

**ANCORLOY PREMIXES:
BINDER TREATED ANALOGS OF THE DIFFUSION ALLOYED STEELS**

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ABSTRACT

The properties at two carbon levels of binder treated analogs of the diffusion alloyed steels are presented. These Ancorloy premixes are made according to a proprietary practice that does not include diffusion alloying. It is shown by direct comparison with compositionally similar premixes of the diffusion alloyed steels that the Ancorloys generally exhibit similar powder, green and dimensional change properties and significantly enhanced mechanical properties. Tensile, impact and fatigue property data in the sintered, sintered and tempered and quenched and tempered conditions are presented.

INTRODUCTION

Diffusion alloying and binder treatment are alternative methods that have essentially the same technical objectives. These are to improve the inherent compositional homogeneity of the resultant powder without adverse effect to its other processing characteristics, especially compressibility. Consequently, as applied to the manufacture of press-ready premixes, they offer many of the same advantages. For example, compared with compositionally similar premixes made according to conventional practices, these typically include: improved powder flow, minimally equivalent and frequently better green properties, and decidedly improved dimensional stability after sintering, (1, 2).

The two processes accomplish their aims and produce the indicated improvements in much the same way. Basically, they each effect superficial bonds between the particles of the base powder and those of the affected admix ingredients. However, as their respective names imply, they employ very different means to do this. Diffusion alloying is a pyrometallurgical process and may involve chemical and/or metallurgical reactions in addition to bonding. Binder treatment, on the other hand, is primarily a simple gluing process and has little if any potential for either chemical or metallurgical effects beyond those of bonding. Thus, in spite of the fact that the two methods accomplish their aims in much the same way, the underlying mechanisms are intrinsically very different. Consequently, there's no guarantee that their application as a general matter will necessarily lead to the same results. For example, diffusion alloying is not applicable to duplicate the properties of binder treated premixes that simply add

carbon as graphite and/or phosphorus as Fe_3P . The difficulty in the first case being the unwanted formation of an intermetallic compound and in the second, the decomposition of one. Alternatively, although binder treatment is generally applicable, it is not suitable in all cases to duplicate the properties of premixes where intermetallics are required. Notable examples include premixes that employ either re-carburized or re-sulfurized powders. As it turns out, the specific compounds that are involved in these cases apparently need to be formed in situ and, in particular, in advance of final mixing to achieve optimum effect with respect to both green and sintered properties.

Until recently, binder treatment has also been unable to duplicate the properties of the premix compositions based on the diffusion alloyed grades according to MPIF Standard 35, (i.e. also known commercially as Distaloy AB® & Distaloy AE®). Unlike the earlier mentioned powders neither of these grades involve intermetallic compounds. However, the diffusion alloying process also accomplishes more than simple bonding and alloying. Indeed, it affects just about every P/M property of interest due to the accompanying base powder annealing that occurs. As a consequence of these effects, as well as of the partial alloying which, of course, also occurs, it turns out that its not an easy matter to reproduce the properties of the resulting powders either by simple admixing of the elemental ingredients or by binder treatment of such premixes.

For example, in independent research sponsored by this laboratory, Bohn et al recently investigated the effects of various alloying modes on the tensile and fatigue properties of a PM steel of nominal FD-0405 composition, (i.e. 0.5 w/o C, 0.5 w/o Mo, 1.5 w/o Cu, 4.0 w/o Ni, bal. Fe). The alloying modes studied included ANCORBOND® enhanced elemental powder mixing, diffusion alloying, and prealloying by water atomization. Compared with the premix based on the diffusion alloyed approach, the binder treated premix exhibited equivalent or slightly better compressibility but significantly different dimensional change characteristics, substantially lower tensile properties and generally lower fatigue properties. The dimensional change values, for instance, differed by more than 0.1% and, depending on density, the yield and tensile strength values were reduced by anywhere from 10% to upwards of 30%. In the case of fatigue, the results were mixed but at the higher densities, the endurance limit of the elemental premix was lower than that of the diffusion alloyed one by 15 to 20%. Thus, this study clearly showed that incidental binder treatment of elemental premixes is not applicable to duplicate the properties of compositionally similar premixes based on the diffusion alloyed powders, (3).

Of course, upon review of these findings, it was also evident that there were a number of possibilities to improve the results based on the elemental mixing approach. These generally included modifications of the binder treatment and mixing processes as well as changes to the admix ingredients. Consequently, an investigation was subsequently initiated in this laboratory with the general objective to optimize the properties according to this approach and, in particular, to duplicate as many of the attributes of the diffusion alloyed grades as possible. The essential commercial consideration being that binder treated enhanced premixing is inherently more economical than the combination of diffusion alloying followed by mixing.

Unexpectedly, the subsequent investigation not only showed that it was possible to duplicate many of the properties of the diffusion alloyed grades but in most cases, to surpass them. In fact, the tensile and fatigue property improvements that were observed were so significant that it was decided to implement the concept as a new product to be known generally as *Ancorloy™*. More specifically, as with the diffusion alloyed steels, Ancorloy consists of two base grades: Ancorloy 2 and Ancorloy 4 which, in general terms, are respectively the compositional analogs of the FD-02XX and FD-04XX grades of the earlier mentioned Standard

35. The purpose of the present paper is essentially to report the property comparisons that led to this decision.

As a matter of general interest, the diffusion alloying concept actually originated in this laboratory in the early 1960's and was initially implemented as a sponge iron based product called 'Ancoloy', (4). In essence, the term Ancorloy is an alliteration based on this earlier name and was chosen in part to commemorate this earliest version of the idea as well as the genius and endeavor of its inventors.

EXPERIMENTAL PROCEDURE

In general, the experimental procedure consisted in preparing premixes of Ancorloy 2 and Ancorloy 4 with various graphite contents in the range from 0.4 to 0.6 w/o and comparing their properties to those of compositionally similar premixes of the diffusion alloyed grades as represented by Distaloy AB and Distaloy AE. The relevant material designations of the premixes in accordance with Standard 35 would be FD-0205 and FD-0405 as shown in following table.

Table 1 - Composition Ranges of the Experimental Premixes Based on MPIF Standard 35

Material Designation	Fe w/o	C w/o	Ni w/o	Cu w/o	Mo w/o	Element
FD-0205	<u>93.15</u>	<u>0.3</u>	<u>1.55</u>	<u>1.3</u>	<u>0.4</u>	Max.
	96.45	0.6	1.95	1.7	0.6	Min.
FD-0405	<u>90.70</u>	<u>0.3</u>	<u>3.60</u>	<u>1.3</u>	<u>0.4</u>	Max.
	94.40	0.6	4.40	1.7	0.6	Min.

The Ancorloy premixes were all binder treated using the ANCORBOND process. Three premix sizes were represented in the studies including: 1) bench size premixes of 1 to 75 lbs; 2) pilot size premixes of 100 to 500 lbs; and, 3) production size premixes of 10,000 to 40,000 lbs. The Distaloy premixes, on the other hand, were all of bench size and made according to regular mixing and blending practices. All of the premixes were lubricated with 0.75 w/o of Acrawax C.

