

Advances in High Performance PM Alloys For Automotive Applications

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ABSTRACT

The as-sintered and the sintered and tempered transverse rupture and tensile properties of seven recently developed high performance PM compositions are reviewed. Two are improved versions of the well known diffusion alloyed grades according to MPIF Standard 35. Two others are likewise improved versions of more highly alloyed analogs of the latter that have only recently been introduced. The remaining three are all new compositions that take advantage of the powerful alloying effects of silicon. The silicon is added by a proprietary method that greatly reduces its susceptibility to oxidation during sintering, an effect that has heretofore limited its use.

INTRODUCTION

Ancorloy® is the trade name of a series of high performance premixes that include binder treatment as an integral processing step in their manufacture. Ancorloy 2 and 4, introduced in 1999, were the first of the series, (1). Compositionally, they are essentially analogs of the diffusion alloyed grades according to MPIF Standard 35. As such, their base alloy contents nominally include 0.5 w/o Mo and 1.5 w/o Cu each and 1.75 and 4.0 w/o Ni respectively.

Ancorloy DH-1 and HP-1 are analogs of diffusion alloyed grades that were originally developed abroad and first introduced

domestically in June of 2000, (2). Both have a base molybdenum content of 1.5 w/o. In addition, the DH-1 grade contains 2.0 w/o Cu and is generally recommended for 'direct hardening' applications, (i.e. sinter hardening), from which it derives the DH designation. In comparison, the HP-1 grade contains 1.75 w/o Cu and 4.0 w/o Ni in addition to the alloy base and consequently is basically a high molybdenum version of the aforementioned Ancorloy 4. The HP in its designation is to indicate that it is designed for 'high performance' applications.

The remaining grades in the series, also introduced in June of 2000, are the Ancorloy MD compositions including Ancorloy MDA, MDB and MDC, (3, 4). The MD in their designations derives from the fact that their properties rival those exhibited by the malleable and ductile cast irons. All three include 0.7 w/o Si in their base compositions. Ancorloy MDA is otherwise a plain carbon grade whereas Ancorloy MDB and MDC are both alloy grades containing 0.85 w/o Mo each and 2.0 and 4.0 w/o Ni respectively.

Taken together, these seven grades incorporate the very best of what is currently known of premix technology and alloying theory. As binder treated premixes, they offer a virtually unsurpassed combination of advantages including both economy and reproducibility in parts

making. In terms of alloying, the MPIF Standard 35 compositions are generally recognized as providing properties that are among the highest attainable by the PM process, (5). Consequently, they generally find use in applications which have fairly demanding requirements. As will be seen, both the Ancorloy analogs of these grades and, in all but one case, the other grades in the series exhibit still higher properties. Thus, the purpose of the present report is to review these improvements with a view to extending the general applicability of the PM process to the manufacture of parts of yet more demanding requirements.

EXPERIMENTAL PROCEDURE

In general, the experimental procedure consisted of making binder treated mixes of the subject compositions and determining their mechanical properties in accordance with standard test methods. The details of the procedure differed somewhat for the analogs of the diffusion alloyed grades and the MD compositions. Test specimens of the diffusion alloyed analogs were sintered at 2050 °F, (1120 °C), and referenced with comparably processed specimens of the actual diffusion alloys as standards of comparison. In contrast, the specimens of the MD alloys were sintered at 2300 °F, (1260 °C), and were generally not referenced with other PM compositions since the comparison in this case was ultimately to the properties of the malleable and ductile cast irons. In other respects, the details of the procedure were generally the same for every composition.

All of the Ancorloy premixes were binder treated using the ANCORBOND® process. Either of two mix sizes were used in the study: 1) pilot size mixes of 500 lbs.; or 2) production size mixes of 10,000 lbs. The premixes of the diffusion alloyed standards, however, were all bench size and made according to regular mixing practices. The carbon content of the MDA mix was nominally 0.90 w/o whereas the carbon content of the other mixes was in every

case nominally 0.6 w/o. All of the mixes were lubricated with 0.75 w/o of Acrawax C. The transverse rupture, tensile and apparent hardness properties of the premixes were determined. The reported values are in all cases based on a minimum of three measurements and, in most cases, five measurements per condition.

