New Higher Performance Materials

By

Michael C. Baran, Francis G. Hanejko, Robert J. Causton, and K.S. Narasimhan

Hoeganaes Corporation
1001 Taylors Lane
Cinnaminson, NJ 08077

Abstract: Through the use of enhanced atomization, annealing, and binder treatment technologies, several new silicon-containing alloy grades have been introduced for high performance automotive applications. This presentation will include data on compacts produced from these new grades using conventional compaction, warm compaction, and double press / double sinter processing. With these new material systems, single compaction can achieve ultimate and yield strengths in excess of 1200 MPa and 800 MPa with elongation over 2%. Such tensile properties can be developed in conjunction with apparent hardness values over 65 HRA and impact energies exceeding 25 Joules.

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 has 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.

Malleable iron is produced originally as a white cast iron and undergoes subsequent heat treating to form a ferritic, pearlitic, or martensitic structure. The heat treatment cycle for malleable cast irons consists of heating the white cast iron to ~925 °C up to 20 hours followed by rapid cooling to ~760 °C, then subsequent slow cooling to room temperature.

Given the vast array of possible microstructures, malleable and ductile irons can exhibit a varied range of mechanical properties. Tensile strengths have been known to range from 350 to 1000 MPa with corresponding elongation values of 20 to 2%. As with many other materials, ductile and malleable iron grades traditionally lose ductility as higher tensile strengths are achieved.

P/M part manufacturers have long been searching for materials and processing routes capable of producing pressed and sintered parts that meet or exceed the properties of ductile and/or malleable cast irons. Although strength, ductility, impact, or apparent hardness specifications can often be achieved separately, it has been relatively difficult to meet all targets simultaneously for more demanding applications. For instance, previous work has shown that a warm compacted FLN4-4405 material sintered at 1260 °C meets the ultimate strength of a heat treated malleable cast iron (900 MPa), and almost meets the yield strength (690 MPa) but falls short of the 4% elongation of the cast iron [3,4]. When sintered at 1120 °C, the FLN4-4405 material exceeds the strength of the pearlitic malleable iron but has much less ductility (2.5% compared with 8%).

The materials investigated in this paper were designed to meet or exceed the property requirements of various malleable and ductile cast iron grades. Conventional processing was initially considered [5,6]. However, in pursuit of high performance levels, double press / double sinter (DP/DS) and ANCORDENSE® (warm compaction) processing continue to be investigated. The work contained herein represents a work in progress and the collection of data continues on a variety of materials and production processes.

EXPERIMENTAL PROCEDURE

Several binder-treated, press-ready premixes were tested as potential replacements for numerous malleable and ductile cast iron grades. Premixes designated as MDA (Ancorloy®MDA), MDB (Ancorloy MDB), and MDC (Ancorloy MDC) are commercially available. However, materials MDD and MDCL are still experimental and currently being considered for incorporation into the Ancorloy family. The “L” designation denotes a leaner alloy system with half of the silicon content of the original material.

While ANCORDENSE processed materials were compacted using a die temperature of 145 °C, ANCORBOND® processed materials were pressed at ambient laboratory temperature. In testing of ANCORBOND processed materials, compressibility was measured by compacting cylindrical specimens per ASTM B 331 and MPIF Standard 45. The compressibility of ANCORDENSE materials was determined on rectangular test pieces. 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.

DP/DS specimens were produced from ANCORBOND premixes pressed at ambient laboratory temperature, pre-sintered at 800 °C, machined to fit back into the die, repressed at the original compaction pressure, and sintered as noted below.

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

Sintering Temperature:	1260 ºC
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 made using or converted to 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 mm/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 except MDC and MDCL were tested in the as-sintered condition. MDC and MDCL were tempered at 190 °C for 1 hour in air.

RESULTS AND DISCUSSION

Chemistry and Compressibility

Nominal chemical compositions of all materials tested and the size of premixes sampled for testing are listed in Table I. As previously stated, the "L" designation indicates a "lean" silicon content of 0.35 w/o versus 0.70 w/o in the original material.