The powder, green and sintered transverse rupture, tensile, impact, hardness and fatigue 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). In some cases, the green densities were determined at 30 tsi and in others at 30, 40 and 50 tsi, (i.e. at 415, 550 and 690 MPa respectively). The green strengths were determined exclusively at 30 tsi. However, two determinations were typically made: one with the die at ambient temperature; and, the other with the die heated to 145 °F, (~63 °C), in order to simulate production compaction conditions.

The transverse rupture properties including the strength, (ASTM B 528), % dimensional change, (ASTM B 610), and the sintered density, (ASTM B 331), were determined on standard 0.25 in., (~10mm), bars pressed to 6.8 g/cm³. Sintering was in a Lucifer belt furnace at 2050 °F, (1120 °C), 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, sintered and tempered and quenched 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 350 °F, (175 °C), for 30 minutes in air. The quench and temper treatment consisted of austenitizing the sintered specimens at 1600 °F, (~870 °C), for 30 minutes at temperature in an endothermic atmosphere followed by quenching in oil at 140 °F, (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 400 °F, (205 °C), for 1 hour in N₂.

The as-sintered and sintered and tempered tensile properties were based on as-pressed dog-bone specimens and the quenched and tempered properties, on machined round specimens, (ASTM E 8). The round specimens were polished parallel to the tensile axis to a 32 microinch RMS finish using metallurgical grade emery paper. In some studies, the specimens were pressed to density and in others, to 30, 40 and 50 tsi. 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 1 in., (25 mm), extensometer and provides automated readouts of the 0.2% offset yield strength, ultimate tensile strength and % elongation values.

Impact testing in all conditions of sintering and heat treatment was at ambient temperature, (i.e. ~70 °F or 20 °C), using standard unnotched Charpy specimens, (ASTM E 23). The specimens in these studies were pressed to 30, 40 and 50 tsi.

The hardness values representing the as-sintered and sintered and tempered conditions were determined on the grip end faces of the dog-bone tensile specimens prior to testing and those representing the quenched and tempered condition, on the impact specimens, again prior to testing. 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 hardness falls in the low end of the C scale and/ or the high end of the B scale.

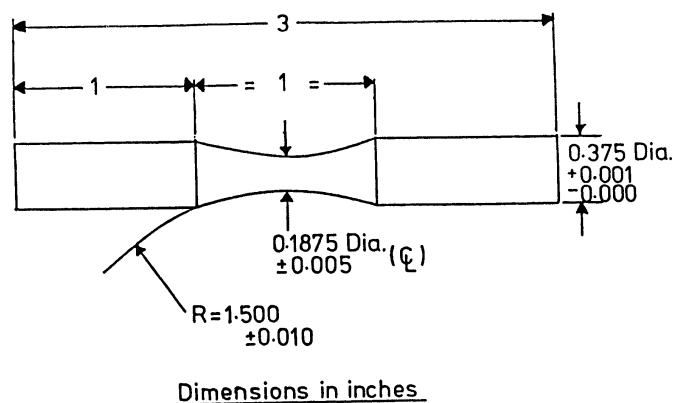


Figure 1 - Rotating Bending Fatigue Specimen Schematic.

The fatigue determinations were done in the rotating bending mode using specimens as shown in Figure 1 above. The specimens were machined from pressed and sintered blanks measuring 1 x 1 x 7.6 cm and finish polished parallel to their longitudinal axes to a 32 microinch RMS surface. The determinations were limited to the as-sintered and quenched and tempered conditions and to pressings at 30 and 50 tsi. Typically, twenty five specimens were

used for each determination. Testing was at 8000 rpm with survival to 10^7 cycles considered a runout. The stress levels were chosen by the staircase method aiming for a two point estimate of the fatigue endurance limit, defined as the 99.9% survival value, (5).

RESULTS AND DISCUSSION

The decision, as indicated in the foregoing, to limit the present studies to premixes with graphite contents in the range of 0.4 to 0.6 w/o was based on a review of the relevant production records which showed that most Distaloy applications fall in this range. In addition, as will become apparent, most of the property comparisons that are reported here are for premixes at the 0.6 w/o graphite level. This is primarily because virtually all of the early development work on the Ancorloys was done at this particular level.

Property Comparisons Of Premixes Adding 0.4 w/o Graphite.

Powder and Green Properties - The powder and green properties of production size premixes of the Ancorloys versus bench size premixes of the Distalloys at the 0.4 w/o graphite level are shown below in Table 2.

Table 2: Powder and Green Properties at 0.4 w/o Graphite

Premix ID	AD g/cm ³	Flow sec/50g	Grn. Den. g/cm ³	Grn. Stg. at RT psi (MPa)	Grn. Stg. at 145 °F psi (MPa)
Ancorloy 2	3.24	28	6.89	1070 (7.4)	1340 (9.2)
Distaloy AB	3.16	33	6.83	2360 (16.3)	2330 (16.1)
Ancorloy 4	3.30	27	6.92	1020 (7.0)	1350 (9.2)
Distaloy AE	3.18	33	6.86	2500 (17.2)	2340 (16.1)

A cursory review of these data will show that the apparent density, flow rate and compressibility values of the Ancorloys were uniformly all much higher than those of the Distalloys. On the other hand, the green strengths of the Distalloys were all much higher than those of the Ancorloys.

As a general matter, the differences in powder properties shown here are typical of the differences that are normally seen between bonded and regular premixes. Accordingly, bonded premixes virtually always exhibit higher apparent densities and significantly improved flow rates when compared with compositionally similar premixes made according to regular practices, (6). In contrast, the very significant differences in green properties indicated in the data cannot be similarly explained. Instead, these differences are due essentially to the overall differences in processing and primarily to the partial alloying and the metal to metal agglomeration that are incidental to the diffusion alloying process. In particular, the partial alloying is considered to be primarily responsible for the lower compressibilities of the Distalloys and the particle agglomeration, for their higher green strengths.

As regards green strength, those familiar with the art will appreciate that while the green strengths of the Ancorloys are low by comparison with the Distalloys, they are nevertheless quite adequate for most practical purposes. Moreover, as has recently been shown, polymer bonding is not only applicable to modify the properties of premixes in general but to increase the green strength to almost any desired value, (7). Thus, while the plan at present is to

produce the Ancorloys with the properties as indicated, the possibility exists to increase their green strengths either generally or, as is more likely, in a specific case to suit a particular need.

Finally, there may be a concern that the comparisons, in this case, are somewhat flawed owing to the disparity in the premix sizes. For example, actual production size premixes would generally be expected to exhibit higher powder properties and lower green properties than bench size premixes. However, according to our QC records, the properties shown here for the bench size premixes compare quite favorably with those of typical production size premixes. Thus, although the comparisons may leave something to be desired in terms of precision to the purist, they are nevertheless considered to be quite reasonable from a practical standpoint.

Standard Sintered Properties - The standard sintered properties including the density, transverse rupture strength and dimensional change values of the 0.4 w/o graphite premixes are shown below in Table 3. The table also lists the corresponding apparent hardness and sintered carbon values of the premixes.