The transverse rupture properties including the strength, (ASTM B528), % dimensional change, (ASTM B610), and density, (ASTM B331), were determined on standard 0.25", (~10mm), specimens. The premixes of the diffusion alloyed analogs were compacted to a common density of 6.8 g/cm³ whereas those of the MD alloys were compacted to a common pressure of 40 tsi, (550 MPa). Sintering in each case was at the earlier mentioned temperatures and otherwise for 30 minutes at temperature under cover of a synthetic dissociated ammonia atmosphere.

The tensile properties were in all cases based on as-compacted dog-bone specimens, (ASTM E 8), pressed to 30, 40, and 50 tsi, (415, 550 and 690 MPa). Limited density checks of the specimens were conducted prior to testing by the immersion method, (ASTM B 328). Sintering in this phase of the studies employed essentially the same conditions as previously listed. Tensile testing was performed on an Instron machine at a crosshead speed of 0.02 ins./minute. The machine is equipped with a 1 inch, (25 mm), extensometer and provides automated readouts of the 0.2% offset yield strength, ultimate tensile strength and percent elongation values.

As indicated in the accompanying discussion, some of the specimens were tested in the as-sintered condition and some in the sintered and tempered condition. The tempering treatment most generally employed was basically a stress relief at 375 °F, (190 °C), for 30 minutes in air. For ease of comparison, all of the apparent hardness measurements of the study were made using the Rockwell "A"

scale, (a 60 kgf load and a diamond indenter).

RESULTS AND DISCUSSION

The Ancorloy series represents an essentially natural progression of alloying theory and PM processing capabilities, starting with Ancorloy 2 and 4, continuing through Ancorloy DH-1 and HP-1 and culminating in Ancorloy MDA, MDB and MDC. Consequently, it's appropriate to report and discuss their properties accordingly.

Ancorloy 2 and 4

The base powders of the premixes that were used to reference the Ancorloy 2 and 4 compositions in these studies were the well known diffusion alloyed grades, Distaloy® AB and AE. Although the Ancorloy premixes had identically the same compositions as the respective Distaloy premixes, there was nevertheless a significant alloying difference between them. The Ancorloys were made with Ancorsteel 50 HP, a 0.5 w/o molybdenum containing prealloy which was specially developed for these compositions. In contrast, the Distalloys were made with a commercially pure iron powder that was subsequently submitted to diffusion alloying. Since the primary objective of this process is to bond the alloy additives to the iron rather than to homogenize them, the alloying inherent in the Distalloys, especially as regards the molybdenum is relatively incomplete in comparison with that of the Ancorloys. Thus, given the fact that the specific hardenability of molybdenum in

these compositions is second only to that of carbon, the upshot is that the Ancorloys typically exhibit substantially better mechanical properties than the Distalloys.

The as-sintered transverse rupture properties of Ancorloy 2 and 4 versus their similarly processed Distaloy references are shown below in Table 1. As will be evident from a cursory review of the data, the strength and hardness values of the Ancorloys are upwards of 10% higher than those of the Distalloys.

Its also noteworthy here that the data show that the sinterabilities of the Ancorloys, as indicated by their slightly lower dimensional change values, are somewhat greater than those of the Distalloys. Presumably, this too is a result of the differences in the respective methods of manufacture. For example, the base powders of the Ancorloys are essentially in the as-is condition prior to premixing and therefore, in their most sinterable state. The base powders of the Distalloys, on the other hand, are almost certainly not. The reason is simply that one of the attendant effects of the bonding and agglomeration that's inherent in the diffusion alloying process is to reduce the specific surface of the base powder and hence its sinterability.

The sintered and tempered tensile properties of these same four premixes are shown overleaf in Table 2. Here again, a cursory review of the data will show that the strength and hardness values of the Ancorloys were substantially in excess of those of the Distalloys.

Table 1 - As-Sintered Transverse Rupture Properties of Ancorloy 2 and 4 Versus Those of Distalloys AB and AE

Grade ID	Sintered Density	Trans. Rupt. Stg.		Dim. Chg.	Hardness
	gms/cm ³	psi x 10 ⁻³	(MPa)	%	R _A
Ancorloy 2	6.77	176.3	1216	-0.05	54
Distaloy AB	6.77	158.0	1090	0.01	49
Ancorloy 4	6.82	202.9	1399	-0.27	60
Distaloy AE	6.80	172.9	1192	-0.16	54

