Binder-treated Analogs of Diffusion Alloyed Compositions Based On Ancorsteel 150 HP

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Presented at PM^{2}TEC2000
International Conference on Powder Metallurgy & Particulate Materials
May 30 – June 3, 2000, New York, New York.

ABSTRACT

The powder, green and sintered properties of binder-treated analogs of two diffusion alloyed steels based on Ancorsteel 150 HP are presented. These new additions to the binder-treated family of compositions are made according to a proprietary practice that does not include diffusion alloying. It is shown by direct comparison that these new premixes offer significantly improved compressibility and otherwise generally similar powder, green and sintered properties to compositionally similar premixes of the diffusion alloyed steels. The sintered property comparisons presented include theTRS, tensile, and impact properties of the subject compositions in the as-sintered and sintered and tempered conditions.

INTRODUCTION

It was shown last year that binder treatment is a viable alternative to diffusion alloying. Ancorloy 2® and Ancorloy 4® were introduced to the market as the compositional equivalents of Distaloy 4600A® and Distaloy 4800A® and were generally shown to exhibit superior properties in many cases of practical interest, (1). The purpose of the present paper is to report the development of two new additions to the Ancorloy family. Both grades are analogs of diffusion alloyed compositions based on Ancorsteel 150 HP®. Although not yet well known, they are of technical interest overseas and have been generally available in the USA for a few years.

Diffusion alloying is a mature P/M concept. Originally conceived at the Hoeganaes Corporation Riverton laboratory in the early 1960s, it was first applied to the manufacture of a sponge iron based composition. This earliest grade, the compositional forerunner of the present day Distaloy 4600A and Ancorloy 2, was initially marketed under the trade name of Ancoloy, (2). Subsequently, with the advent of the first world class water atomizing facilities at our Riverton plant, the process was adapted to the manufacture of the inherently more compressible water atomized iron powders, (3). Correspondingly, the aforementioned Distaloy 4600A composition eventually displaced the Ancoloy and the more highly alloyed 4800A composition evolved and was likewise marketed under the Distaloy trade name.

Significantly, Distaloy 4600A and Distaloy 4800A are also well known worldwide having been made and marketed abroad as Distaloy AB® and Distaloy AE®. Interestingly, over the years, many more diffusion alloyed compositions have been developed in overseas markets than have been developed here. The underlying reasons appear to be mainly a matter of market dynamics which, of course, vary from place to place. In addition, it seems likely that the lack of large scale water atomizing facilities overseas until recently and the consequent relative expense of the prealloyed powders that were contemporaneously available there versus here were also contributing factors.

In any case, it turns out that in addition to the aforementioned Distaloy 4600A and Distaloy 4800A compositions as well as sponge based versions of each, there presently exist six other diffusion alloys including three so-called copper distaloys and three special performance grades, (4). Two of the three copper grades are sponge iron based and one is steel based. All three are used as premix sources of copper rather than as base powders; their purpose being to provide better dimensional change control than is possible with undiluted copper. The special performance grades mentioned are essentially high molybdenum variants of the Distaloy 4600A and Distaloy 4800A grades. Briefly, they include: Distaloy DC-1, specifically designed for dimensional control and containing 2 w/o Ni and 1.5 w/o Mo; Distaloy DH-1, designed for direct hardening, (i.e. sinter hardening), and containing 2 w/o Cu and 1.5 w/o Mo; and, Distaloy HP-1, an high performance alloy containing 2 w/o Cu, 4 w/o Ni and 1.5 w/o Mo. Currently, all three are made with Ancorsteel 150 HP which is known abroad by the Höganäs trade name of Astaloy Mo. As may also be of interest, these last three compositions are necessarily among the most recent additions to the Distaloy family having been developed subsequent to the independent development in this laboratory of the molybdenum containing prealloys in the late 1980s, (5).

Of these six alloys, the two which were selected for development as Ancorloy grades and which are thus the topics of the present report are the direct hardening and the high performance alloys, (i.e. the DH and HP grades). Actually, all six compositions are potentially manufacturable as binder-treated products. However, only these two appeared to offer anything that was unique in terms of properties and economy compared to what's already available or otherwise feasible. For example, as regards the copper distaloys, preliminary studies here as well as practical experience abroad have shown that it's possible to get the same effects using prealloyed powders which, of course, are both easier and more economical to produce, (6). Similarly, in the case of the dimensional change alloy, (i.e. the DC-1 grade), there is again an attractive alternative. Accordingly, it turns out that the lower molybdenum variant of this composition as made with Ancorsteel 85 HP and binder-treated offers essentially the same dimensional stability and very nearly the same mechanical properties. In addition, this leaner alloy is both more compressible and, of course, more economical, (7).

In comparison, the potential benefits which the direct hardening and high performance grades appeared to offer were as follows. The direct hardening grade was viewed as a lean alloy alternative to the recently developed Ancorsteel 737 SH®, (8). As such, it was expected to provide an economic option in situations where the high hardenability of the latter is greater than what’s actually needed. Correspondingly, the high performance grade was viewed as a potential high alloy extension of the existing Ancorloy grades, especially Ancorloy 4. In this case, the relatively higher molybdenum and copper contents and otherwise similar nickel content were expected to provide a significant incremental strength increase while maintaining much of the ductility and toughness for which the leaner grade is generally well known.

EXPERIMENTAL PROCEDURE

Originally, the experimental plan was to prepare premixes of the direct hardening and high performance grades according to the Ancorloy process and compare their properties with those of compositionally similar premixes of the corresponding diffusion alloyed grades. However, as it happened, Distaloy HP-1 was in short supply just at the outset of the study and there was uncertainty as to when a sufficiently large sample would become available. Consequently, rather than delay matters, it was decided to substitute Ancorloy 4 as an alternate standard of comparison for the high performance grade. Subsequently, about three months into the study, the required Distaloy HP-1 was obtained and was duly introduced as the primary reference but, as will be seen, only as it was convenient or essential to do so.