Table 3: Standard Sintered Properties at 0.4 w/o Graphite

Premix ID	Density g/cm ³	TRS 10 ³ psi (MPa)	Dim. Chg. %	App. Hard. HRA	Sint. Carbon w/o
Ancorloy 2	6.76	138.7 (956.6)	+0.11	44.0	0.38
Distaloy AB	6.78	143.5 (989.7)	+0.07	44.0	0.37
Ancorloy 4	6.79	176.2 (1215.2)	-0.06	50.0	0.37
Distaloy AE	6.80	174.5 (1203.4)	-0.08	50.0	0.37

A review of these findings will show that the properties of the Ancorloys in this case were essentially equivalent to those of the Distalloys. Although one or two of the differences indicated in the data are statistically significant, none are considered to be practically significant.

Interestingly, although most of these data are typical of what's been seen throughout much of the development work on the Ancorloys, the TRS values are not. Normally, the Ancorloys have tended to average anywhere from 5 to 10% higher in strength than the Distalloys. The reason why the present values were disappointingly low is probably due to the fact that these particular premixes were also part of a study to determine the effects of variations within the Standard 35 compositional requirements and were purposely made to the low side of the molybdenum range and as fate would have it, providentially fell to the low side of the nickel range as well. In comparison, the molybdenum and nickel contents of the Distalloys were both typically midrange of the specification.

Tensile Properties - The as-sintered tensile properties of the premixes at the 0.4 w/o graphite level are shown below in Table 4a. In addition to the standard properties, the table also lists the corresponding sintered density and apparent hardness values of the premixes. The sintered densities, in this case, were the result of compacting the Ancorloys at 40 tsi and adjusting the compacting pressures used for the Distalloys to produce approximately the same green densities.

A review of the findings in Table 4a will show that the strength and apparent hardness values of the Ancorloys exceeded those of the Distalloys in every case. The largest improvements were in yield strength where the average relative difference was upwards of 15%. The

improvements in ultimate strength and apparent hardness, on the other hand, were more modest but were nevertheless statistically significant. In contrast, the elongation values of the Ancorloys were decreased in comparison with those of the Distalloys. Here again, the average difference was upwards of 15%.

Table 4a: As-Sintered Tensile Properties at 0.4 w/o Graphite

Premix ID	Density g/cm ³	Yld. Stg. 10 ³ psi (MPa)		Ult. Stg. 10 ³ psi (MPa)		Elong. %	App. Hard. HRA
Ancorloy 2	7.07	56.6	390.3	84.2	580.7	3.6	46.9
Distaloy AB	7.05	50.0	344.8	82.2	566.9	4.2	45.5
Ancorloy 4	7.12	64.8	446.9	107.3	740.0	3.4	54.0
Distaloy AE	7.12	54.9	378.6	102.7	708.3	4.1	53.6

Significantly, the fact that the data showed the percentage increases in the yield strength to be of the same magnitude as the decreases in elongation was apparently not coincidental. Indeed, an analysis of the strain hardening characteristics that were indicated in the underlying load-extension results of the tests showed the existence of an inverse relationship between the two. In effect, the indications were that the decreases in elongation were an inevitable outcome of the increases in yield strength and visa versa. In fact, as was confirmed by findings to be presented later, the prediction of the analysis was that at equivalent yield strengths, the Ancorloys and the Distalloys would exhibit roughly equivalent elongations and since the flow stress in tension is a function of the strain, roughly equivalent ultimate strengths as well.

The effects of tempering subsequent to sintering are shown in Table 4b. Here again, the table lists the corresponding apparent hardnesses of the premixes but not the densities which did not change markedly from the as-sintered condition. Instead, the true stress at fracture values that were indicated in the findings are listed. Since P/M specimens virtually always fail in tension without appreciable necking, the true stress at fracture, σ_f , may be estimated with reasonable precision from the ultimate strength, S_u , and the strain at failure, e_u , (i.e. the % elongation / 100), by the following simple formula: $\sigma_f = S_u(1 + e_u)$, (8).

Table 4b: As-Sintered and Tempered Tensile Properties at 0.4 w/o Graphite

Premix ID	Yld. Stg. 10 ³ psi (MPa)		Ult. Stg. 10 ³ psi (MPa)		Elong. %	Fract. Stg. 10 ³ psi	Hardness R _A
Ancorloy 2	57.2	(394.5)	83.6	(567.6)	3.8	86.7	45.8
Distaloy AB	51.1	(352.4)	82.1	(566.2)	4.1	85.4	47.0
Ancorloy 4	70.0	(482.8)	107.8	(743.4)	3.6	111.8	53.2
Distaloy AE	57.4	(395.9)	100.5	(693.1)	4.0	104.5	52.3

Tempering after sintering, of course, is not a common practice. However, even given the moderate cooling rates typical of an average sintering furnace, highly alloyed molybdenum containing steels such as the present grades frequently precipitate low temperature transformation products that result in varying states of residual tension. Such stresses normally affect tensile properties adversely, especially the yield strength. Thus, in view of the pre-eminence of the yield strength differences in the above findings, it was considered prudent to

submit the specimens to a low temperature stress relief in order to minimize any incidental cooling rate differences that might exist and hence, provide the best possible data to assess the differences.

As comparison of the data in Tables 4a and 4b will show, the treatment in this instance apparently had effects on each of the commonly listed properties. In general, the effects were modest and for the most part mixed, resulting in increases in some cases and decreases in others. However, as expected, the yield strength was the exception in this respect in that it increased in every case. The largest increases were in the Ancorloy 4 and Distaloy AE premixes and although greater in the former than the latter were nonetheless reasonably substantial in both cases.

As will be seen, tempering after sintering had much more pronounced effects at the 0.6 w/o graphite level. In addition to the yield strength, significant increases were observed in most instances in both the ultimate strength and elongation values. In contrast, the apparent hardness either decreased slightly or was unaffected thus indicating that the underlying origin of the effects is, as suggested above, primarily a matter of stress relief rather than say, aging or some similar metallurgical process.

Finally, the fracture stress values that are indicated in the present data are also of interest. The near equivalency of the Ancorloy values shown here to those of the Distaloys in each case was also in the as-sintered data and was basically what suggested the analysis that led to the idea that the yield strengths and elongations are inversely related. In addition, the true stress at fracture of a material is directly proportional to its fracture toughness. Thus, the present findings may also be regarded as a qualitative indication that the fracture toughness properties of the Ancorloys are very probably reasonably similar to those of the Distaloys.

Property Comparisons Of Premixes Adding 0.6 w/o Graphite.

The property comparisons in this case were far more extensive than in the foregoing but were largely limited to the mechanical and dynamic properties of the premixes as opposed to the standard QC properties. With one or two exceptions, the studies covered each of three compaction pressures and included tensile and impact determinations in the as-sintered, sintered and tempered, and quench and tempered conditions and fatigue determinations in the as-sintered, and quenched and tempered conditions. The Ancorloy premixes in this instance were Pilot size and the Distaloy premixes were again bench size.

Powder, Green and Standard Sintered Properties - The powder, green and standard sintered properties of the premixes were checked as a QC measure but were not extensively tested. In general, the findings were very similar to the earlier reported ones. The actual values, of course, were not the same but the trends which they indicated were very much the same.