Table 2 - Sintered and Tempered Tensile Properties of Ancorloy 2 and 4 Versus Those of Distalloys AB and AE.									
Grade ID	Comp. Press.		Yield Stg.		UTS		Elong.	Hard.	Sint. Den.
	tsi	(MPa)	psi x 10 ⁻³	(MPa)	psi x 10 ⁻³	(MPa)	% in 1"	R _A	grms/cm ³
Ancorloy 2	30	415.0	74.6	514.4	91.1	628.0	1.14	54.1	6.95
	40	550.0	81.0	558.5	107.8	743.7	1.84	56.8	7.15
	50	690.0	81.4	561.3	115.9	799.5	2.12	58.8	7.23
Distaloy AB	30	415.0	59.9	413.1	88.8	612.4	2.23	50.6	6.95
	40	550.0	63.6	438.6	98.9	682.1	2.75	53.6	7.16
	50	690.0	65.1	449.0	97.2	670.3	2.60	55.3	7.24
Ancorloy 4	30	415.0	78.4	540.7	114.2	787.6	1.66	57.3	7.01
	40	550.0	85.4	589.0	126.3	871.0	1.92	60.7	7.21
	50	690.0	86.0	593.1	134.5	927.6	2.26	61.8	7.28
Distaloy AE	30	415.0	59.7	411.7	97.1	669.7	2.59	52.7	6.97
	40	550.0	68.6	473.1	113.8	784.8	3.06	56.1	7.17
	50	690.0	66.1	455.9	116.1	800.7	3.13	57.5	7.25

It is of interest here to note that while tempering after sintering is not a common P/M practice, it's not that unusual with high alloy compositions containing molybdenum. Even at low cooling rates these steels will frequently precipitate low temperature transformation products that give rise to residual stresses which may vary markedly from specimen to specimen in both magnitude and direction. Consequently, to assure valid property comparisons, it's prudent even in the case of adjacent specimens to submit such grades to a low temperature stress relief prior to testing.

Ancorloy DH-1 and HP-1

The studies that were conducted to develop these grades were similar in most details to the earlier studies. The base powders of the premixes that were used to reference the studies were again the analogous diffusion alloyed grades, specifically Distaloy DH-1 and HP-1. Interestingly, however, whereas there had been a significant alloying difference relating to the molybdenum homogeneity of the respective base powders in the Ancorloys and the reference premixes in the earlier study, this

was not the case here. In this instance, both the Ancorloys and the Distalloys were made with the same base powder; this being Ancorsteel® 150 HP, a 1.5 w/o molybdenum containing prealloy that had actually been developed originally for the Distalloys. As a consequence, there was little difference in alloy homogeneity to be expected between the two and, as it turned out, virtually no evidence of the existence of such differences in their respective property levels. Thus, unlike what was seen earlier, the Ancorloy premixes, in this case, exhibited essentially the same properties as the comparable Distaloy premixes.

The most direct indication of this was in the transverse rupture property comparisons which were based on specimens that were initially compacted to the same density. The tensile property comparisons which were based on specimens that were compacted to the same pressures also showed it but not without an analysis to correct for the presence of some rather significant sintered density differences that were also observed. The transverse rupture data are shown below in Table 3.

Table 3 - Sintered and Tempered Transverse Rupture Properties of Ancorloy DH-1 and HP-1 Versus Those of Distalloys DH-1 and HP-1

Grade ID	Sintered Density	Trans. Rupt. Stg.		Dim. Chg.	Hardness
	g/cm ³	psi x 10 ⁻³	(MPa)	%	R _A
Ancorloy DH-1	6.74	164.6	1135	0.23	53
Distaloy DH-1	6.74	154.2	1063	0.30	51
Ancorloy HP-1	6.81	218.2	1505	-0.14	58
Distaloy HP-1	6.82	218.4	1506	-0.11	59

Notice also here that according to the dimensional change figures in these data, the Ancorloys once again exhibited slightly better sinterabilities than the Distalloys.

In addition to the Distaloy references, the tensile property determinations in this case were also referenced with an Ancorloy 4 premix that was submitted to the same processing and otherwise made to the same graphite and lubricant contents. The objective was to assess the effects of the higher molybdenum content of the Ancorloy HP-1 versus the Ancorloy 4 which in other respects is compositionally similar to it. However, in addition, the comparison to the DH-1 grade also showed something of interest. Thus, the results of both grades versus the Ancorloy 4 are shown below in Table 4.