Grade	Quantity Produced (kg)	Mix Type(s) Tested	Fe (w/o)	Si (w/o)	Cr (w/o)	Mn (w/o)	Ni (w/o)	Mo (w/o)	C (w/o)
MDA	4,600	ANCORBOND	Bal.	0.7	0.03	0.16	0.05	0.03	0.9
MDB	2,300 / 230	ANCORBOND / ANCRODENSE	Bal.	0.7	0.03	0.13	2.0	0.85	0.6
MDD	230	ANCORDENSE	Bal.	0.7	0.03	0.13	2.0	0.85	0.3
MDCL	230	ANCORDENSE	Bal.	0.35	0.03	0.13	4.0	0.85	0.6
MDC	2,300 / 230	ANCORBOND / ANCORDENSE	Bal.	0.7	0.03	0.13	4.0	0.85	0.6

TABLE I: Nominal Material Chemical Compositions and Quantities Produced for Testing

Enhanced processing methods were employed to increase density and mechanical properties. The compressibility of selected materials in conventional compaction, warm compaction, and DP/DS are shown in Figures 1-3. The higher density levels reached by enhanced processing of these materials may be required for future high performance applications such as automotive gearing. The rotating bending fatigue (RBF) and rolling contact fatigue (RCF) behaviors of these materials would be expected to be even more impressive at higher density levels.

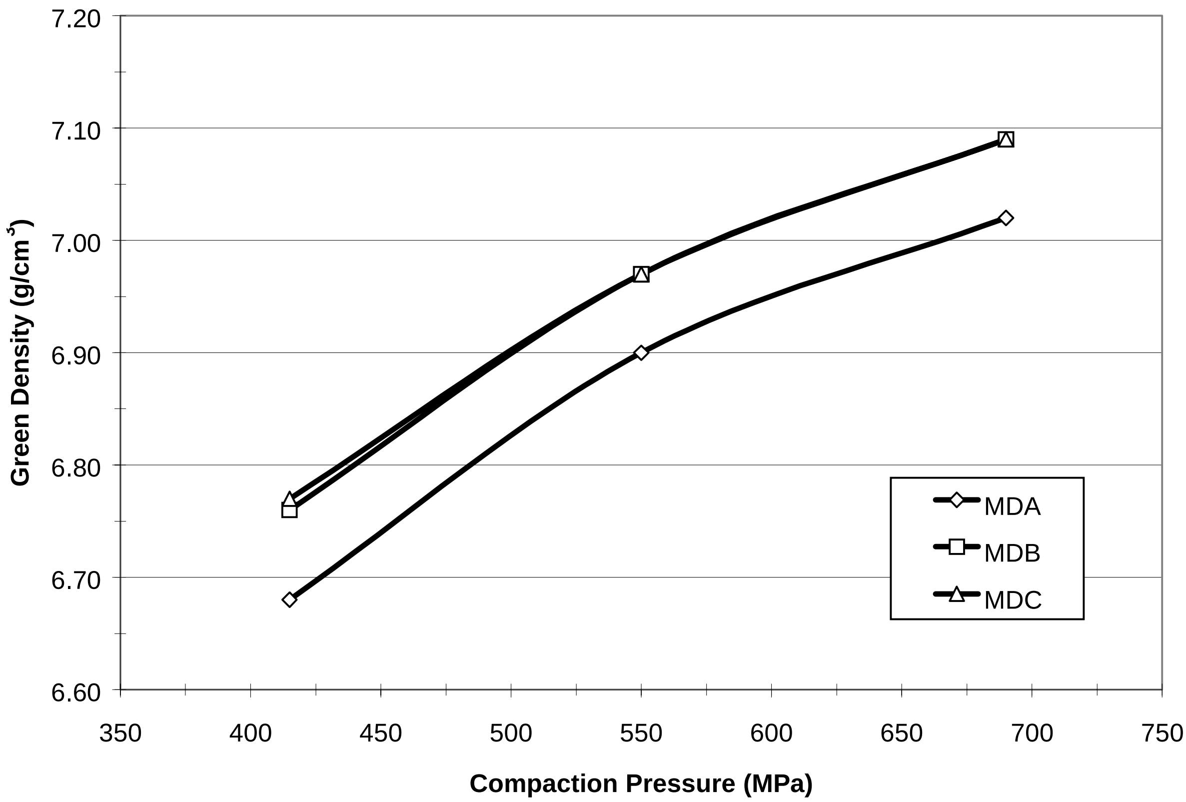

FIGURE 1: Compressibility of ANCORBOND processed MDA, MDB, and MDC Materials Pressed Under Ambient Laboratory Conditions

