

New High Performance Ferrous P/M Materials for Demanding Automotive Applications

by

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Abstract - Diffusion-alloyed powders have been used for many years in automotive applications such as synchronizer hubs where there is a need for a combination of tensile strength, ductility, and impact energy. Recently, engineered binder-treated premixes have been developed as alternatives to diffusion-alloyed powders including those based on a prealloyed powder (1.5 w/o molybdenum). The engineered binder-treated materials will be compared with their diffusion-alloyed counterparts.

In addition, a series of new ferrous P/M alloys has been developed to match the performance characteristics of malleable and ductile cast irons. The new materials maintain excellent tensile ductility at high strength levels while possessing good impact resistance. Potential applications for these new products include ring gears, helical pinion gears, and parking lock gears for automatic transmissions.

Introduction

While ferrous P/M materials often match the tensile strength of wrought or cast materials they generally have lower tensile ductility, impact energy, and fracture toughness than their wrought or cast counterparts. Diffusion-alloyed materials have become popular because they provide a special combination of tensile strength, ductility, and impact energy in the as-sintered condition coupled with good response to heat treatment. Quench-hardened and tempered ferrous P/M materials based on diffusion-alloyed powders even possess some ductility; a rarity in heat-treated P/M materials.

The additional steps involved in producing diffusion-alloyed powders result in a price premium for such products. Attempts at matching the combination of performance characteristics exhibited by materials based on diffusion-alloyed powders have, until recently, met with no success. Even binder-treated hybrid alloys, based on prealloyed powders that use molybdenum as the principal alloy addition, have failed to match the *combination* of performance characteristics of materials based on diffusion-alloyed powders [1]. They may meet or exceed one or more of the characteristics of the diffusion-alloyed material but they do not match the *combination* of properties of the latter material.

Recently, however, new powders have been developed that match and may even exceed the combination of performance characteristics exhibited by diffusion-alloyed materials [2-6]. The new powders have been given the tradename "Ancorloy™". Ancorloy powders are supplied as binder-treated premixes and are made using a proprietary practice that *does not include diffusion alloying*. Part I of this paper will summarize the mechanical properties of four Ancorloy powders that are binder-treated analogs of commercially available diffusion-alloyed powders.

Gray, malleable, and ductile cast irons are used widely in automotive applications. Gray irons have moderate strength and ductility and P/M copper steels have comparable properties. However, malleable and ductile cast irons have significantly higher mechanical properties compared with gray cast iron, their strength/ductility values depend on whether the cast irons are in the ferritic, pearlitic, or martensitic condition ; ultimate tensile strengths range from 650 to 1000 MPa, yield strengths from 500 to 700 MPa, and elongation values from 2 to 4%.

Ferrous P/M materials, generally, are unable to match the combination of strength and ductility of these higher performance cast irons. Hanejko has shown that while 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), it falls short of the 4% elongation of the cast iron [7,8]. 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 material development program reviewed in Part II of the present paper was aimed at meeting the performance characteristics of malleable and ductile irons without the need for warm compaction. Warm compaction processing of the materials covered in the present paper will result in higher densities and hence increased mechanical properties compared with those reported here. The performance of three new commercial products, marketed under the Ancorloy tradename, will be compared with a number of selected high performance ferrous P/M alloys. These powders are the first in the Ancorloy MD series of binder-treated press-ready premixes.

Part I – Binder-Treated Analogs of Diffusion-Alloyed Powders

Premixes corresponding to MPIF material designations FD-0205 (Distaloy AB base) and FD-0405 (Distaloy AE base) were made using the appropriate diffusion-alloyed powder base and additions of 0.6 w/o (weight %) graphite. Binder-treated premixed analogs of these diffusion-alloyed materials were prepared using a proprietary practice. The premix corresponding to FD-0205 was designated Ancorloy 2, and the one corresponding to FD-0405 was designated Ancorloy 4. Premixes of Distaloy DH-1 and Distaloy HP-1 also were prepared along with binder-treated premixed analogs of the same chemistry as the diffusion-alloyed materials. The binder-treated premix corresponding to Distaloy DH-1 was designated Ancorloy DH-1 while the binder-treated premix corresponding to Distaloy HP-1 was designated Ancorloy HP-1. All the premixes contained 0.6 w/o graphite and all of the premixes were lubricated with 0.75 w/o of Acrawax C. The Ancorloy premixes matched the chemical composition of the corresponding diffusion alloyed materials as indicated in Table 1.

Tensile and impact properties of the various materials were evaluated in the as-sintered, and sintered and tempered conditions. In addition, the FD-0205, Ancorloy 2, FD-0405, and Ancorloy 4 materials were tested in the quench-hardened and tempered condition. Samples were compacted at 415, 550, and 690 MPa respectively. Sintering was carried out at 1120 °C in a Hayes pusher furnace for 30 minutes at temperature in a synthetic dissociated ammonia atmosphere.

The as-sintered and sintered and tempered tensile properties were based on as-pressed dog-bone specimens while the quenched and tempered properties were measured on machined round

Material Designation	Fe	Ni	Cu	Mo
FD-0205 Ancorloy 2	balance	1.75	1.5	0.5
FD-0405 Ancorloy 4	balance	4.0	1.5	0.5
Distaloy DH-1 Ancorloy DH-1	balance	-	2.0	1.5
Distaloy HP-1 Ancorloy HP-1	balance	4.0	2.0	1.5

Table 1 - Composition of the Experimental Premixes (w/o)

specimens conforming to ASTM E 8. The round specimens were polished parallel to the tensile axis to a 1 μ m RMS finish using metallurgical grade emery paper. The reported values are, in all cases, based on a minimum of three measurements and, in most cases, five measurements per condition.

When applied, the after sintering tempering treatment was a stress relief at 175 °C for 30 minutes in air.

The through-hardening heat treatment consisted of austenitizing the sintered specimens at 870 °C for 30 minutes at temperature in an endothermic gas atmosphere followed by quench-hardening in oil at 60 °C. To prevent decarburization, the carbon potential of the atmosphere was set to the nominal carbon content of the specimens. Tempering, in this case, was at 200 °C for 1 hour in nitrogen.