Compositionally, the DH-1 grade differs from the Ancorloy 4 in all three of the major alloy additions but the main differences are in the molybdenum and nickel contents. The molybdenum of the DH-1 at 1.5 w/o is nominally 1 w/o higher than that of the Ancorloy 4. In contrast, the Ancorloy 4 contains 4 w/o of nickel as against a residual level in the DH-1. Thus, the comparison, in this case, gives an indication of the effects of molybdenum on tensile properties versus those of nickel.

A review of the data in Table 4 will show that of the three premixes, the Ancorloy 4 exhibited the highest sintered density at each compacting pressure. In the case of the HP-1 premix, these differences were fairly modest and were due largely to the lower molybdenum content and consequent higher compressibility of the Ancorloy 4. In

Table 4 - Sintered and Tempered Tensile Properties of Ancorloy DH-1 and HP-1 Versus Those of Ancorloy 4.

Grade ID	Comp. Press.		Yield Stg		UTS		Elong.	Hard.	Sint. Den.
	tsi	(MPa)	psi x 10 ⁻³	(MPa)	psi x 10 ⁻³	(MPa)	% in 1"	R _A	grms/cm ³
Ancorloy DH-1	30	415.0	70.8	488.3	76.1	524.8	0.7	52	6.79
	40	550.0	81.2	560.0	99.0	682.8	1.2	55	7.03
	50	690.0	87.3	602.1	108.0	744.8	1.4	56	7.16
Ancorloy HP-1	30	415.0	71.7	498.9	103.6	714.5	1.2	62	6.94
	40	550.0	80.0	551.5	129.9	895.9	1.9	64	7.15
	50	690.0	86.3	595.5	137.8	950.3	1.8	65	7.27
Ancorloy 4	30	415.0	64.0	441.8	97.9	675.2	2.0	54	6.97
	40	550.0	66.9	461.5	110.9	764.8	2.9	57	7.21
	50	690.0	70.5	486.5	118.4	816.6	3.4	59	7.32

the case of the DH-1 premix, however, the differences were more substantial and were considered to be due both to the higher compressibility of the Ancorloy 4 and an effect of its higher nickel content on sinterability. However, regardless of the explanation of these differences, it will be appreciated that direct comparisons of the tensile data in this instance are not appropriate. Instead, it is necessary to limit the comparisons to the findings which correspond to the minimal density differences between the two premixes. As reference to the table will show, these include the data of the Ancorloy 4 premix at the 30 and 40 tsi compacting pressures versus those of the DH-1 at the 40 and 50 tsi pressures.

Interestingly, what these data show is that the compositional differences of the two premixes evidently produced very significant yield strength and ductility differences but almost no difference in their respective ultimate strengths and apparent hardness values. Thus, at both density levels, the yield strengths of the DH-1 premix are upwards of 25% higher than those of the comparable Ancorloy 4 values whereas the elongations of the Ancorloy 4 are well in excess of twice those of the DH-1.

The increased yield strengths of the DH-1 are thought to be correlated with its increased molybdenum content while the higher ductility of the Ancorloy 4 is likely to be an effect of its higher nickel content, (6). The fact that the ultimate strengths and hardnesses of the two premixes were very nearly the same in spite of such significant yield strength differences is likewise almost certainly attributable to the effects of the indicated ductility differences on their respective strain hardening responses and thus, indirectly, to the higher nickel content of the Ancorloy 4, (7).

Somewhat unexpectedly, the comparison of the tensile data of the HP-1 premix with those of the Ancorloy 4 showed something of interest not only about the effects of the

increased molybdenum but also about its effects when present in combination with nickel. As already indicated, the density differences between these premixes were fairly modest. Thus, in this case, direct comparisons of the tensile data at each compacting pressure were considered reasonable if still not quite exact.

In general, what these comparisons showed is that the HP-1 premix exhibited both increased yield strengths as well as higher ultimate strength and hardness values but lower ductility values. The yield strength increases, although more modest than previously, were still fairly substantial being of the order of about 15%. The ultimate strength and apparent hardness increases were likewise of the order of 10 to 15%. In the case of ductility, the differences were smaller than earlier but again rather significant. The Ancorloy 4 elongations now averaged somewhat less than twice those of the HP-1 premix.