The data shown in Figures 2a and 2b provide an indication of how the green density and sintering differences of the premixes were manifested in the processing of the test specimens. The figures present the as-sintered dimensional change values of the impact specimens and the immersion densities of the dogbone tensile specimens versus the compacting pressure.

A review of the findings in Figure 2a will show that the Ancorloy 2 grew slightly, (~0.03%), relative to the Distaloy AB during sintering but nevertheless exhibited essentially the same sintered densities thus indicating that it also had a somewhat improved compressibility initially. In the case of Figure 2b, the data are equivocal in this respect. They indicate both relative shrinkage, (-0.04%), and increased sintered densities, (~0.03 g/cm³), for the Ancorloy 4 versus

the Distaloy AE. However, as it happened, only about a third of the indicated density increases were actually attributable to sintering. Thus, the balance were due to accompanying compressibility improvements. Its also of interest to note that the dimensional change values of both the Ancorloys and the Distalloys that are shown here for the impact specimens generally ran anywhere from 0.15 to 0.20% higher than the values that were observed in the QC checks using standard TRS specimens.

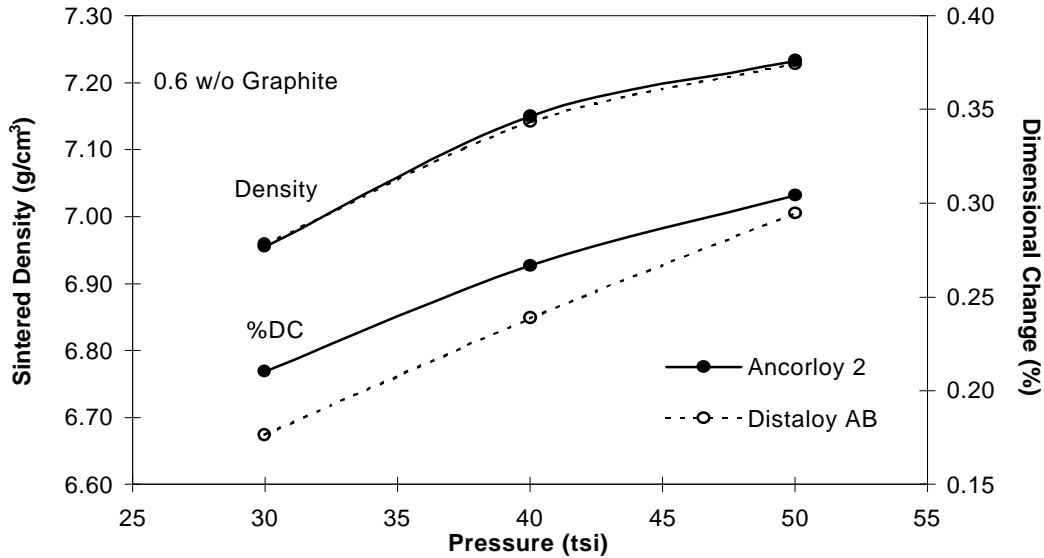


Figure 2a: Ancorloy 2 and Distaloy AB - Sintered Density and Dimensional Change vs Compacting Pressure

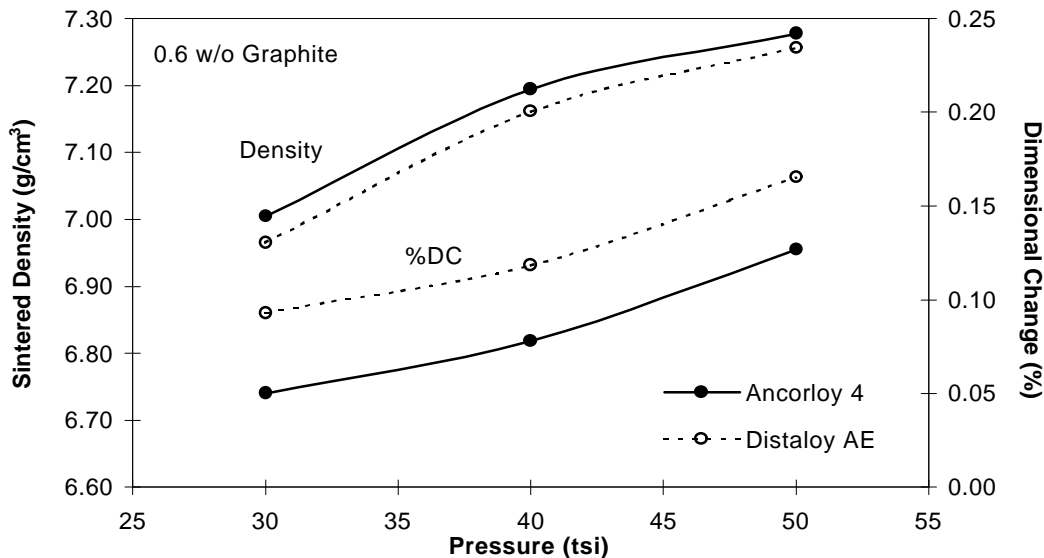


Figure 2b: Ancorloy 4 and Distaloy AE - Sintered Density and Dimensional Change vs Compacting Pressure

As-Sintered and Sintered and Tempered Tensile Properties. - The data in this instance are presented in four sets of figures including one each for the yield, ultimate, elongation and apparent hardness values that were observed.

The as-sintered and sintered and tempered yield strength results versus compacting pressure are shown below in Figures 3a and 3b. A cursory review of these findings will show that the yields strengths of the Ancorloys exceeded those of the Distalloys in both the as-sintered and 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%.