Tensile testing was performed on a Tinius Olsen machine at a crosshead speed of 0.6 mm/min. The machine was equipped with a 25 mm extensometer and provided automated readouts of the 0.2% offset yield strength, ultimate tensile strength, and percentage elongation values.

Apparent hardness measurements were made using the Rockwell A scale (diamond indenter and 60 kgf load). The “A” scale has the convenience of covering the whole of the “C” scale and most of the “B” scale.

Ancorloy 2 and Ancorloy 4 vs. Distaloy AB and Distaloy AE

The quench-hardened and tempered tensile properties of the various materials are shown graphically in Figures 1a and 1b. The yield and ultimate strength values for the Ancorloys generally exceeded those of the diffusion-alloyed materials. However, the magnitude of the difference was not great. The yield strength improvements typically were less than 10% overall. The ultimate strength of the material based on Ancorloy 4 was similar to that for the corresponding diffusion-alloyed material while that for Ancorloy 2 was about 5% higher than its counterpart. The differences in elongation were too small to be of practical significance.

The as-sintered and the sintered and tempered ultimate tensile strength data versus compaction pressure for the various materials are summarized graphically in Figures 2a and 2b. Tempering, or

more precisely stress relieving, of the sintered specimens was performed because of the improvement in properties known to result from such a treatment for diffusion-alloyed materials with graphite additions of 0.6 w/o and higher [9]. The ultimate strengths of the Ancorloy materials exceeded those of the diffusion-alloyed materials in both the as-sintered and the sintered and tempered conditions at all three compaction pressures.

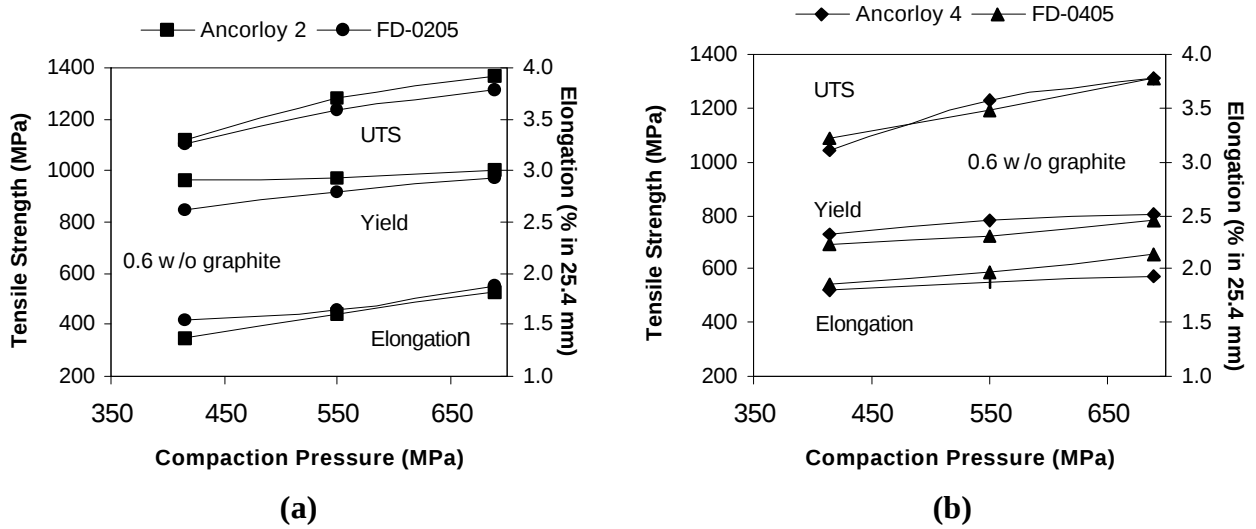


Figure 1: Quench-hardened and tempered tensile properties versus compaction pressure; (a) Ancorloy 2 vs. Distaloy AB, and (b) Ancorloy 4 vs. Distaloy AE.

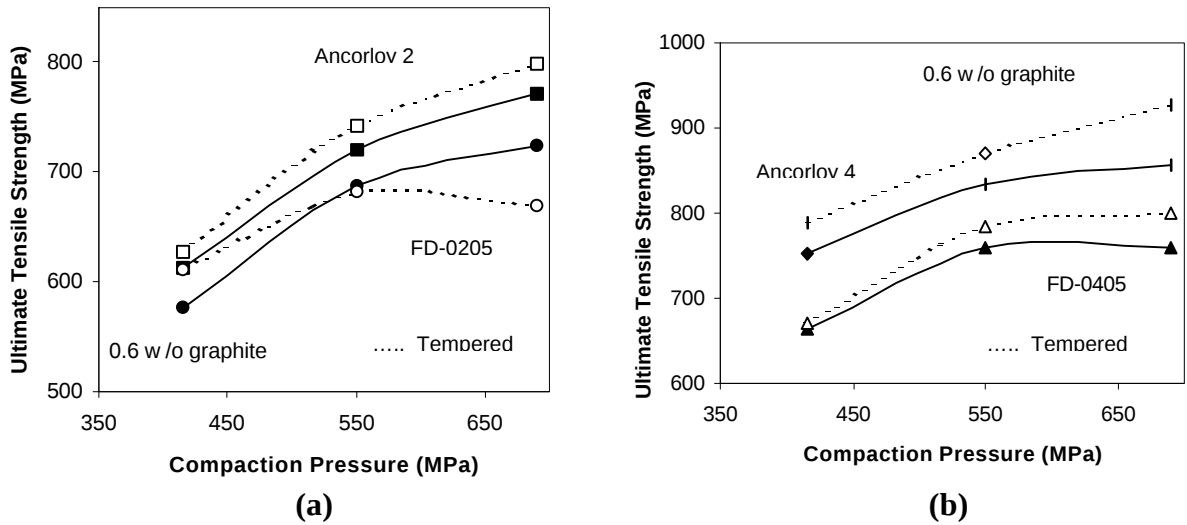


Figure 2: Ultimate tensile strength versus compaction pressure; (a) Ancorloy 2 vs. Distaloy AB, and (b) Ancorloy 4 vs. Distaloy AE.