The increased yield strengths in this case are again thought to be correlated with the increased molybdenum. The increased ultimate and hardness values are evidently also correlated with it as well. However, the simple fact that the latter increases ran counter to what would be expected on the basis of the ductility differences that were observed was thought to indicate that there was something more going on in the HP-1 than was true with the DH-1. An analysis of the possibilities in this regard suggested the likely existence of significant microstructural differences between the two and subsequent microscopical examinations confirmed their presence. The implication was that the observed ultimate strength and hardness improvements in the HP-1 relative to the Ancorloy 4 reference mix were due not only to its increased molybdenum but also to the presence of the high nickel content of this composition and in particular, to the well known synergy between nickel and molybdenum on hardenability, (8).

Ancorloys MDA, MDB and MDC

These alloys essentially represent a new genre of PM compositions in that they each contain silicon in addition to iron as a base ingredient. The use of silicon as a standard addition is a common attribute of many compositions in ferrous metallurgy and is due largely to its natural affinity for oxygen, (9). However, until recently the various sintering pitfalls associated with this characteristic has prevented its widespread usage in P/M, (10). Thus, its significant then to report that the present alloys came about as a result of the serendipitous discovery of a novel means to incorporate silicon in a P/M composition which completely circumvents these pitfalls.

Other than its affinity for oxygen, silicon is also known for its potent solution hardening effects and for its moderate but notable effects on martensite hardenability, (11, 12). Less well known are its effects in increasing iron diffusivity and brittle fracture resistance, (13, 14). Thus, its addition to existing compositions had considerable potential to effect significant property improvements. As it turned out, this is exactly what was found.

properties that not only exceeded all of the latter but of many of the various malleable and ductile irons that exist as well.

These improvements, of course, are best illustrated by the tensile properties of the subject Ancorloys but are already hinted at in their transverse rupture properties. These are shown below in Table 5. The MDA data in this table are in the as-sintered condition while the MDB and MDC results reflect the sintered and tempered condition. As a matter of interest, the MDA grade was neither expected nor found to be much affected by the tempering conditions that were used with the MDB and MDC grades.

Comparison of these data with those in Tables 1 and 3 will show that the strength and hardness of the MDB equaled the highest values listed for the earlier Ancorloy grades while those of the MDC substantially exceeded them. A similar comparison in the case of the MDA, of course, is not very meaningful because its not truly an alloy steel in the same sense as these other Ancorloys. Interestingly, however, its strength and hardness values

Table 5 - Transverse Rupture Properties of Ancorloy MDA, MDB and MDC.

Grade ID	Sintered Density gms/cm ³	Trans. Rupt. Stg. psi x 10 ⁻³ (MPa)		Dim. Chg. %	Hardness R _A
Ancorloy MDA	6.77	141.5	976	-0.14	46
Ancorloy MDB	6.76	222.6	1535	-0.31	61
Ancorloy MDC	6.83	283.0	1952	-0.61	64

Ancorloy MDA which is otherwise a straight carbon steel like an MPIF Standard 35 F-0008, exhibited properties like those of the copper steels, FC 0208. Ancorloy MDB which is basically a silicon modified version of a widely used hybrid alloy with nickel and molybdenum exhibited properties that somewhat exceeded all but the most highly alloyed of the earlier mentioned Ancorloys. Ancorloy MDC which nominally doubles the nickel content of the MDB exhibited

were nominally equivalent to the most current averages obtained from standard FC 0208 QC testing of almost an entire year's production of Ancorsteel 1000, (15).

The tensile properties of the subject grades are shown overleaf in Table 6. Here again, the MDA data in the table are in the as-sintered condition while the MDB and MDC results are in the sintered and tempered condition.

Table 6 - Tensile Properties of Ancorloy MDA, MDB and MDC.									
Grade ID	Comp. Press.		Yield Stg		UTS		Elong.	Hard.	Sint. Den.
	tsi	(MPa)	psi x 10 ⁻³	(MPa)	psi x 10 ⁻³	(MPa)	% in 1"	R _A	grms/cm ³
Ancorloy MDA	30	415.0	47.0	325	71.3	492	2.6	46	6.66
	40	550.0	52.3	360	84.2	581	3.6	50	6.91
	50	690.0	58.2	400	94.3	650	3.8	52	7.04
Ancorloy MDB	30	415.0	73.1	504	97.6	673	1.8	56	6.80
	40	550.0	81.5	562	113.6	783	2.2	61	7.02
	50	690.0	89.8	619	127.0	876	2.6	61	7.13
Ancorloy MDC	30	415.0	111.1	766	151.3	1043	1.9	63	6.83
	40	550.0	122.4	844	168.1	1159	2.1	67	7.03
	50	690.0	119.3	823	181.0	1248	2.4	68	7.13