The premixes for the study were all made with 0.6 w/o of Asbury Grade 3203 HSC graphite and 0.75 w/o Acrawax C. The Ancorloy premixes were made according to a proprietary practice which included binder treatment using the ANCORBOND® process. The nominal mix size was 500 lb. The Distaloy premixes were made according to traditional mixing practices. The nominal premix size in this case was 25 lb. The base chemistries of the various premixes as determined by x-ray florescence of samples prepared from sintered specimens are shown below.

Table 1 - Base Chemistries of the Experimental Premixes.

Prepremix Designation	S w/o	P w/o	Ni w/o	Cu w/o	Mo w/o	Fe
Ancorloy DH-1	0.003	0.014	0.06	2.01	1.38	balance
Ancorloy HP-1	0.005	0.013	4.07	1.99	1.31	balance
Ancorloy 4	0.006	0.008	3.88	1.42	0.52	balance
Distaloy DH-1	0.003	0.013	0.08	1.89	1.32	balance
Distaloy HP-1	0.002	0.012	4.11	2.02	1.29	balance

The powder, green and sintered transverse rupture, tensile, impact 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 powder properties included the apparent density, (ASTM B 212), and Hall flow rates, (ASTM B 213). The green properties included the green density, (ASTM B 331), and the green strength, (ASTM B 312). The green densities were determined at 415, 550 and 690 MPa, (i.e. 30, 40 and 50 tsi respectively). The green strengths were determined exclusively at 415 MPa, (30 tsi). However, two determinations were typically made: one with the die at ambient temperature; and, the other with the die heated to 65 ^{o}C, (150 ^{o}F), in order to simulate production compaction conditions.

The transverse rupture properties including the strength, (ASTM B 528), percent dimensional change, (ASTM B 610), and the sintered density, (ASTM B 331), were determined on standard 10 mm, (~0.25 in.), bars pressed to 6.8 g/cm^3. Sintering was in a Lucifer belt furnace at 1120 ^{o}C, (2050 ^{o}F), for 30 minutes at temperature under cover of a synthetic dissociated ammonia atmosphere.

The balance of the mechanical property determinations were in the as-sintered and sintered and tempered conditions. Sintering in this phase of the studies was in an Hayes pusher furnace employing essentially the same conditions as previously listed. The tempering treatment after sintering was basically a stress relief at 175 ^{o}C, (350 ^{o}F), for 30 minutes in air.

The tensile properties were in all cases based on as-compacted dog-bone specimens pressed to 415, 550 and 690 MPa, (ASTM E 8). Density checks of the specimens were conducted prior to testing by the immersion method, (ASTM B 328) and were typically limited to two specimens per condition. Tensile testing was performed on an Instron machine at a crosshead speed of 0.05 cm/minute. The machine is equipped with a 25 mm, (1 inch), extensiometer and provides automated readouts of the 0.2% offset yield strength, ultimate tensile strength and percent elongation values.

Impact testing in all conditions of sintering and heat treatment was at ambient temperature, (i.e. ~70 ^{o}F or 20 ^{o}C), using standard unnotched Charpy specimens, (ASTM E 23). Here again, the specimens were pressed to 415, 550 and 690 MPa. The apparent hardness values representing the as-sintered and sintered and tempered conditions were determined on the grip end faces of the dog-bone tensile specimens. In all cases, the measurements were made on the Rockwell A scale, (diamond indenter and 60 kgf load). As may be verified by reference to ASTM E 140, the A scale has the advantage that it covers the whole of the C scale and most of the B scale. Consequently, its use obviates the need to deal with the discontinuities that typically arise when the apparent hardness falls in the low end of the C scale and/ or the high end of the B scale.

RESULTS AND DISCUSSION

It is relevant to mention here that the decision to set the graphite content of the experimental premixes at 0.6 w/o was based on the fact that experience over the years has generally indicated this to be the midpoint of the range of greatest interest in alloy grades, (i.e. ~0.4 w/o to 0.8 w/o). Also, tempering subsequent to sintering is, of course, not a common practice. However, as was shown in the earlier studies of the Ancorloy 2 and Ancorloy 4 grades and as will be shown here as well, molybdenum bearing steels are generally sensitive to cooling subsequent to sintering. Hence, they frequently precipitate low temperature products that give rise to residual stresses which may vary significantly in both magnitude and direction from specimen to specimen. Consequently, to assure valid property comparisons, its prudent even in the case of adjacent specimens to submit these grades to a low temperature stress relief prior to testing.

Powder and Green Properties

The powder and green properties of the Ancorloy premixes and the Distaloy reference mixes are shown below. The powder and green strength properties are listed in Table 2. The green density properties are presented graphically in Figure 1. The Ancorloy 4 reference mix was not included in these determinations.

Table 2 - Powder and Green Strength Properties of the Experimental Premixes

Base Powder	Powder Properties		Green Strengths at 415 MPa			
	Apparent Density gms / cm^3	**Hall Flow** s / 50 g	**Laboratory** MPa	psi	**Production** MPa	psi
Ancorloy DH-1	3.10	31	10.4	(1510)	11.5	(1670)
Distaloy DH-1	3.12	33	9.3	(1350)	10.5	(1520)
Ancorloy HP-1	3.19	30	10.5	(1520)	13.2	(1910)
Distaloy HP-1	3.22	34	9.2	(1340)	11.5	(1670)

A review of the findings in this table will show that in both cases the Ancorloy and the corresponding Distaloy exhibited reasonably comparable values of each of the three properties listed. The flow values of the binder-treated premixes were typically better than those of the regular premixes but the differences were not great. Superficially, the green strengths of the Ancorloy premixes also appeared to be greater than those of the comparable Distaloy premixes. However, the comparison here was not direct owing to concomitant compressibility differences which, as will be discussed shortly, favored the Ancorloy premixes. Thus, qualitatively, the green strength differences, if actually different at all, were likewise small.