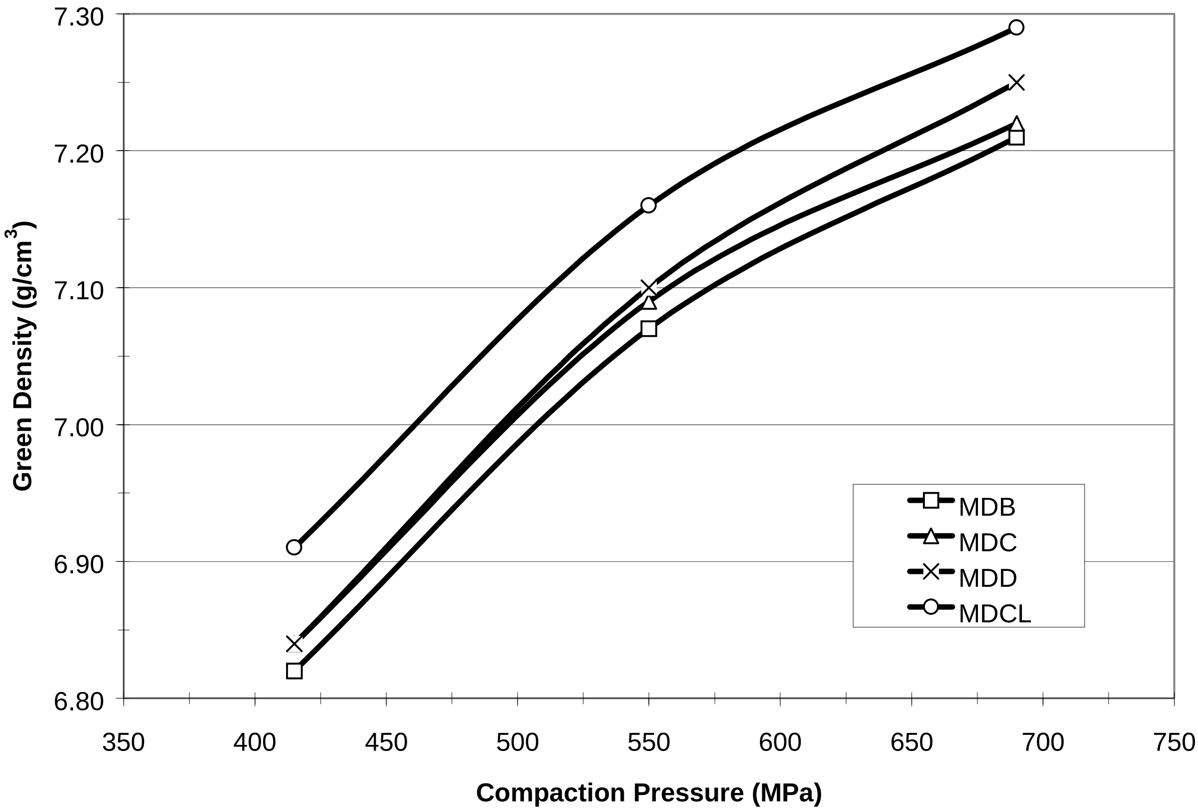

FIGURE 2: Compressibility of ANCORDENSE processed MDB, MDC, MDD, and MDCL Materials Pressed at 145 °C