The as-sintered and the sintered and tempered yield strength results versus compaction pressure are shown graphically in Figures 3a and 3b. The yield strengths of the Ancorloy materials exceeded those of the diffusion-alloyed materials in both the as-sintered and the sintered and tempered conditions and at all three compaction pressures. The relative improvement was generally upwards of 15%, and in a few instances exceeded 20%.

In contrast to the results for ultimate tensile strength and yield strength, the elongation of the Ancorloy materials was less than that of the diffusion-alloyed materials. The data indicates an

inverse relationship between yield strength and elongation. The trendline for Ancorloy 4 and Distaloy AE in the as-sintered condition for a compaction pressure of 550 MPa is shown in Figure 4. It seems likely that at an equivalent yield strength the Ancorloy and diffusion-alloyed materials should exhibit equivalent tensile ductility. Tensile specimens of the Ancorloy materials were prepared, therefore, with graphite additions of 0.45 w/o at compaction pressures of 415, 550, and 690 MPa, in both the as-sintered and the sintered and tempered conditions. The results of the

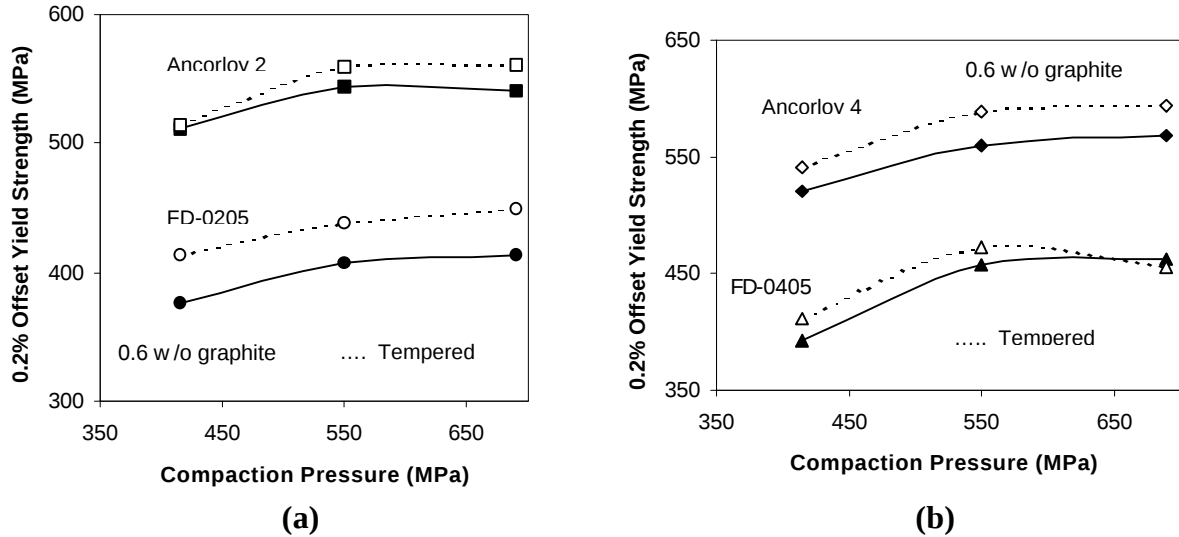


Figure 3: Yield strength versus compaction pressure; (a) Ancorloy 2 vs. Distaloy AB, and (b) Ancorloy 4 vs. Distaloy AE.

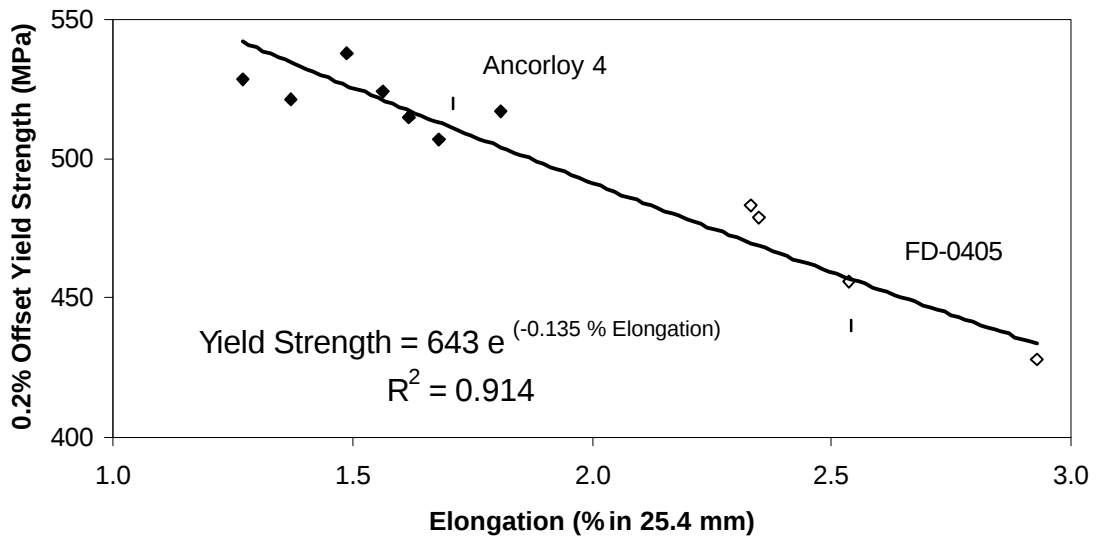


Figure 4: Relationship between the as-sintered yield strength and elongation for Ancorloy 4 and Distaloy AE samples compacted at 550 MPa.

tensile testing are summarized for Ancorloy 4 in Figures 5 and 6. The reduced graphite addition (0.45 w/o) in the Ancorloy materials resulted in yield strength values equivalent to those of the diffusion-alloyed materials with 0.6 w/o graphite (Figure 5). At an equivalent yield strength, the Ancorloy materials have comparable elongation values to the diffusion-alloyed materials (Figure 6).