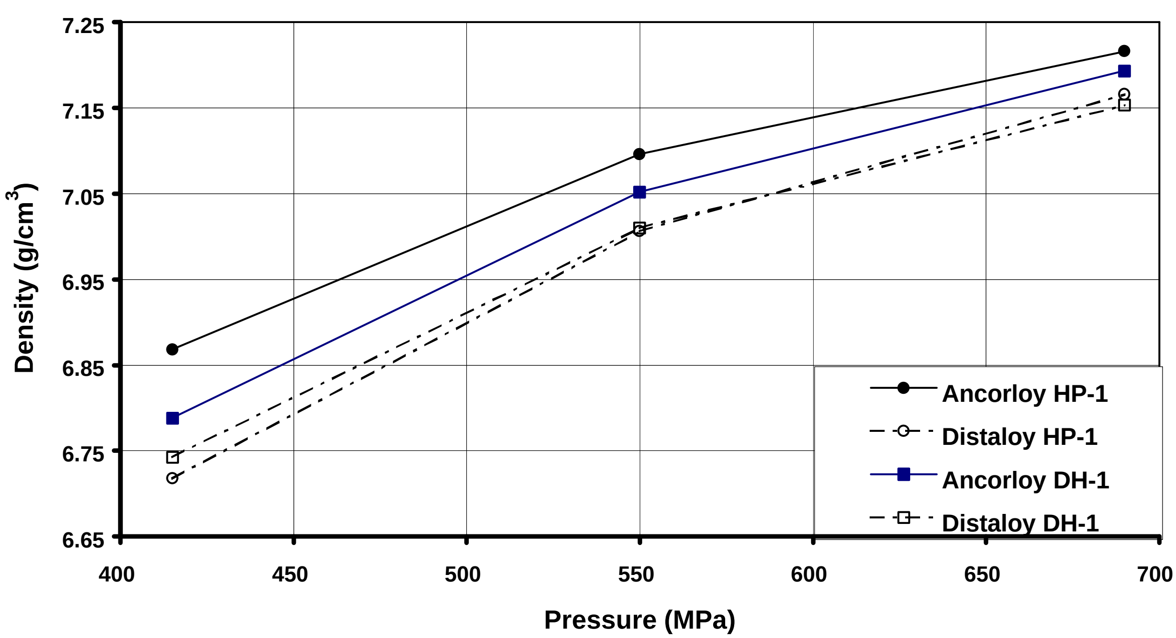

Figure 1 - Results of the Green Density Determinations on the Experimental Premixes

In contrast, the green density findings presented a very different picture. As will be evident from a cursory review of the data in Figure 1, both of the Ancorloy premixes exhibited better compressibility than either of the Distaloy premixes. The greatest green density increases were in the HP grade. Although the magnitudes of the increases, of course, typically decreased with increasing pressure, the average increase in this case was very substantial being just a little under 0.10 g/cm^3. By comparison, the compressibility increases in the DH grade were more modest but still significant. They averaged 0.045 g/cm^3.

The obvious benefit of higher compressibility, of course, is the potential to make parts of higher density. A more subtle benefit but one that may be of equal or greater importance depending on circumstances is the possibility to optimize press utilization in terms of part size. In other words, larger parts can be made on the same press and / or higher density parts can be made on a smaller press. Thus, as a practical matter, it will be appreciated that the indicated compressibility improvements endow the Ancorloy grades with very significant potential advantages over their Distaloy counterparts in terms of manufacturing flexibility.

As-sintered and Sintered and Tempered Transverse Rupture Properties

The as-sintered and sintered and tempered transverse rupture properties of the premixes are shown in Tables 3 and 4. In view of the earlier findings, the specimens in this case were all compacted to 6.8 g/cm^3 rather than to 415 MPa, (30 tsi). Here again, the Ancorloy 4 reference premix was not included in the determinations.

Table 3 – Summary of As-sintered Transverse Rupture Properties

Base Powder	Density g/cm^3	Transverse Rupture Stg. MPa	Transverse Rupture Stg. 10^3 psi	Dim. Chg. %	App. Hardness HRA
Ancorloy DH-1	6.75	1160.0	(168.2)	+0.23	52
Distaloy DH-1	6.73	1042.8	(151.2)	+0.31	51
Ancorloy HP-1	6.81	1346.2	(195.4)	-0.12	60
Distaloy HP-1	6.81	1457.9	(211.4)	-0.10	61

The data in Table 3 show modest dimensional change differences and suggest the existence of significant strength differences between the Ancorloy premixes and their Distaloy counterparts. The strength differences favored the Ancorloy premix in the case of the direct hardening grade and the Distaloy premix in the case of the high performance grade. The magnitudes of the differences in both instances were fairly substantial, being upwards of 100 MPa, (~15,000 psi). In dimensional change, the Ancorloy premixes were both negative of the corresponding Distaloy premixes. The magnitudes of the differences, however, were reasonably moderate, being 0.08% in the case of the DH grade and only 0.02% in the case of the HP grade.

Table 4 – Summary of Sintered and Tempered Transverse Rupture Properties

Base Powder	Density g/cm3	Transverse Rupture Stg. MPa	10^3 psi	Dim. Chg. %	App. Hardness HRA
Ancorloy DH-1	6.75	1135.2	(164.6)	+0.23	52
Distaloy DH-1	6.74	1063.4	(154.2)	+0.30	50
Ancorloy HP-1	6.81	1504.8	(218.2)	-0.14	58
Distaloy HP-1	6.82	1506.2	(218.4)	-0.11	59

Corresponding to Table 3, the data in Table 4 show that the tempering treatment mainly affected the strength and apparent hardness properties of the premixes. The largest effects were on the strength values which increased in three of the four premixes and decreased in one. The absolute magnitudes of the changes ranged from 20 MPa to just under 160 MPa, (i.e. from 3000 psi to 23,000 psi). In contrast, the apparent hardness values either decreased very slightly or remained the same.