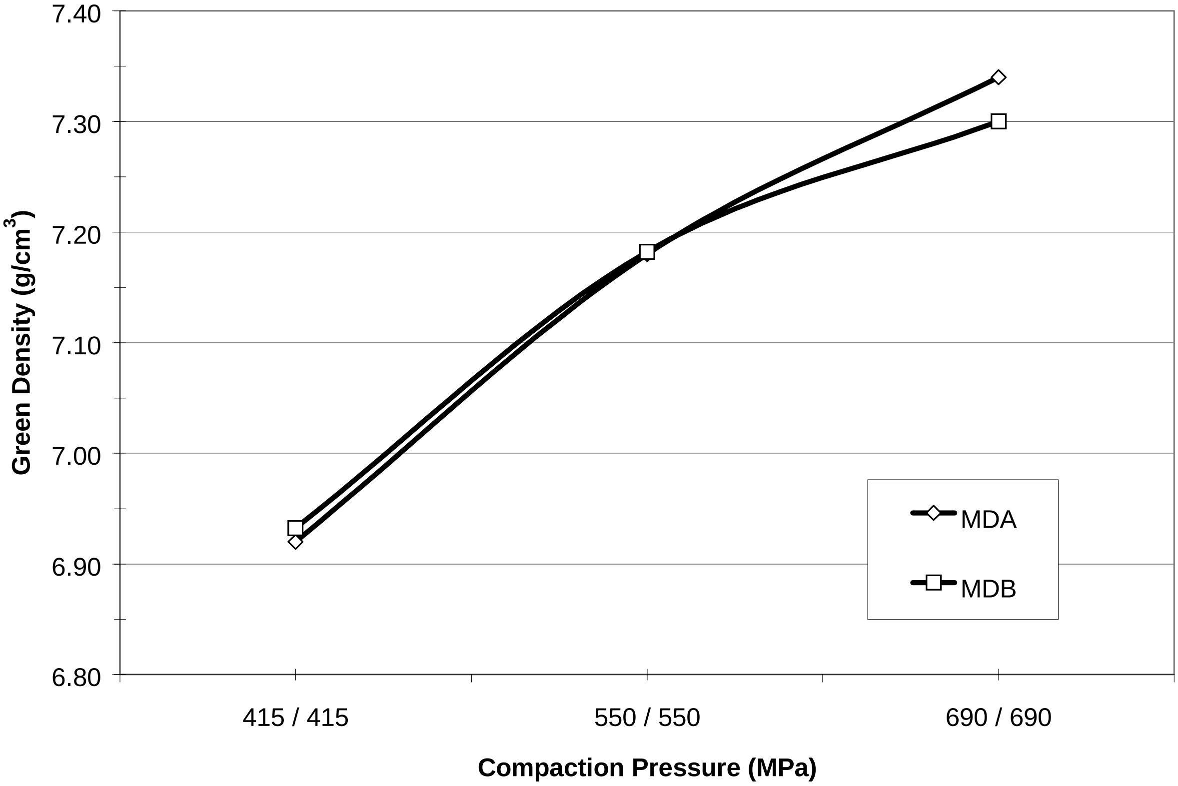

FIGURE 3: Compressibility of MDA and MDB Materials Pressed Under Ambient Laboratory Conditions, Presintered at 800 °C, and Repressed Under Ambient Laboratory Conditions

Sintered Density and Dimensional Change

The exclusion of copper from these systems led to sintered densities that were nearly equivalent to or higher than the green densities. The sintered density and dimensional change information of all materials under the different processing routes are shown in Table II. Dimensional change values for DP/DS specimens were not meaningful due to machining required prior to repressing.

Beyond the obvious advantage of warm compaction in attaining higher densities without requiring additional processing steps, its effect on dimensional change was found to be marked. Identical material compositions (MDB and MDC) were observed to exhibit dimensional change values much closer to die size when warm compaction was chosen over conventional processing. The combination of dimensional control and a 0.13 – 0.16 g/cm^3 increase in density over conventional compaction at comparable pressures made warm compaction an economical choice for higher density processing.

Tensile and Impact Properties

At the time of submission of this manuscript, mechanical testing was continuing on each material under various processing conditions. Therefore, the full matrix of properties was unavailable for presentation. However, several interesting results have been noted. While tensile properties for conventionally processed MDA, MDB, and MDC are presented in Figure 4, notable results achieved by enhanced processing methods are presented in Figure 5. Impact testing data, completed to date, is presented in Figure 6.

Material	Processing Method	Compaction Pressure (MPa)	Sintered Density (g/cm^3)	Dimensional Change (%)	Apparent Hardness (HRA)
MDA	Conventional	550	6.89	-0.12	47
		690	7.01	-0.10	50
	DP / DS	550 / 550	7.18	N/A	53
		690 / 690	7.33	N/A	55
MDB	Conventional	550	7.02	-0.25	61
		690	7.13	-0.23	62
	Warm Compaction	550	7.15	-0.11	62
		690	7.29	-0.01	64
	DP / DS	550 / 550	7.23	N/A	63
		690 / 690	7.36	N/A	64
MDD	Warm Compaction	550	7.15	-0.07	55
		690	7.29	0.00	57
MDCL	Warm Compaction	550	7.25	-0.14	63
		690	7.36	-0.09	64
MDC	Conventional & Tempered	550	7.05	-0.59	69
		690	7.16	-0.56	70
	Warm Compaction & Tempered	550	7.17	-0.16	66
		690	7.30	-0.09	69