Owing to sintered density differences, comparison of these data with those of the earlier Ancorloys is not quite as direct as in the case of the transverse rupture findings. However, the general indications of the data are nevertheless essentially the same. Accordingly, for comparable sintered densities, the strengths and hardnesses of the MDB premix either equaled or slightly exceeded the highest values recorded in the earlier data while those of the MDC substantially exceeded them and moreover, did so quite independently of density. In general, the elongation values in the two data sets were reasonably similar.

Here again, owing to its lower alloy content, comparison of the MDA premix with the earlier Ancorloys is not really appropriate.

However, at equivalent or near densities, its of interest to note that the values shown for it in the Table 6 are substantially in excess of the minimum requirements which are set out at in MPIF Standard 35 for both the well known copper bearing FC 0208 and nickel bearing FN 0208 grades.

Even more interesting is a general comparison of the data in Table 6 with the specifications for automotive applications of malleable iron castings as reproduced below in Table 7. A cursory review of the data in these tables will show that the Ancorloy properties generally compare very well with the requirements of all but the highest ductility grade, (i.e. the first one listed). Thus, given the present threat to the ductile iron industry due to environmental

Table 7 - Tensile Property Requirements Of Malleable Iron Castings For Automotive Applications According To SAE J158, (ASTM A 602).						
Grade ID	Yield Strength		Tensile Strength		Elongation	Hardness
	psi x 10 ⁻³	(MPa)	psi x 10 ⁻³	(MPa)	% in 2"	R _A
M3210(b)	32	224	50	345	10	50 max
M4504(c)	45	310	65	448	4	52 - 59
M5003(c)	50	345	75	517	3	56 - 62
M5503(d)	55	379	75	517	3	56 - 62
M7002(d)	70	483	90	621	2	60 - 65
M8501(d)	85	586	105	724	1	65 - 67

issues relating to the capital costs of controlling emissions, it will be appreciated that these new PM grades not only represent potentially viable alternatives but may prove in many cases to be timely ones as well.

SUMMARY AND CONCLUSIONS

The transverse rupture and tensile properties of seven recently developed P/M compositions as so-called Ancorloy premixes were reviewed. All include binder treatment as an integral processing step in their manufacture and thus, all offer a virtually unsurpassed combination of advantages over regular premixing in terms of economy and reproducibility in parts making.

In addition, the Ancorloy compositions start with and subsequently build upon the very best of what is known of P/M alloying theory. Thus, Ancorloy 2 and 4, the first two of the series, are the compositional analogs of the diffusion alloyed grades according to MPIF Standard 35. Heretofore, the latter were generally recognized as providing properties that are among the highest attainable by the PM process. However, by virtue of substituting a prealloy as the base powder of the Ancorloys and thus incorporating greater alloy homogeneity than is normally attainable by diffusion alloying, it was shown that substantially better properties were attainable in these new grades.

The next two in the series were Ancorloy DH-1 and HP-1. These two were also the compositional analogs of diffusion alloyed grades that were yet more highly alloyed than the earlier grades. However, in this case, there was no inherent difference between the Ancorloys and the diffusion alloys in terms of alloy homogeneity in that each was made with the same prealloyed base powder. Thus, there was virtually no difference in the properties which they each exhibited. However, it was shown that these new Ancorloys nevertheless did represent a substantial improvement over

the earlier ones in this regard and thus that they offered the possibility of making parts to yet more stringent requirements than was heretofore possible.

The last three in the series are the Ancorloy MDA, MDB and MDC grades. All contain a standard addition of 0.7 w/o of silicon. The MDA grade is otherwise a straight carbon steel whereas the MDB and MDC are both alloy grades which additionally contain nickel and molybdenum. At comparable sintered densities, the properties of the MDA rival those of the well known copper and nickel bearing steels according to MPIF Standard 35 whereas the properties of the MDB and MDC either equal or exceed those of the previously discussed Ancorloys. Of greater significance to the automotive designer, perhaps, is the fact that taken together, these three grades cover almost all of the requirements that are specified for the ductile cast irons in such applications and what's more, are both inherently more economic and very likely to be more available in the very near future as well.

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