As a general matter, mixed changes in strength with little or no change in apparent hardness or, more particularly, significantly increased strengths with attendant slight decreases in apparent hardness are indicative of residual stress relief, (9). Since residual stresses basically reflect local differences in cooling rate which are likely to be non-reproducible, it will be appreciated that comparisons that aim to detect reproducible differences are only valid if these stresses are relieved.

Thus, the as-sintered data here suggested the existence of significant strength differences between the Ancorloy and Distaloy premixes in both grades. However, after tempering these differences largely disappeared. More specifically, the differences in the direct hardening grade were reduced by nearly half while those in the high performance grade were completely eliminated. Thus, contrary to the indications of the as-sintered data, there is no reason to believe that there is more than a moderate disparity in the sintered strengths of the Ancorloy premixes and their Distaloy counterparts. As will be seen, the tensile property findings led to essentially the same conclusion.

Tensile Properties of the Direct Hardening Grade

The as-sintered and sintered and tempered tensile properties of the direct hardening premixes are shown below in Tables 5 and 6.

Table 5 – As-sintered Tensile Properties of the Direct Hardening Premixes

Compaction Pressure MPa	tsi	**Sintered Density** g/cm^3	**0.2% Yield Strength** MPa	10^3 psi	**Ultimate Strength** MPa	10^3 psi	**% Elongation** in 25 mm	**Apparent Hardness** HRA
Ancorloy DH-1								
415	(30)	6.78	476.6	(69.1)	576.6	(83.6)	1.0	53
550	(40)	7.02	536.6	(77.8)	671.0	(97.3)	1.2	56
690	(50)	7.16	571.7	(82.9)	756.8	(109.7)	1.6	57
Distaloy DH-1								
415	(30)	6.70	346.2	(50.2)	530.3	(76.9)	1.2	50
550	(40)	6.98	501.4	(72.7)	650.9	(94.4)	1.5	54
690	(50)	7.11	520.0	(75.4)	690.2	(100.1)	1.4	56

A cursory appraisal of the as-sintered data as listed above in Table 5 showed that each of the several properties of the premixes generally increased with increasing compaction pressure. However, the data also showed mix to mix differences in sintered density at each pressure. Thus, it will be evident that direct comparison of the balance of the data as a function of pressure was not appropriate. Instead, as will be appreciated, it was necessary to assess these data graphically as a function of sintered density.

A similar appraisal of the sintered and tempered data as listed below in Table 6 showed a similar trend with compaction pressure and similar mix to mix differences in sintered density. Thus, here again, direct comparison of the data as a function of pressure was likewise not appropriate. However, comparisons between the tables to assess the effects of the tempering treatment were proper and, of course, of interest.

Table 6 – Sintered and Tempered Tensile Properties of the Direct Hardening Premixes

Compaction Pressure MPa	tsi	**Sintered Density** g/cm^3	**0.2% Yield Strength** MPa	10^3 psi	**Ultimate Strength** MPa	10^3 psi	**% Elongation** in 25 mm	**Apparent Hardness** HRA
Ancorloy DH-1								
415	(30)	6.79	488.3	(70.8)	524.8	(76.1)	0.7	52
550	(40)	7.03	560.0	(81.2)	682.8	(99.0)	1.2	55
690	(50)	7.16	602.1	(87.3)	744.8	(108.0)	1.4	56
Distaloy DH-1								
415	(30)	6.71	453.8	(65.8)	506.9	(73.5)	1.0	51
550	(40)	6.98	517.2	(75.0)	660.7	(95.8)	1.5	54
690	(50)	7.11	544.8	(79.0)	671.7	(97.4)	1.2	56

In general, the indicated comparison showed that the main effect of tempering was to increase the yield strength. However, the magnitudes of the increases were generally modest. With one exception, they were all less than 35 MPa, (5000 psi). The exception was in the case of the Distaloy premix at the 415 MPa, (30 tsi), compaction level where the increase was a little over 105 MPa, (15,000 psi). In contrast, although the effects on the rest of the tensile properties including the ultimate strength, elongation and apparent hardness were likewise modest, they were also mixed. The ultimate strength, in particular, tended to increase as the yield strength. Interestingly, however, the data also showed that it was strongly co-dependent on the effects of the treatment on the elongation as well. Thus, if the elongation remained the same or increased upon tempering, the ultimate strength increased; otherwise, it decreased. In the case of the sintered density, the tempering treatment either had no effect or increased the density slightly.

The as-sintered and the sintered and tempered yield and ultimate strengths of the two premixes are shown graphically versus the sintered densities in Figures 2 and 3. Note that the solid data markers in these figures refer to the Ancorloy premix while the open ones indicate the Distaloy premix.

Each of the figures indicate essentially the same thing relative to the strength behavior of the two premixes. As a casual inspection will show, the data points of both premixes fall on the same trendlines in both figures. Thus, the implication is that if specimens of the two premixes are made to the same sintered density, they will exhibit reasonably the same values of yield and ultimate strength. As may be recalled, the tempered TRS data gave basically the same indication.