TABLE II: Sintered Densities, Dimensional Change, and Apparent Hardness Values for Materials Produced by Conventional Compaction, Warm Compaction, and DP/DS

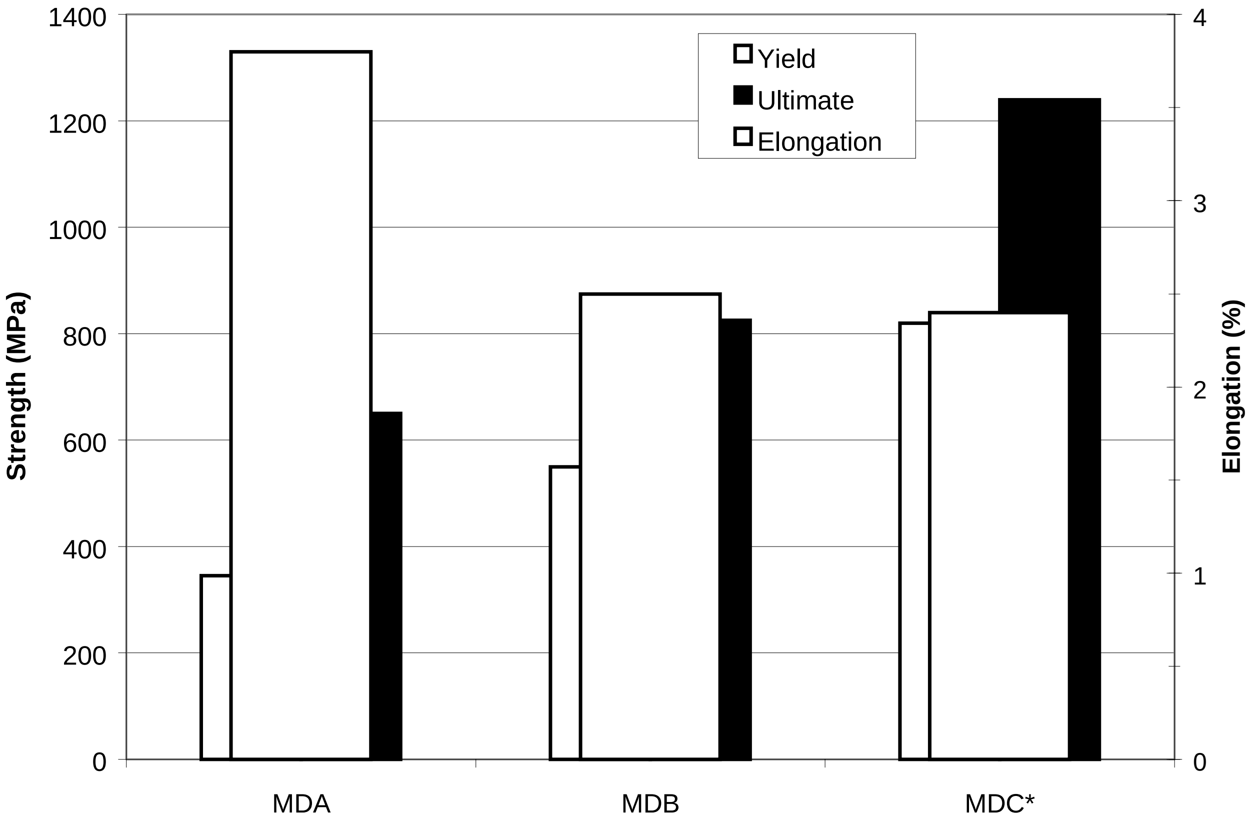

FIGURE 4: Tensile Properties for Materials Compacted at 690 MPa Under Ambient Laboratory Conditions (* MDC Tempered at 190 °C)