Ancorloy DH-1 vs. Distaloy DH-1

The tensile strength of Distaloy DH-1 and a binder-treated analog are shown to be comparable in Figure 7a. The specimens were stress relieved at 175 °C. Their apparent hardness values are also shown to be comparable in Figure 7b.

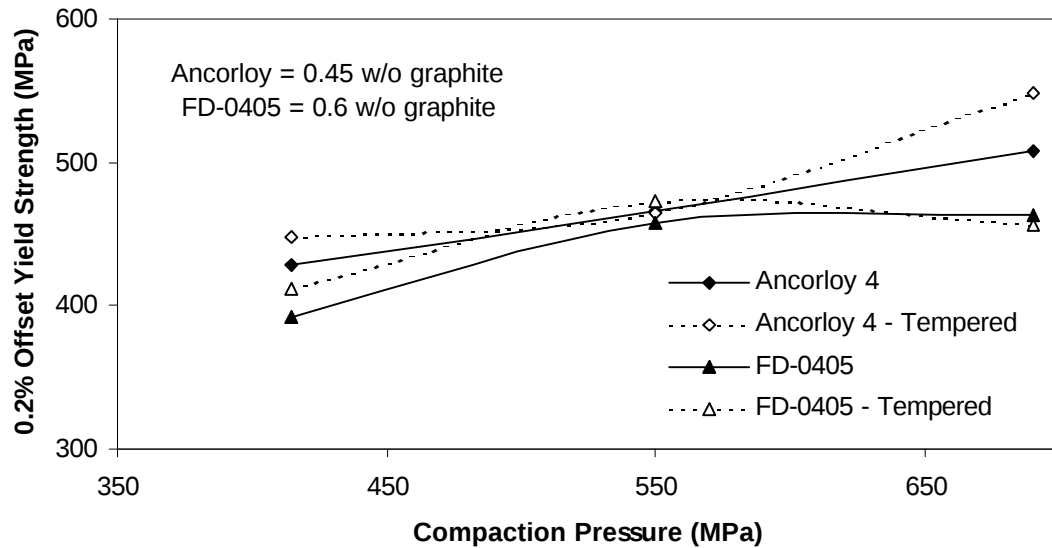


Figure 5: 0.2% offset yield strength versus compaction pressure for Ancorloy 4 and Distaloy AE samples with equivalent yield strength.

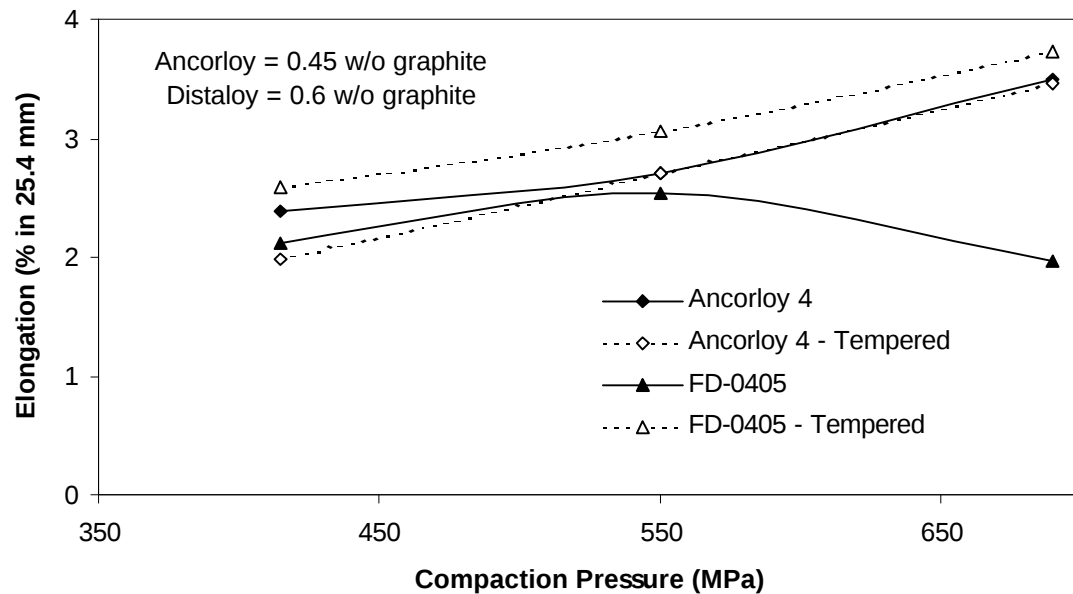


Figure 6: Elongation versus compaction pressure for Ancorloy 4 and Distaloy AE samples with equivalent yield strength.

Ancorloy HP-1 vs. Distaloy HP-1

The tensile strength and ductility of samples compacted from Ancorloy HP-1 and Distaloy HP-1 are shown to be similar in Figures 8a and 8b. They also have comparable apparent hardness values – Figure 8c.

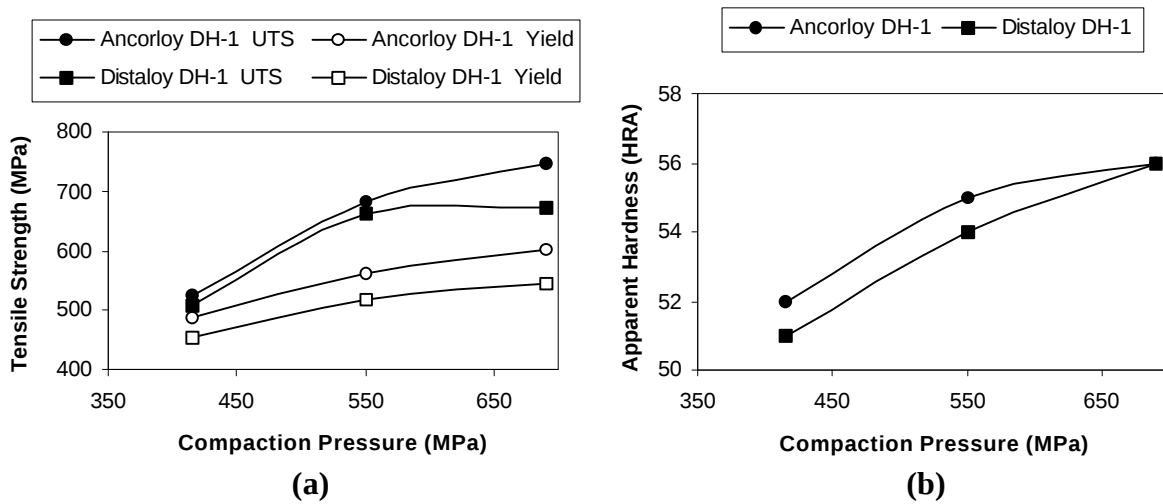


Figure 7: Tensile strength and apparent hardness versus compaction pressure for Ancorloy DH-1 and Distaloy DH-1 samples.