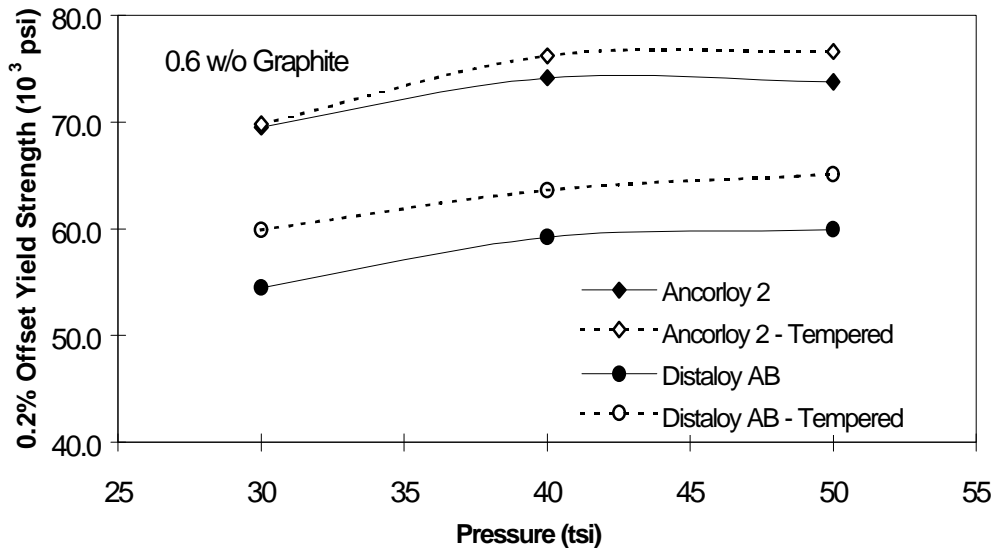


Figure 3a: Ancorloy 2 and Distaloy AB - Yield Strength vs Compacting Pressure

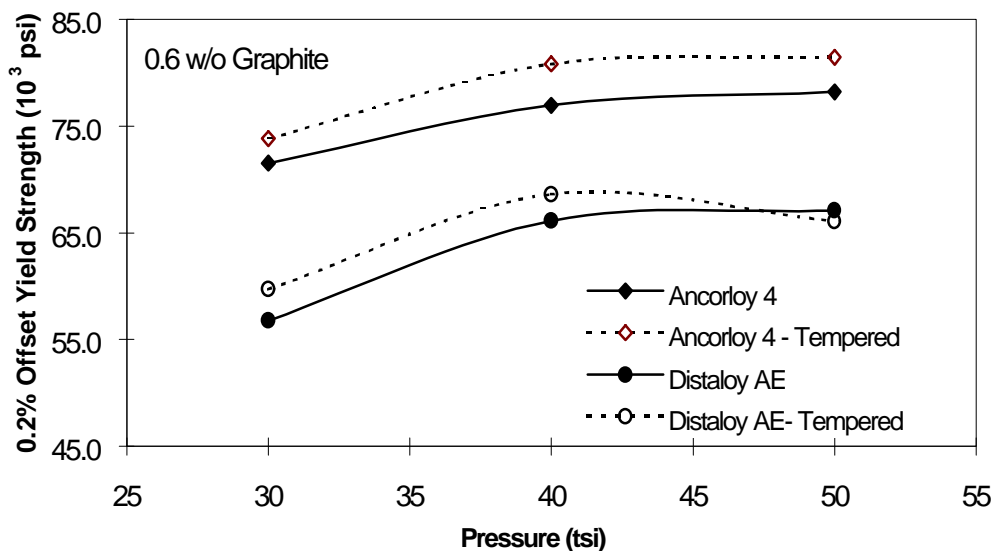


Figure 3b: Ancorloy 4 and Distaloy AE - Yield Strength vs Compacting Pressure

Interestingly, the data in Figure 3a indicate that the tempering treatment was of greater benefit to the Distaloy AB than to the Ancorloy 2 whereas the data in Figure 3b show that it was of greater benefit to the Ancorloy 4 than to the Distaloy AE. The precise reason for these differences is unknown. Presumably, they are due principally to incidental cooling rate differences. However, as will be seen, whatever the cause, similar inconsistencies in the effects of the treatment occur throughout the data.

The as-sintered and sintered and tempered ultimate strength results versus compacting pressure are shown below in Figures 4a and 4b. Here again, a review of the findings in these figures will show that the ultimate strengths of the Ancorloys exceeded those of the Distalloys in both the as-sintered and sintered and tempered conditions and at all three compaction pressures. The relative improvement was generally more modest than in the case of the yield strength but was still rather significant, typically being between 10 and 15%.

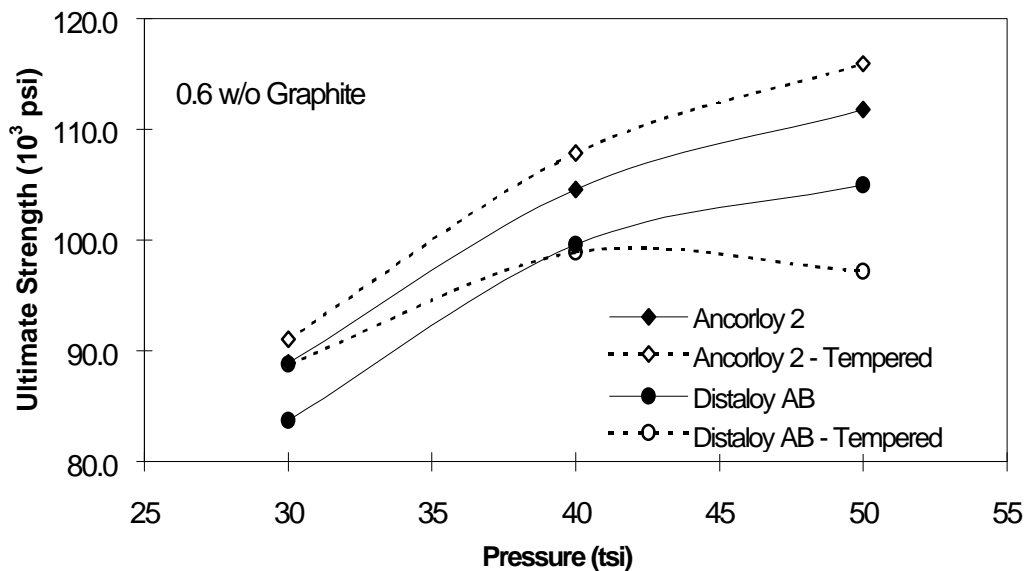


Figure 4a: Ancorloy 2 and Distaloy AB - Ultimate Strength vs Compacting Pressure

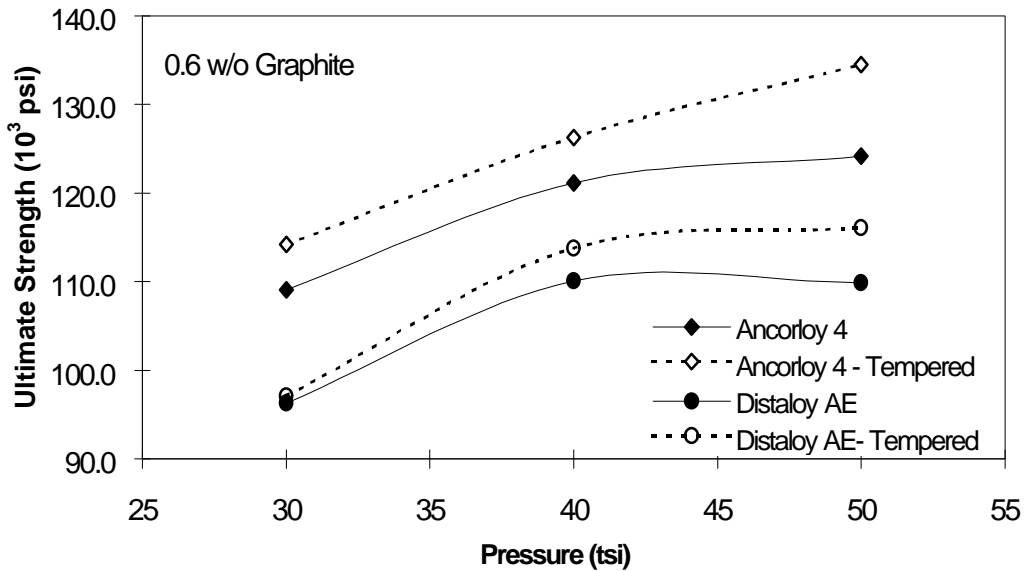


Figure 4b: Ancorloy 4 and Distaloy AE - Ultimate Strength vs Compacting Pressure

The as-sintered and sintered and tempered elongation results versus compacting pressure are shown below in Figures 5a and 5b. In contrast to the foregoing, a review of the findings in these figures will show that the values of the Distalloys now exceeded those of the Ancorloys in both the as-sintered and sintered and tempered conditions and at all three compaction pressures. As earlier mentioned, this reversal in the comparison of the Ancorloys with the Distalloys is thought to be consistent with the existence of an inverse relationship between yield strength and elongation and is thus in the nature of an effect that is ordinarily to be expected.