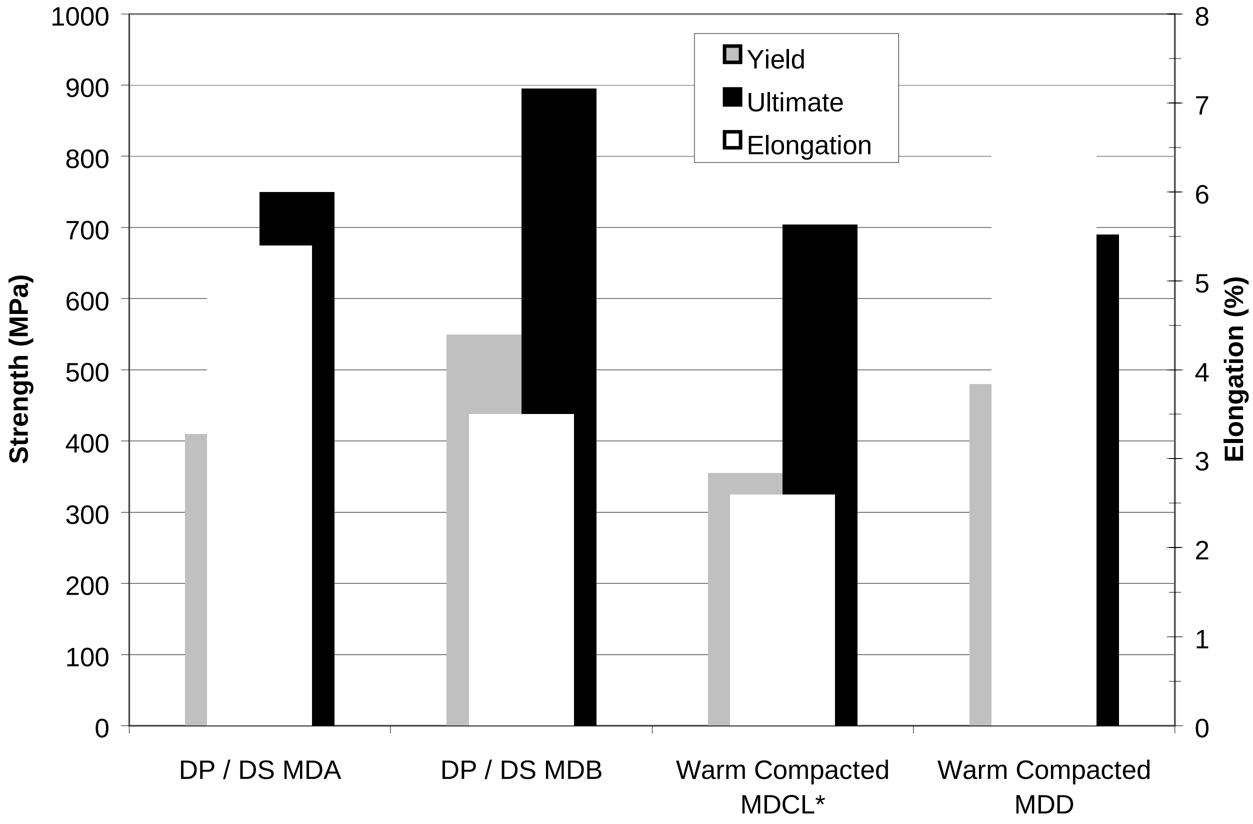

FIGURE 5: Tensile Properties for Selected Materials Processed to Higher Densities by Warm Compaction (690 MPa) or DP/DS (690 / 690 MPa) (* MDCL Tempered at 190 °C)