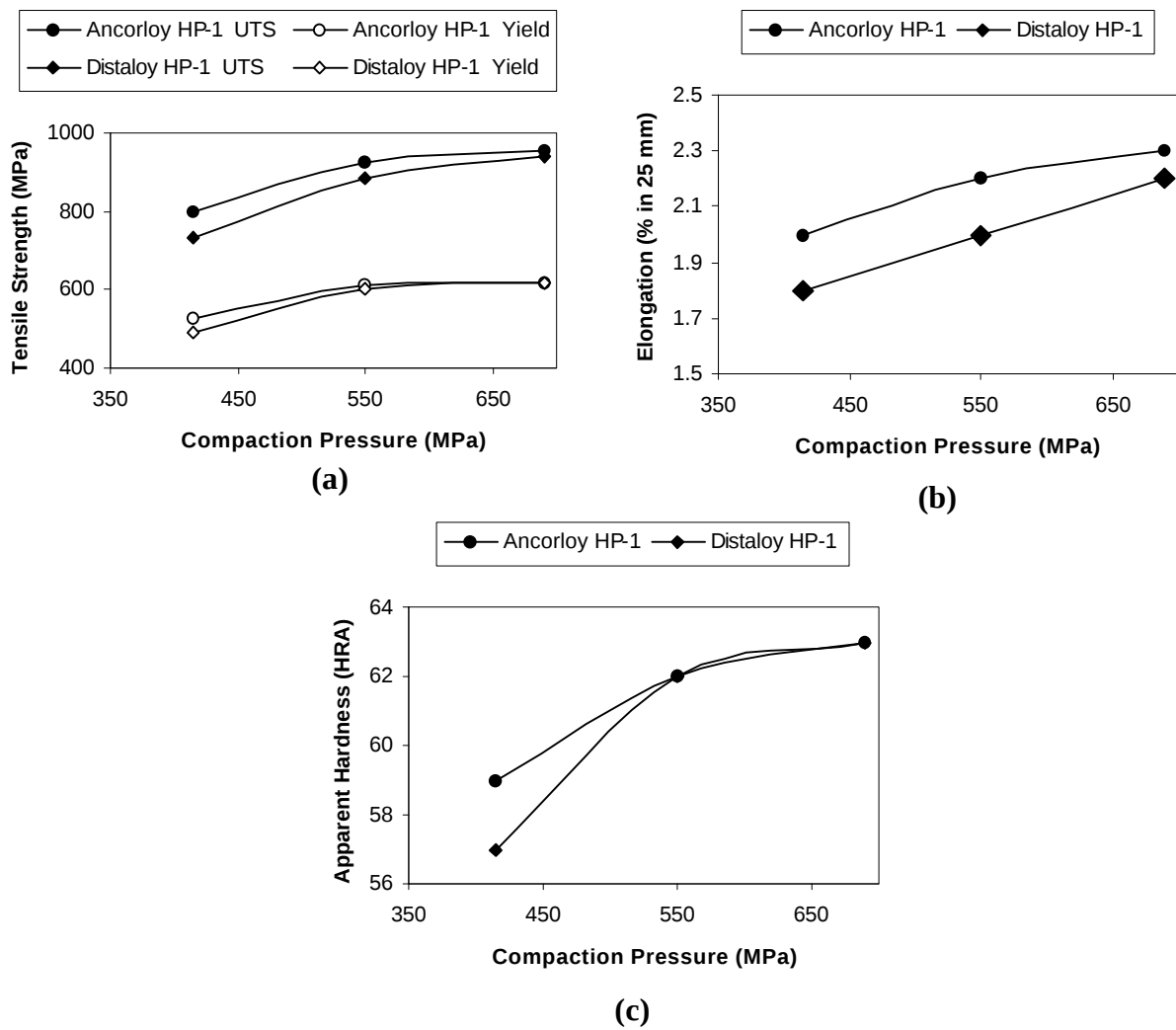


Figure 8: Tensile strength, elongation and apparent hardness versus compaction pressure for Ancorloy HP-1 and Distaloy HP-1 samples.

Conclusions: Part I – Binder-Treated Analogs of Diffusion Alloyed Powders

Engineered binder-treated premixes have been developed as alternatives to diffusion-alloyed powders. The new materials have been given the tradename of “Ancorloy”. In the as sintered as well as the sintered and stress relieved condition, Ancorloy 2 and Ancorloy 4 based materials exhibit higher ultimate tensile strength, yield strength, and apparent hardness than diffusion alloyed materials of similar chemistry with the same graphite addition. However, the elongation of the diffusion-alloyed materials is greater than that of the Ancorloys.

An inverse relation has been demonstrated, in the as-sintered condition, between the yield strength and elongation of the materials. At comparable levels of yield strength the materials have equivalent values of tensile elongation. The difference in as-sintered strength at equivalent carbon contents may be explained on the basis of the base powder used to make the materials. The diffusion-alloyed powders are based on a water atomized iron powder whereas the binder-treated analogs are hybrid alloys based on a prealloyed water atomized alloy base.

In the quench-hardened and tempered condition, for samples with a 0.6 w/o graphite addition, the ultimate tensile strengths, yield strengths, elongations, apparent hardness values, and impact energies of the Ancorloy and diffusion-alloyed materials are very similar.