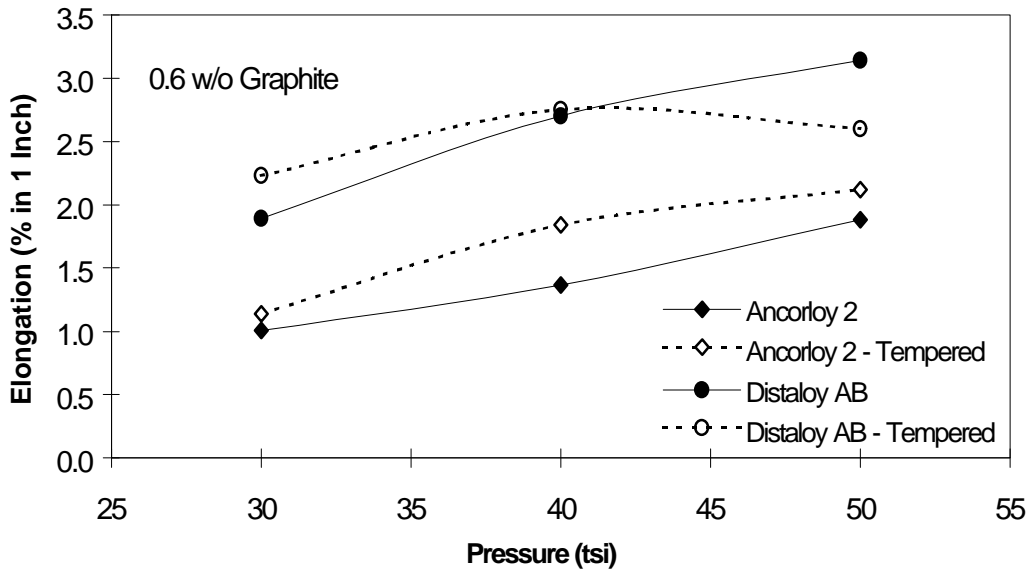


Figure 5a: Ancorloy 2 and Distaloy AB - Elongation vs Compacting Pressure

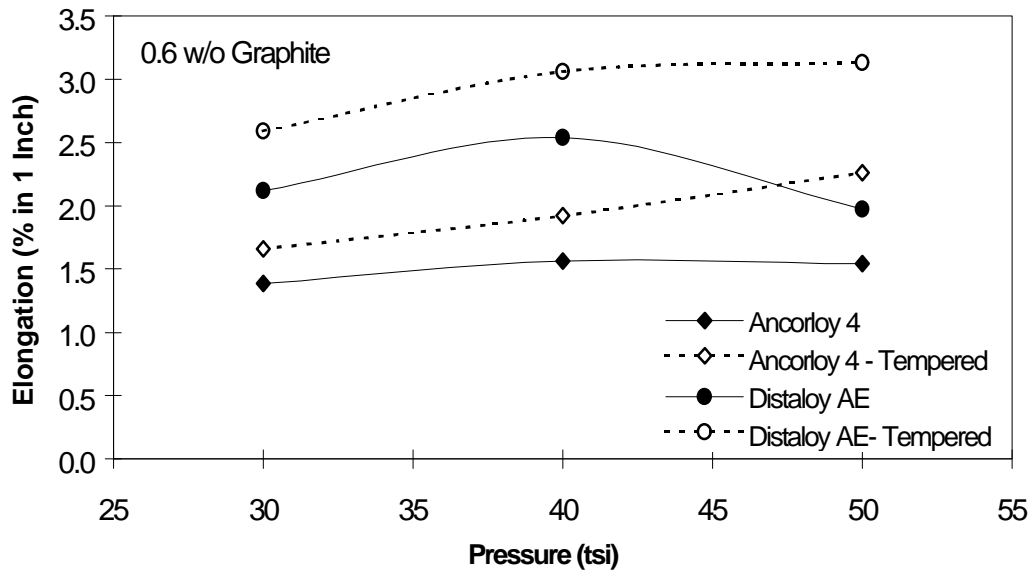


Figure 5b: Ancorloy 4 and Distaloy AE - Elongation vs Compacting Pressure

Its also interesting to note that these data clearly show that the tempering treatment generally increased the elongation. However, when this finding is taken together with the fact that the tempering likewise increased the yield strength, it may seem to contradict the idea of an inverse relationship between the two. Yet, as data to be presently shortly will clearly demonstrate, there is absolutely no doubt about the existence of this relationship. Thus, there is a subtle implication here that there may be more separating the as-sintered and sintered and tempered conditions than a mere change in the residual or macro stress state. For instance, given the likelihood of low temperature transformation products in these steels, actual first stage tempering entailing precipitation of epsilon carbides and consequent stress relief on a microscale may be going on as well, (9).