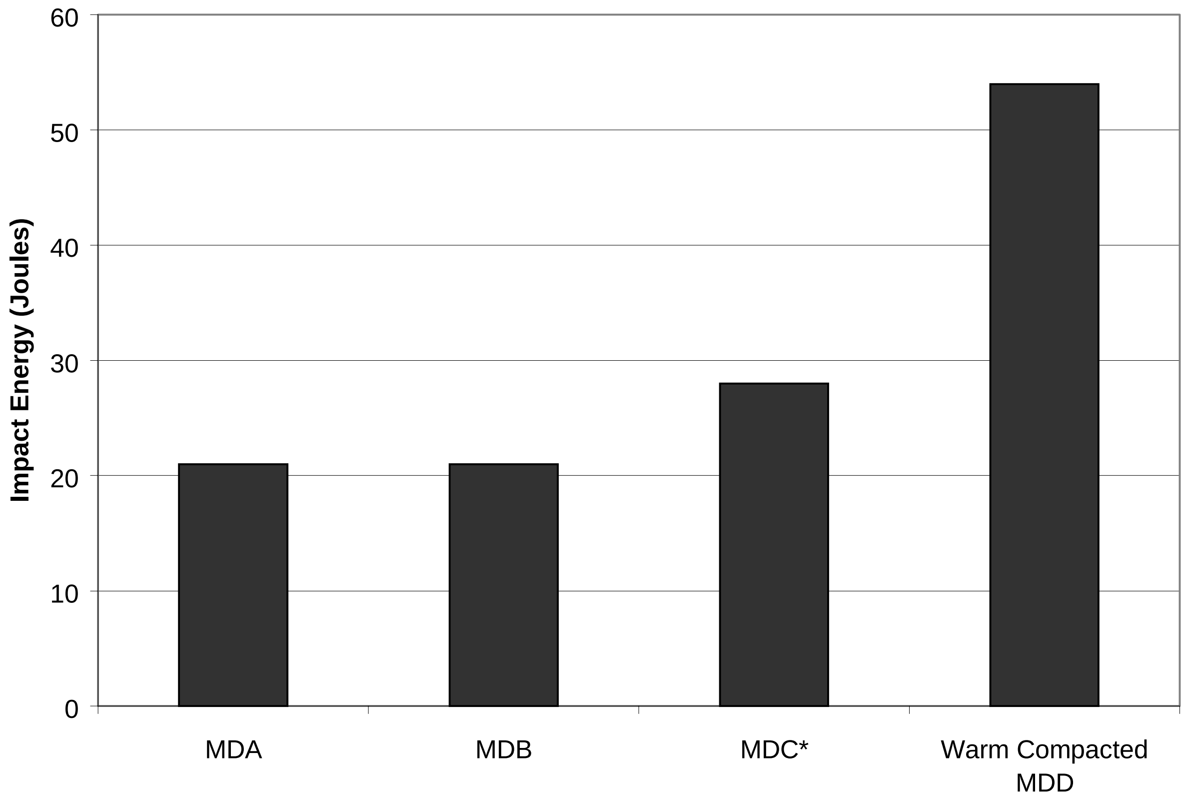

FIGURE 6: Room Temperature Unnotched Charpy Impact Properties for Materials MDA, MDB, and MDC Compacted at 690 MPa Under Ambient Lab Conditions and Warm Compacted MDD Compacted at 690 MPa (* MDC Tempered at 190 °C)

The combination of strength, ductility, and impact properties for these materials was of primary interest. Conventional compaction of Ancorloy MDA, Ancorloy MDB, and Ancorloy MDC was capable of producing property combinations that were extremely competitive with some ductile and malleable cast iron grades. The employment of higher density processing was capable of achieving high ductility at nearly equivalent or higher strength levels than were produced in conventional compaction. Furthermore, the experimental material MDD was found to exhibit tensile and yield strength exceeding 675 MPa and 475 MPa, respectively, while achieving an elongation of nearly 7% and an impact energy over 50 Joules.

CONCLUSIONS

Several new commercial (Ancorloy MDA, Ancorloy MDB, and Ancorloy MDC) and experimental materials (MDCL and MDD) have been evaluated using a number of processing routes. Conventional compaction of ANCORBOND processed materials was found to produce parts with extremely good combinations of strength, ductility, and impact properties. These properties become even more significant when the lower densities / lighter weights of the parts were noted.

The advantages of warm pressing over conventional compaction were found to be 0.13-0.16 g/cm^3 higher densities and dimensional change values closer to die size. Warm compaction offered an economical method to produce higher densities in a single compaction process. As an added advantage to warm compaction, experimental material MDD was able to achieve 7% elongation and over 50 Joules impact energy at moderately high strength levels. The ductility values and impact energies of ANCORDENSE processed MDD coupled with its moderately high tensile strength (675 MPa) were found to be competitive with several grades of malleable and ductile cast iron.

FUTURE WORK

To more fully characterize the properties of the material systems presented in this paper, work continues on the following:

- RCF and RBF testing at several density levels processed by conventional and warm compaction
- Completion of mechanical property testing for the full matrix of materials and processes
- Investigations on quenched and tempered properties
- Utilization of production technology to expand on the material systems presented herein

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