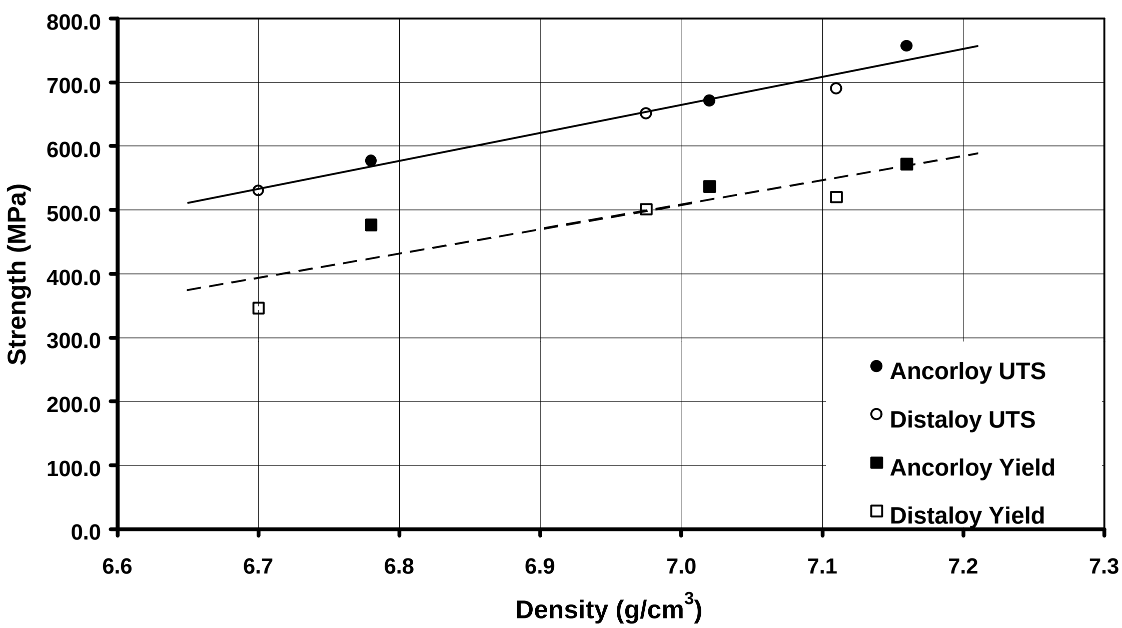

Figure 2 – As-sintered Ultimate and Yield Strengths of the DH Premixes versus Sintered Density

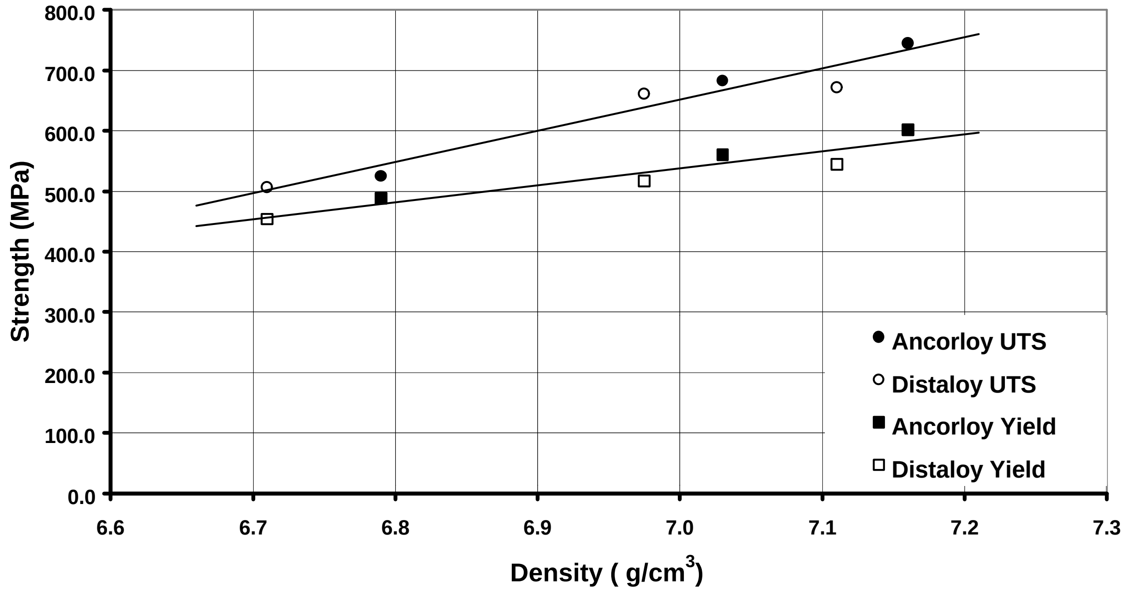

Figure 3 – Sintered and Tempered Ultimate and Yield Strengths of the DH Premixes Versus Sintered Density

Unfortunately, it was not possible to submit the elongation data to a similar analysis. The difficulty here was that earlier studies had indicated it be dependent on the yield strength as well as the sintered density and the available data were simply not sufficient to separate the effects of both. Suffice it to say that the elongation behaviors of the two premixes appear reasonably comparable but may actually be otherwise.

Tensile Properties of the High Performance Grade

The as-sintered and sintered and tempered tensile properties of the high performance premixes along with those of the Ancorloy 4 reference premix are shown below in Tables 7 and 8.

Table 7 – As-sintered Tensile Properties of the High Performance Premixes

Compaction Pressure MPa	tsi	Sintered Density g/cm^3	0.2% Yield Strength MPa	10^3 psi	Ultimate Strength MPa	10^3 psi	% Elongation in 25 mm	Apparent Hardness HRA
Ancorloy HP-1								
415	(30)	6.94	498.9	(71.7)	714.5	(103.6)	1.2	62
550	(40)	7.15	551.5	(80.0)	895.9	(129.9)	1.9	64
690	(50)	7.27	595.5	(86.3)	950.3	(137.8)	1.8	65
Distaloy HP-1								
415	(30)	6.79	489.0	(70.9)	709.0	(102.8)	1.4	60
550	(40)	7.02	534.5	(77.5)	824.1	(119.5)	1.6	63
690	(50)	7.17	571.6	(82.9)	913.1	(132.4)	1.7	66
Ancorloy 4								
415	(30)	6.97	441.5	(64.0)	675.2	(97.9)	2.0	54
550	(40)	7.21	461.5	(66.9)	764.8	(110.9)	2.9	57
690	(50)	7.32	486.5	(70.5)	816.6	(118.4)	3.4	59

Here again, a review of the data in Tables 7 and 8 showed generally increasing property values with increasing compacting pressure but sintered density differences that precluded the possibility of quantitative comparisons, especially between the high performance premixes. However, the data also showed that the Ancorloy 4 premix exhibited the highest sintered densities of the three premixes at each pressure. Thus, mix to mix comparisons were permissible in this case since the findings are qualitatively indicative of the minimal property differences to be expected as a consequence of the alloy differences that exist between the Ancorloy 4 and the high performance grades.