In addition, compacts made from binder-treated analogs of Distaloy DH-1 and Distaloy HP-1 have been shown to have comparable performance characteristics to those of materials based on the diffusion-alloyed powders. The diffusion-alloyed materials and their binder-treated analogs, in this instance, are both based on a water atomized prealloyed powder (1.5 w/o Mo).

Part II – P/M Alloy Substitutes for Malleable and Ductile Cast Irons

Press-ready, binder-treated premixes were made with 0.75 w/o additions of an ethylenebis-stearamide wax (Acrawax C). The as-sintered materials had the nominal compositions listed in Table 2.

Material	Fe	Si	Cr	Mn	Ni	Mo	C
MDA	Balance	0.7	0.06	0.17	0.05	0.03	0.85
MDB	Balance	0.7	0.03	0.13	2.0	0.85	0.55
MDC	Balance	0.7	0.03	0.13	4.0	0.85	0.55
MDD	Balance	0.7	0.03	0.13	2.0	0.85	0.25

Table 2: Nominal Compositions of the Sintered Materials (w/o)

Tensile and room temperature unnotched Charpy impact properties of the materials were evaluated for samples compacted at 415, 550, and 690 MPa. Materials MDA, MDB, and MDD were tested in the as-sintered condition whereas material MDC was tested after tempering at 190 °C for one hour. Sintering was carried out at 1260 °C in a laboratory Hayes pusher furnace for 30 minutes at temperature in a 75 v/o hydrogen : 25 v/o nitrogen atmosphere.

The as-sintered, and sintered and tempered tensile properties were based on flat, unmachined (dog-bone) specimens conforming to ASTM E 8 (MPIF Std. 10). Tensile testing was performed on a Tinius Olsen machine at a crosshead speed of 0.6 mm/min. Data from an extensometer attached to

the specimens permitted automated readouts of the 0.2% offset yield strength, ultimate tensile strength, and percentage elongation values.

Impact testing was performed at ambient temperature (approximately 20 °C) using standard unnotched Charpy specimens in accordance with ASTM E 23 (MPIF Std. 40).

The reported values for tensile and impact properties were, in all cases, based on a minimum of three measurements and, in most cases, five measurements per condition.

The ultimate tensile strength and yield strength of materials MDA, MDB, and MDD are compared in Figure 9a, their tensile elongation in Figure 9b, and apparent hardness in Figure 9c. Material

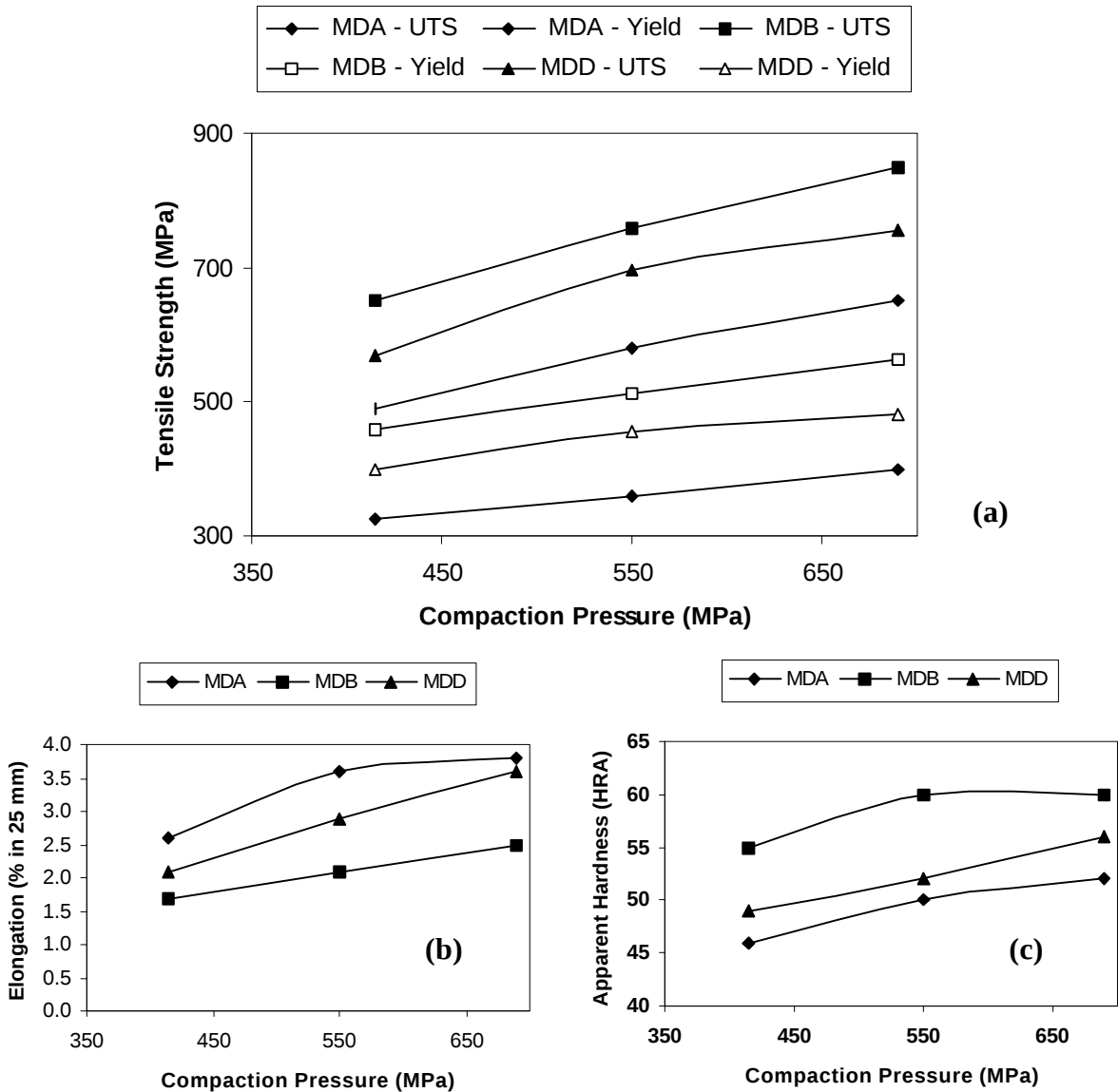


Figure 9: Ultimate tensile strength, yield strength, and apparent hardness versus compaction pressure for materials MDA, MDB, and MDD.