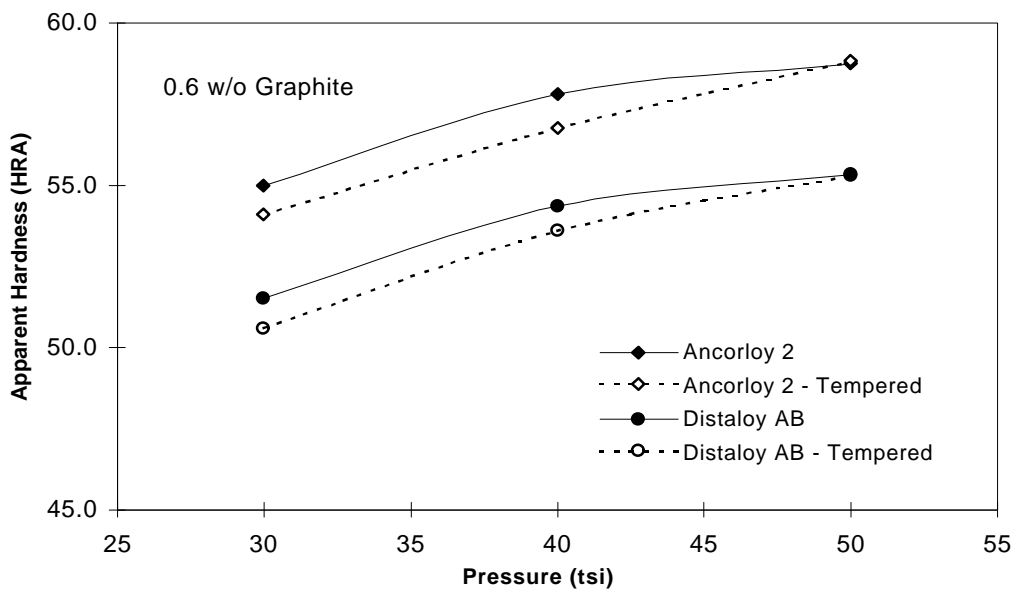


Figure 6a: Ancorloy 2 and Distaloy AB - Hardness vs Compacting Pressure

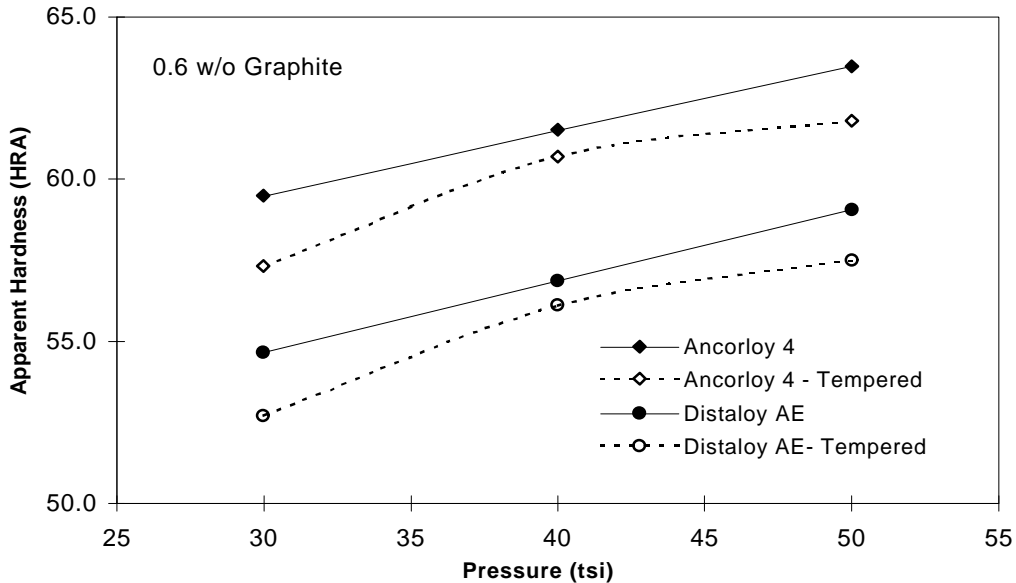


Figure 6b: Ancorloy 4 and Distaloy AE - Hardness vs Compacting Pressure

Finally, the as-sintered and sintered and tempered apparent hardness results of the tensile specimens versus compacting pressure are shown below in Figures 6a and 6b. Here again, a review of the findings in the figures will show that the apparent hardnesses of the Ancorloys exceeded those of the Distalloys in both the as-sintered and sintered and tempered conditions and at all three compaction pressures. Coincident with the improvements in ultimate strength, the relative increases in apparent hardness were typically between 10 and 15%.

The data in these figures also confirm the earlier assertion regarding the probable effects of the tempering treatment. Accordingly, the findings clearly show that apparent hardness either decreased slightly or remained the same on tempering and thus indicate stress relief as the principal cause of the accompanying strength and ductility improvements. Interestingly, unlike much of the earlier tempering data, the present findings also show that the responses of the Ancorloys and the Distalloys to the treatment were very similar to each other, in fact, almost identical. No doubt this reflects the inherent composition and processing similarities of the two as well as indicating the relative insensitivity of the apparent hardness property to variations in these factors.

The Relation Of Yield Strength To Elongation . - The analysis that led to the idea that these properties are inversely related was based on the fact that the load-extension data showed that the individual specimens were behaving in strict accordance with the well known power law: $\sigma = K\varepsilon^n$; where σ and ε are the instantaneous values of the true stress and the true strain, K is the so-called strength constant and n is the strain hardening coefficient, (10). Without going into the details, the specific relationship that the analysis suggested should exist was of exponential form as follows: $YS = k \cdot \exp(-\%EI)$; where YS is the yield strength, %EI is the % elongation and k is a constant of the same order of magnitude as the aforementioned strength constant K. Quite unexpectedly, when the individual values that made up the earlier reported averages of the yield strength and elongation were plotted graphically, it was found that the resultant trendlines in the data appeared to confirm this relationship. For example, the trendlines in the findings that constituted the data that were presented for the as-sintered condition at the 40 tsi compaction pressure are shown below in Figures 7a and 7b.

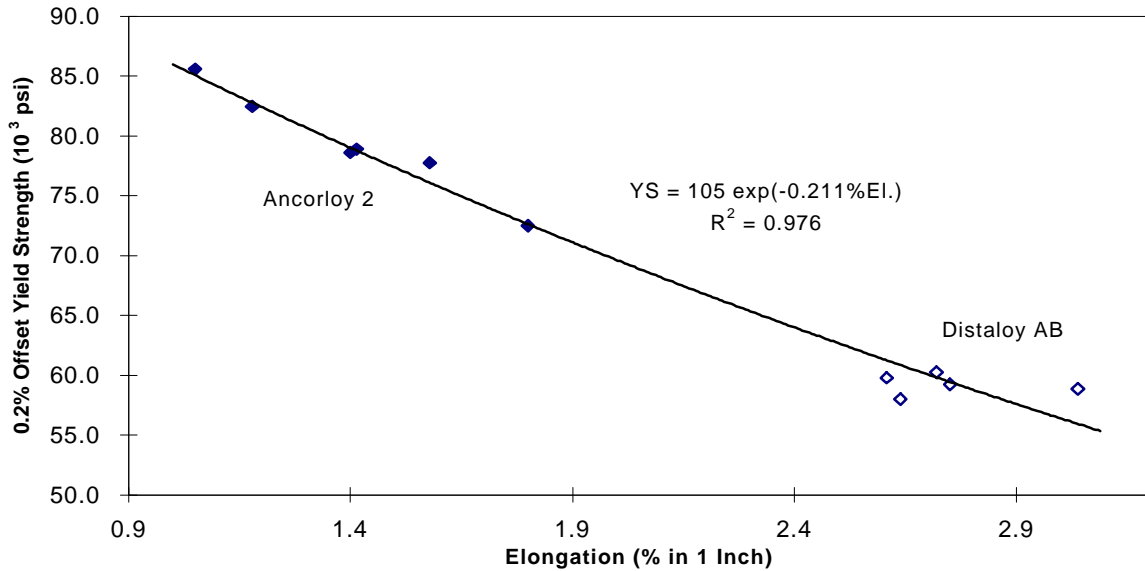


Figure 7a: Ancorloy 2 and Distaloy AB - As-Sintered Yield Strength vs Elongation

The solid points in these figures are the values of the Ancorloy specimens while the open ones are those of the Distaloy. Also shown in each case is the least squares equation of the respective trendline along with the squared value of the corresponding correlation coefficient, R. Based on the fact that each of the latter values is in excess of 0.9, it will be appreciated that its improbable that the indicated trends are chance relationships. Thus, as indicated, the findings appear to provide strong support for the idea of the proposed inverse relationship.