Since the indicated disparities in density were least in the case of the Ancorloy HP-1, the comparisons were made with this premix. Thus, according to the as-sintered data in Table 7, the higher alloyed grade exhibited the higher strength and apparent hardness but lower elongation values. The average increase in the yield strength was 84.1 MPa, (12,200 psi), while the average increase in the ultimate strength was slightly higher at 101.4 MPa, (14,700 psi). The corresponding average apparent hardness values were 63.7 versus 56.7 respectively. The elongation averages differed by 1.1%.

A similar comparison of the sintered and tempered data as presented in Table 8 again showed that the higher alloyed grade exhibited the higher strength and apparent hardness but lower elongation values. Interestingly, the findings showed very nearly the same difference in yield strength, (i.e. 100 MPa or 14,500 psi). However, there was a substantially smaller difference in average elongation and apparently corresponding to the powerful effect that strain hardening has on flow stress, a much larger average difference in the ultimate strength. Accordingly, the indicated decrease in elongation was 0.3% whereas the increase in strength was 193.1 MPa, (27,600 psi), almost twice the value indicated in the as-sintered data. The average apparent hardness values were now 62.3 versus 55.3.

Table 8 – Sintered and Tempered Tensile Properties of the High Performance Premixes

Compaction Pressure MPa	tsi	**Sintered Density** g/cm^3	**0.2% Yield Strength** MPa	10^3 psi	**Ultimate Strength** MPa	10^3 psi	**% Elongation** in 25 mm	**Apparent Hardness** HRA
Ancorloy HP-1								
415	(30)	6.94	526.2	(76.3)	796.7	(115.5)	2.0	59
550	(40)	7.15	611.1	(88.6)	925.4	(134.2)	2.2	62
690	(50)	7.27	618.5	(89.7)	956.4	(138.7)	2.3	63
Distaloy HP-1								
415	(30)	6.79	492.4	(71.4)	732.4	(106.2)	1.8	57
550	(40)	7.02	601.8	(87.3)	883.9	(128.2)	2.0	62
690	(50)	7.17	617.0	(89.5)	941.1	(136.5)	2.2	63
Ancorloy 4								
415	(30)	6.96	445.1	(64.5)	623.4	(90.4)	1.7	52
550	(40)	7.21	487.6	(70.7)	718.2	(104.1)	2.5	56
690	(50)	7.32	523.0	(75.8)	765.7	(111.0)	3.1	58

As in the case of the direct hardening premixes, the data in Tables 7 and 8 are also applicable to assess the effects of the tempering treatment. Interestingly, the effects of the treatment on the high performance premixes were approximately of the same magnitude but more consistent and generally different in direction than in the case of the direct hardening premixes. The major difference was in the elongation values which instead of decreasing as in the earlier data, here increased after tempering. Conceivably, this difference was connected with the differences in the nickel contents of the two grades. For example, nickel is generally well known for its beneficial effects on ductility and toughness and, of course, is otherwise what basically distinguishes the one grade from the other.

In any event, the details of the changes indicated by the data were as follows. The tempering treatment had almost identical effects on both the Ancorloy and Distaloy premixes. It increased the yield and ultimate strengths of each by approximately 5500 psi, (37.9 MPa), their elongation values by 0.5% and 0.4% respectively and decreased the apparent hardness values of each by about 2 points Rockwell A.