MDD has better tensile strength than material MDA while exhibiting higher tensile ductility. Material MDB has even higher tensile strength but does so at the expense of some ductility. However, the combination of tensile strength and tensile ductility for each of the materials in their

own right is noteworthy. Material MDA has better ductility for a given strength than some copper steels currently used to replace the higher end gray iron cast irons and material MDD extends the range further into the realm of ductile and malleable irons.

In order to establish a frame of reference for the new MDB and MDC alloys, their tensile and impact properties were compared with those of selected high performance ferrous P/M alloys [3,4,9,10]. The materials selected for comparison with materials MDB and MDC were:

1. Ancorloy 4 + 0.6 w/o graphite – sintered at 1120 °C (ref. 3),
2. Ancorloy HP-1 + 0.6 w/o graphite – sintered at 1120 °C (ref. 4),
3. Distaloy HP-1 with 0.5 w/o combined carbon – sintered at 1250 °C (ref. 9), and
4. FLN4-4405 and FLN6-4405 – sintered at 1315 °C (ref. 10).

The ultimate tensile strengths of the various materials are compared in Figure 10a. Material MDC matched the tensile strength of Distaloy HP-1 and FLN6-4405. The diffusion-alloyed material is a hybrid alloy based on a 1.5 w/o prealloyed steel to which 4 w/o nickel and 2 w/o copper have been partially alloyed. The FLN6-4405 material is a hybrid alloy based on a 0.85 w/o molybdenum prealloyed steel to which 6 w/o nickel has been admixed. Material MDC is less highly alloyed than these two materials that exhibited comparable strength.

Material MDB matched the tensile strength of Ancorloy 4, FLN4-4405, and fell just short of matching the strength of Ancorloy HP-1. Each of these materials is more highly alloyed than material MDB.

The only material that reached the yield strength achieved by material MDC was the hybrid alloy FLN6-4405 as illustrated in Figure 10b. The high temperature sintered, high performance diffusion-alloyed material, Distaloy HP-1 fell considerably short of matching the yield strength of the top two materials. The yield strength of material MDB matched that of Ancorloy 4, Ancorloy HP-1, and the hybrid alloy FLN4-4405, all of which are more highly alloyed.

Materials MDB and MDC had tensile elongation values comparable to those for Ancorloy HP-1, FLN4-4405, and FLN6-4405 as shown in Figure 10c. The tensile ductilities of the Ancorloy 4 and the high temperature sintered Distaloy HP-1 were somewhat lower than for the other materials.

The hybrid alloy FLN6-4405 had the best impact properties. However, as may be seen in Figure 10d, material MDC matched the performance of Distaloy HP-1 and FLN4-4405. Material MDB had comparable impact properties to those of Ancorloy 4.

Photomicrographs illustrating the microstructure of materials MDB (as-sintered) and MDC (sintered and tempered) are presented in Figures 11 and 12. The microstructure of material MDB consists of martensite, some bainite, and divorced pearlite with some areas of very fine unresolved pearlite. Material MDC has a predominantly martensitic microstructure with some bainitic areas.

Future work will evaluate the fatigue performance of the new materials and production trials will be conducted on potential part applications.

Conclusions: Part II – P/M Alloy Substitutes for Malleable and Ductile Cast Irons

The new materials MDB and MDC exhibited an extremely good combination of tensile strength, tensile ductility, and impact energy. The elevated sintering temperature needed for the materials results in microstructures that contain significant amounts of martensite and the materials are

effectively sinter hardened. Work in progress indicates the optimum tempering temperature for material MDC is 245 °C rather than the 190 °C used in the initial program. Tempering at 245 °C resulted in a 14% improvement in yield strength while maintaining an apparent hardness of over 65 HRA. The optimum tempering temperature for material MDB appears to be 300 °C. Tempering at this temperature resulted in an 11% increase in yield strength compared with untempered material.

The new materials, MDA, MDB and MDC, are marketed under the tradenames Ancorloy MDA, Ancorloy MDB, and Ancorloy MDC. Their performance matches many of the characteristics of a number of malleable and ductile cast irons and they should be evaluated with respect to potential applications such as ring gears, pinion gears, and carriers.

