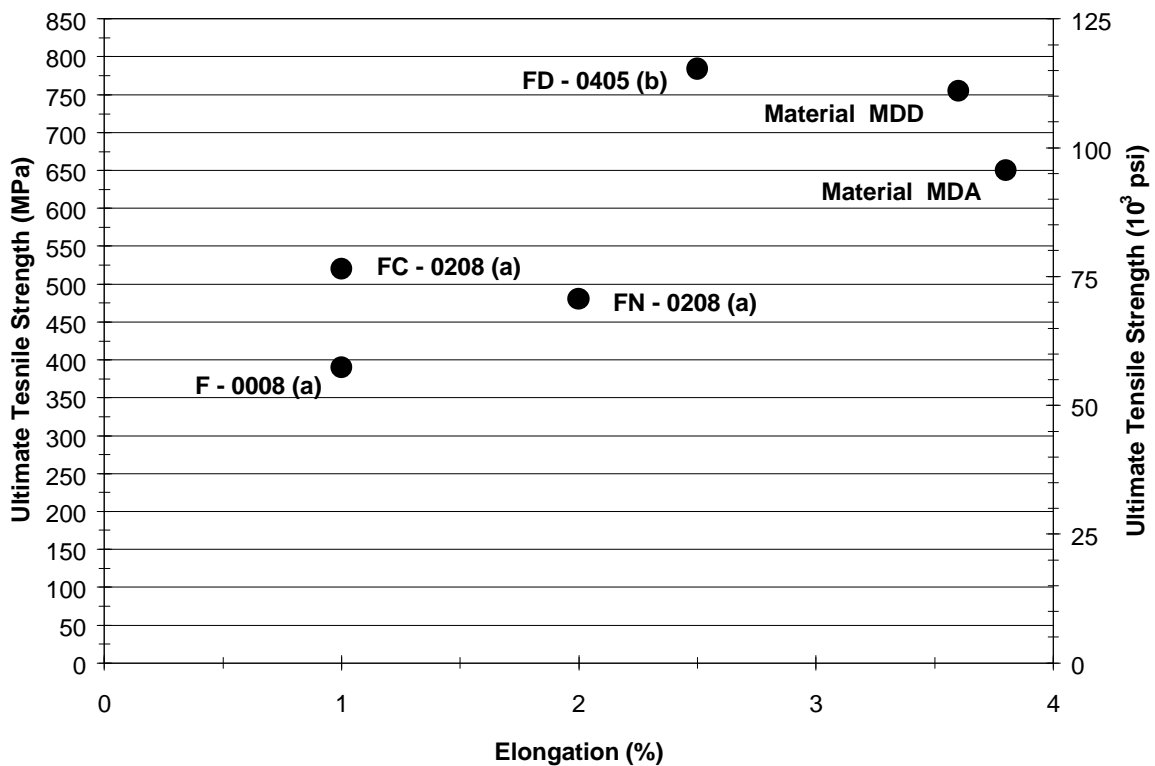


Figure 5: A Comparison of the UTS / Elongation Combinations Possible in Select P/M Materials at Near Equivalent Densities. (a) Conventional Sintering [3]; (b) Sintered at 1250 °C (2280 °F) for 30 minutes [4].

Another method of quantitatively comparing materials was developed in 1970 and refined in 1974 [5]. This method utilizes a combination of tensile strength and elongation to calculate a value known as the Quality Index (QI). The QI is equivalent to the square of the ultimate tensile strength (in 10^3 psi) of a material multiplied by its elongation divided by 1000. A larger QI value indicates a more desirable combination of properties. Ductile iron grades with strengths over 550 MPa have QI values between 29 and 38. The QI of select materials in Figure 5 have been calculated to be 33 (FD-0405), 34 (MDA), and 43 (MDD). Additionally, initial work on double pressed / double sintered or ANCORDERSE[®] processed MDD has yielded QI values near 75, a quantity that exceeds the quality indices enumerated above for common ductile iron grades.

CONCLUSIONS

Two new silicon-bearing materials have been developed to compete with ductile iron grades in automotive and non-automotive applications. These new materials were found to provide:

- Attractive tensile property combinations despite being either copper-free (MDD) or copper-free and nickel-free (Ancorloy[®] MDA),
- Near equivalent tensile properties to a diffusion-alloyed material with 0.5 w/o graphite without the processing expense incurred by diffusion alloying,
- Quality Index values equal to or greater than those possible in ductile cast iron grades, and
- Evidence of the beneficial nature of silicon and the technology / production process to eliminate difficulties previously experienced with its use.

FUTURE WORK

Although preliminary work on rotating bending fatigue (RBF) suggested good fatigue properties, further testing will be done on actual production lots to verify fatigue performance. Rolling contact fatigue (RCF) testing will also be conducted. In addition, customer trials and further studies will be performed under a wider variety of production conditions. In the future, additional materials of the same family will undoubtedly be introduced to further address the needs of the P/M community.

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