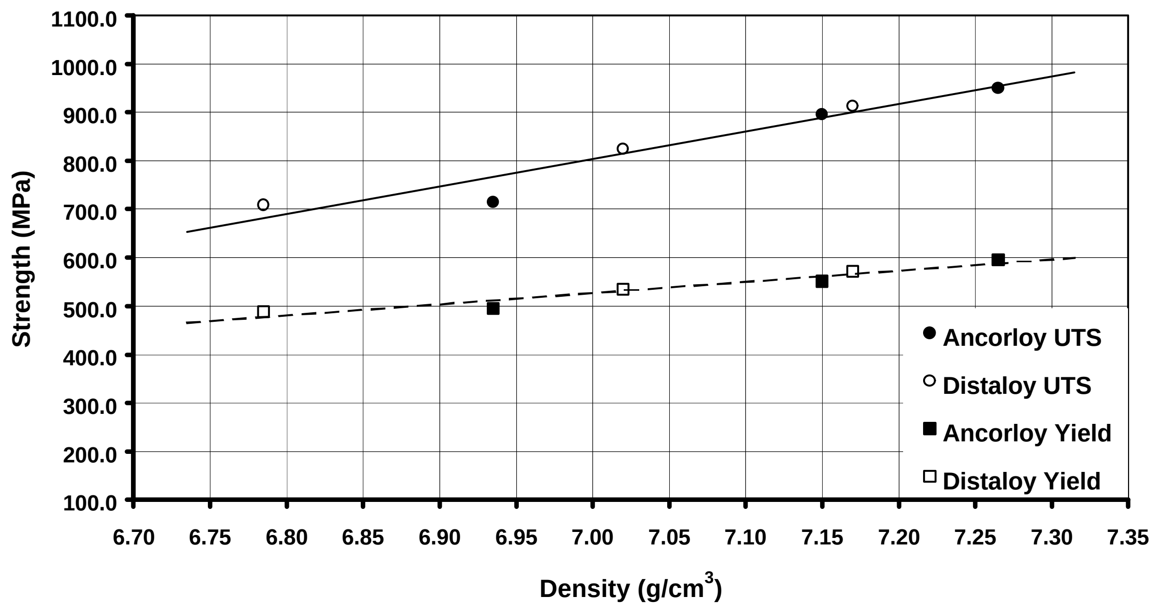

Figure 4 – As-sintered yield and Ultimate Strengths of the HP Premixes

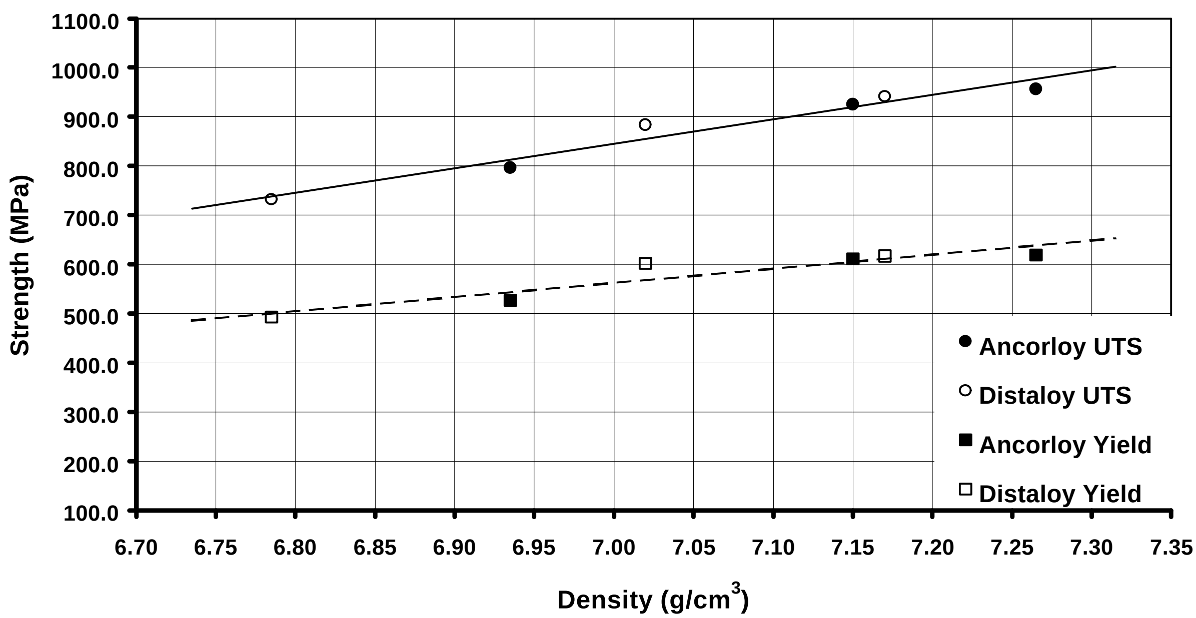

Figure 5 – Sintered and Tempered Yield and Ultimate Strengths of the HP Premixes

The as-sintered and the sintered and tempered yield and ultimate strengths of the two premixes are shown graphically versus the sintered densities in Figures 4 and 5. Note that here again, the solid data markers in the figures refer to the Ancorloy premix while the open ones are for the Distaloy premix.

As previously, the data points of both premixes in these figures essentially fall on the same trendlines. Thus, as was concluded in the case of the DH premixes, both the Ancorloy and Distaloy versions of the high performance grade would be expected to exhibit reasonably the same values of yield and ultimate strengths if made to the same sintered density.

Impact Properties of the Direct Hardening Grade

The as-sintered impact properties of the direct hardening premixes are shown in Table 9. The sintered and tempered data in this case are not reported. Tempering appeared to have little or no effect on impact resistance and about the same effects on the other properties listed as were indicated earlier by the TRS data.

Table 9 – Un-notched Impact Properties of the Direct Hardening Premixes

Compaction Pressure		**Sintered Density**	**Dimensional Change**	**Impact Resistance**		**Apparent Hardness**
MPa	tsi	g/cm^3	**%**	Joules	ft. lbf.	HRA
Ancorloy DH-1						
415	(30)	6.66	+0.36	5.4	(4.0)	53
550	(40)	6.95	+0.40	7.2	(5.4)	58
690	(50)	7.10	+0.42	9.8	(7.2)	59
Distaloy DH-1						
415	(30)	6.58	+0.43	6.5	(4.8)	49
550	(40)	6.87	+0.43	9.0	(6.6)	54
690	(50)	7.04	+0.45	11.1	(8.2)	57

Once again, the data showed sintered density differences and indicated the need of graphical comparisons. However, as will be evident, the actual impact values were all less than 15 Joules, (~10 ft. lbf.), and thus not really of a magnitude to justify such an effort. Qualitatively, the data generally indicated increasing impact resistance with increasing compacting pressure and density. The Distaloy values were uniformly higher than those of the Ancorloy premix but, as will be appreciated, the differences were too small to be conclusive.

Its also of interest to note that the data generally showed increasing dimensional change with increasing pressure thus indicating decreasing sinterability with increasing green density. However, in spite of this trend, the data also showed that the impact specimens of both premixes exhibited higher dimensional change values at the 415 MPa, (30 tsi), level than were earlier indicated by the TRS specimens at substantially higher densities, (cf. Tables 3 and 4). In addition, while the magnitude of the difference in dimensional change between the premixes was about the same at 415 MPa as was earlier reported, it otherwise decreased with increasing pressure. So, at the highest pressure, the dimensional change of the two premixes was very nearly the same.

Impact Properties of Ancorloy HP Versus Ancorloy 4

The as-sintered impact properties of the Ancorloy HP and Ancorloy 4 premixes are presented in Table 10. Here again, there was little effect of tempering on these properties and consequently,
the sintered and tempered data are not reported.