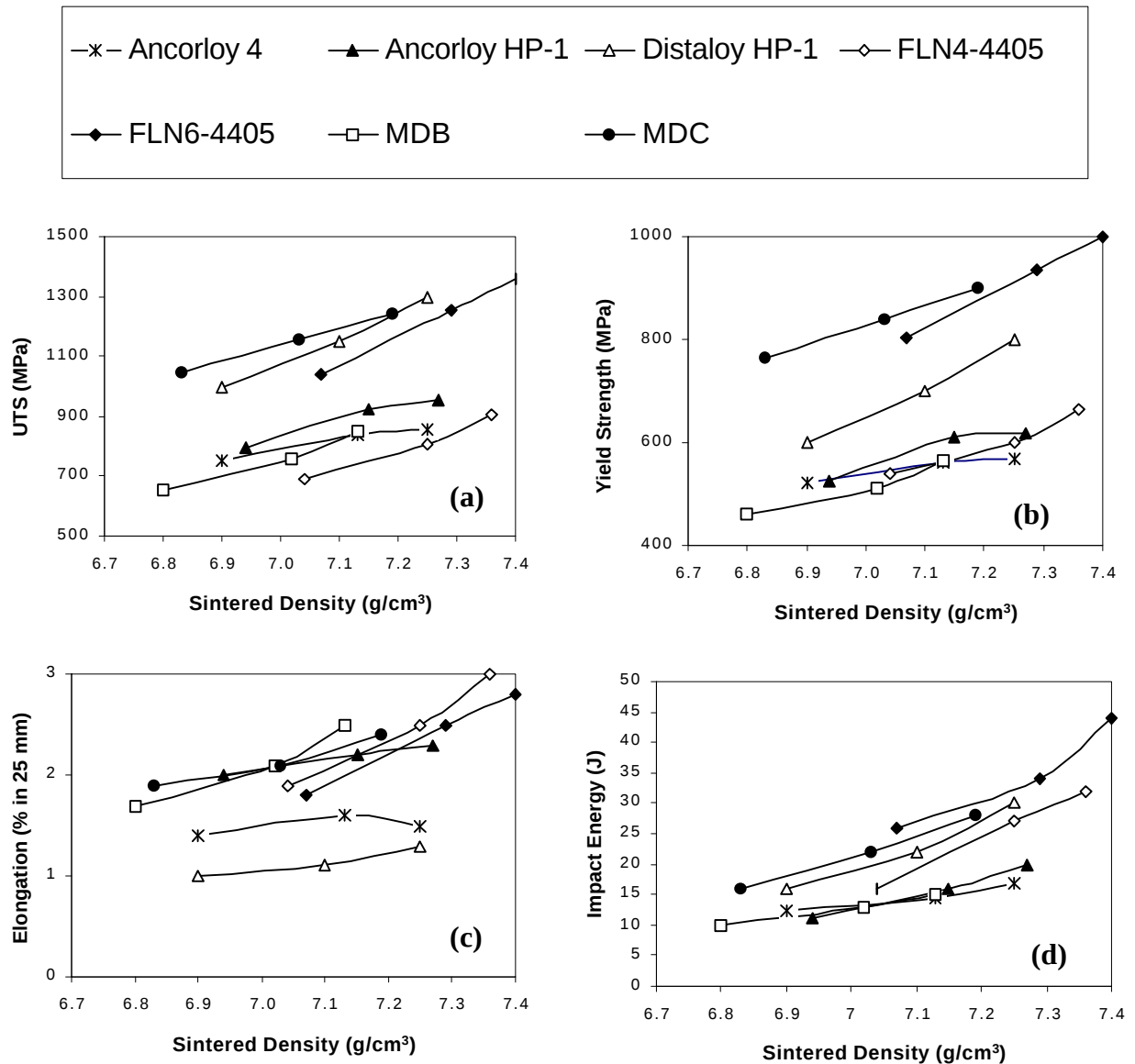


Figure 10: Effect of sintered density on the ultimate tensile strength, 0.2% offset yield strength, tensile elongation, and room temperature impact energy of selected high performance ferrous P/M materials.

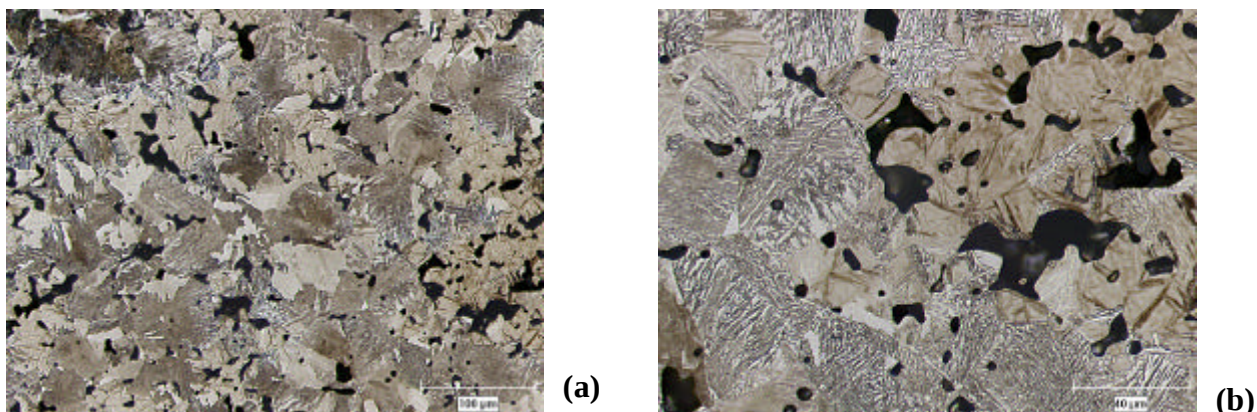


Figure 11: Microstructure of material MDB. Etched 2% nital / 4% picral. Original magnification: a = 200X ; b = 500X.

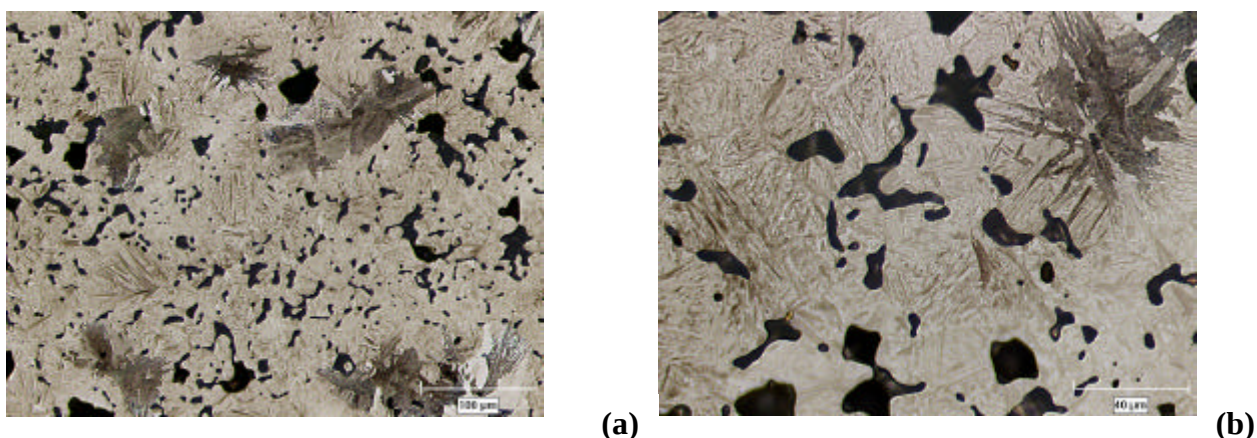


Figure 12: Microstructure of material MDC. Etched 2% nital / 4% picral. Original magnification: a = 200X ; b = 500X.

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