Table 10 - As-sintered Impact Properties of the Ancorloy Premixes

Compaction Pressure MPa	tsi	**Sintered Density** g/cm^3	**Dimensional Change** **%**	**Impact Resistance** Joules	ft. lbf.	**Apparent Hardness** HRA
Ancorloy HP-1						
415	(30)	6.78	-0.02	11.1	(8.2)	60
550	(40)	7.05	+0.07	15.5	(11.5)	62
690	(50)	7.18	+0.12	20.4	(15.0)	65
Ancorloy 4						
415	(30)	6.84	+0.06	11.7	(8.6)	52
550	(40)	7.09	+0.14	17.6	(13.0)	54
690	(50)	7.22	+0.17	21.4	(15.8)	58

The sintered density differences in this case favored the reference premix. Thus, as previously explained in this connection, direct comparisons provide estimates of the minimum differences that are likely to exist between the premixes.

As reference to the data will show, the indicated differences in impact resistance were in all cases small, the overall average difference being less then 1.5 Joules., (~1 ft. lbf). More over, the values were almost exactly twice those of the earlier reported direct hardening grade. Thus, especially relative to the high performance grade, the findings once again underscored its higher nickel content and the resultant benefits on ductility and toughness. Interestingly, the data also gave an indication as to the likely differences in the microstructures of the high performance grade and the Ancorloy 4 which likewise correlated with the known effects of the differences in alloy content. Recall that the earlier data had shown that the yield strength of the high performance premix was significantly higher than that of the Ancorloy 4. In general, the impact resistance of steel decreases with increases in yield strength and increases with decreases in grain size, (10). Hence, the fact that the present data show that each of the premixes exhibited very nearly the same impact resistance is a strong indication that the high performance premix had the finer grain size of the two. Such a difference is, in turn, precisely the expected effect of the differences in alloy content, especially the molybdenum. In particular, molybdenum in steel is well known for its ability to increase bainitic hardenability with higher contents typically leading to an increasingly finer acicular ferrite phase.

Finally, as was seen with the direct hardening premixes, the dimensional change values of both of the present premixes increased with increasing compacting pressure, thus again indicating decreasing sinterability with increasing green density. In addition, its again noteworthy to point out that according to the present data, the high performance premix exhibited a higher dimensional change value at the 415MPa, (30 tsi), level than was indicated In the earlier TRS data.

SUMMARY AND CONCLUSIONS

Ancorloy DH-1 and Ancorloy HP-1 were introduced as the binder-treated analogs of the diffusion alloyed steels, Distaloy DH-1 and Distaloy HP-1. Both grades are based on Ancorsteel 150 HP. The DH grade is for direct hardening and nominally contains 2 w/o copper in addition to the 1.5 w/o molybdenum content of its alloy base. The HP grade is essentially an high performance version of Distaloy 4800A or Ancorloy 4 and nominally contains 2 w/o copper and 4 w/o nickel in addition to the 1.5 w/o molybdenum in its base powder.

The study basically consisted of comparing the powder, green and sintered mechanical properties of Ancorloy and Distaloy based premixes of both grades. In a few cases, owing to a shortfall of the Distaloy HP-1 grade, Ancorloy 4 was used to reference the high performance composition. The premixes otherwise each contained 0.6 w/o graphite and 0.75 w/o lubricant. The powder and green properties determined included the apparent density, the Hall flow and the green strength at 415 MPa. The green density comparisons included determinations at 415, 550, and 690 MPa, (30, 40 and 50 tsi). The mechanical properties determined included the TRS, tensile and un-notched Charpy impact properties in both the as-sintered and sintered and tempered conditions. The tempering treatment was essentially in the nature of a stress relief and was shown to be necessary with these compositions to eliminate the effects of extraneous cooling rate differences.

The results of the study showed that the Ancorloy premixes were reasonably similar to the Distaloy premixes in powder properties and green strengths but significantly superior to them in compressibility. The Ancorloy HP-1 exhibited the greatest improvements. They ranged from 0.15 g/cm^3 at the lowest pressure to 0.05 g/cm^3 at the highest pressure. In the case of the Ancorloy DH-1, the increases were more modest but still significant. They ranged from 0.05 g/cm^3 at the lowest pressure to 0.04 g/cm^3 at the highest pressure.

The results of the sintered properties phase of the study generally indicated that the Ancorloy premixes were essentially the equivalents of the Distaloy premixes in mechanical properties and slightly superior to them in sinterability. There were some property disparities in the as-sintered condition but these either decreased markedly or were completely eliminated in the sintered and tempered condition. The superior sinterability of the Ancorloy premixes was manifest in relatively negative dimensional change values compared with the Distaloy premixes, typically of the order of 0.05 to 0.10%.

As may be recalled, the view was expressed at the outset of the study that the direct hardening grade appeared to have potential as a lean alloy alternative to the recently developed Ancorsteel 737 SH for use in lower hardenability applications. Although, of course, it was not specifically tested as such in this study, it will be appreciated that there was certainly nothing in the present findings to negate this view. In fact, if anything, given the excellent compressibility and the consequent higher sintered density potential, especially of the Ancorloy version, it may happen that this grade will prove capable of providing equivalent or better properties than the high alloy grade in some cases.

It was likewise stated initially that the high performance grade appeared to have potential as an extension of the existing Ancorloy series. As noted, this was because it was essentially an high molybdenum analog of Ancorloy 4 and thus combined the likelihood of higher strengths with an established potential for good ductility and toughness. As it actually turned out, the subsequent comparisons of the two not only confirmed the anticipated strength increases but also showed, somewhat unexpectedly, that they were virtually equivalent in ductility and toughness as well. The indicated strength improvements of the Ancorloy HP-1 included yield strength increases in the neighborhood of 100 MPa, (15,000 psi) and ultimate strength increases of upwards of 175 MPa, (25,000 psi).

Finally, its of interest to note that studies are currently in progress to further characterize these new Ancorloy grades as to fatigue resistance and heat treated properties. Barring unforeseen exigencies, these additional data are expected to be available by years end.

ACKNOWLEDGMENTS

Special thanks are due to Mr. W. R. Bentcliff for his many useful suggestions and to he and Mr. G. Fillari for their help in specimen preparation and testing.

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