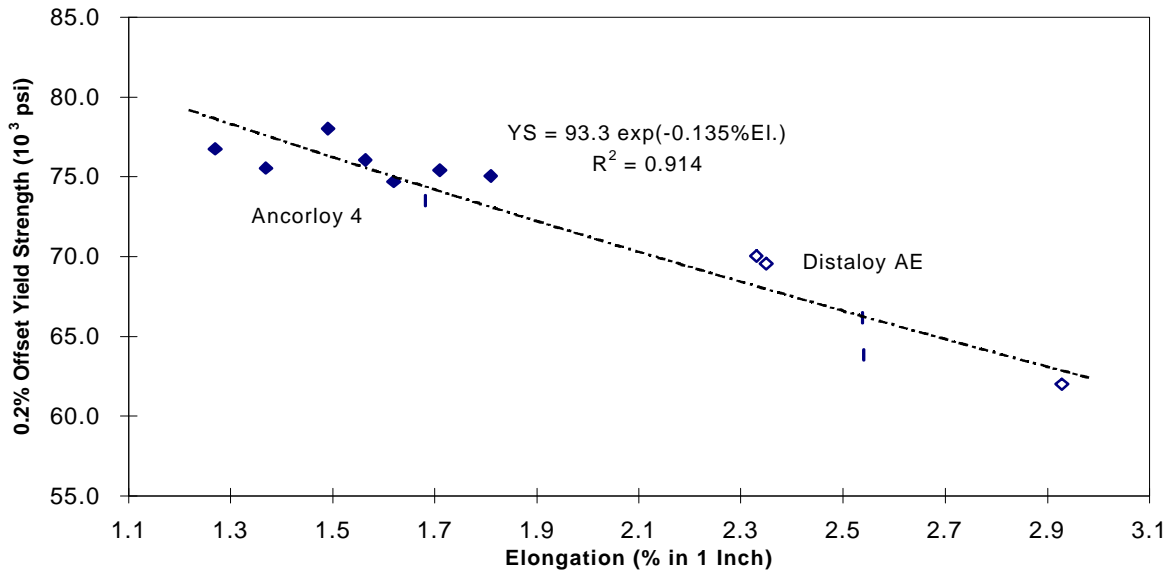


Figure 7b: Ancorloy 4 and Distaloy AE - As-sintered Yield Strength vs Elongation

The particular implication of these findings that was of most interest was the idea that the Ancorloys and the Distalloys should exhibit equivalent elongations at equivalent yield strengths. In an effort to confirm this, tensile specimens of the Ancorloys at the 0.45 w/o graphite level

were prepared at each of the three compaction pressures and tested. The results corresponding to the 40 tsi compaction pressure in both the as-sintered and sintered and tempered conditions versus those of the Distalloys at 0.60 w/o graphite are shown below in Tables 5a and 5b.

Table 5a: As-Sintered Tensile Properties At 40 tsi Of The Ancorloys At 0.45 w/o Graphite Versus The Distalloys At 0.6% Graphite

Premix ID	Yld. Stg. 10 ³ psi (MPa)	Ult. Stg. 10 ³ psi (MPa)	Elong. %	Fract. Stg. 10 ³ psi	App. Hard. HRA
Ancorloy 2	59.7 (411.7)	92.4 (637.2)	3.3	95.5	48.9
Distaloy AB	59.2 (408.3)	99.6 (686.9)	2.7	102.3	54.4
Ancorloy 4	67.5 (465.5)	116.5 (803.4)	2.7	119.7	56.9
Distaloy AE	66.2 (456.6)	110.1 (759.3)	2.5	112.9	56.9

A review of the findings in these tables will show that they reasonably confirmed the expectation of equal elongation at equal yield strength. Actually, in three of the four cases shown, the elongation values of the Ancorloys were slightly better than those of the Distalloys. This tendency was also seen in the specimens that were made at the 30 and 50 tsi compacting pressures, although the findings were somewhat more mixed than here. Consequently, it was concluded that at equal yield strengths, the elongations of the Ancorloys can be expected to be at least equal and may actually be found to be slightly better than those of the Distalloys.

Table 5b: As-Sintered and Tempered Tensile Properties at 40 tsi of the Ancorloys at 0.45 w/o Graphite Versus The Distalloys at 0.6 w/o Graphite

Premix ID	Yld. Stg. 10 ³ psi (MPa)	Ult. Stg. 10 ³ psi (MPa)	Elong. %	Fract. Stg. 10 ³ psi	App. Hard. HRA
Ancorloy 2	63.0 (434.5)	92.2 (635.9)	3.0	94.9	49.9
Distaloy AB	63.6 (438.6)	98.9 (682.1)	2.8	101.6	53.6
Ancorloy 4	67.3 (464.1)	112.9 (778.6)	2.7	116.0	56.1
Distaloy AE	68.6 (473.1)	113.8 (784.8)	3.1	117.4	56.1

As-Sintered And Sintered And Tempered Impact Properties. - Returning to the 0.60 w/o graphite level, the un-notched Charpy impact properties of the Ancorloys and the Distalloys in the as-sintered and sintered and tempered conditions are shown below in Figures 8a and 8b.

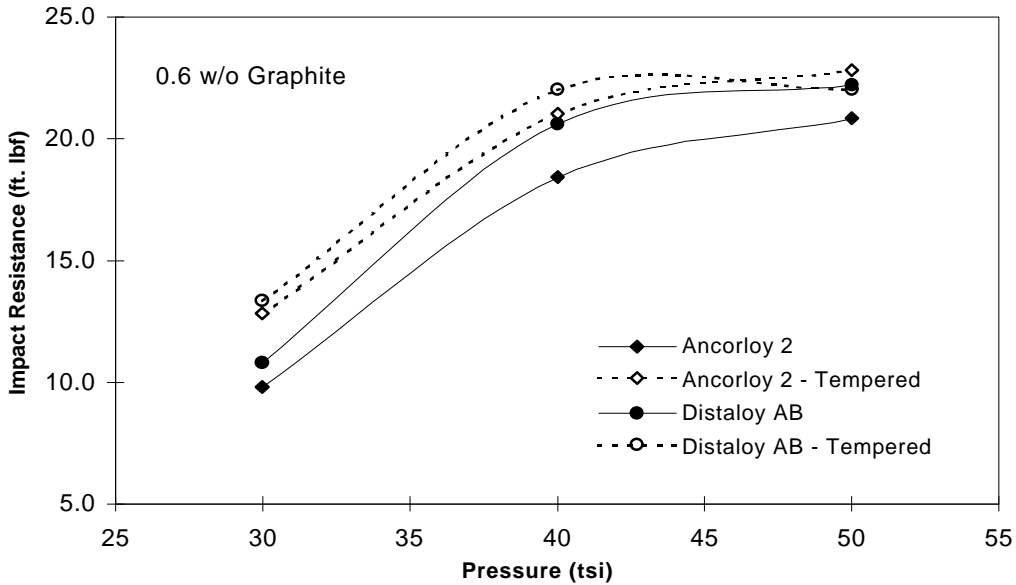


Figure 8a: Ancorloy 2 and Distaloy AB - Impact Resistance vs Compacting Pressure

A review of the findings in these figures will show that the Distalloys generally performed better than the Ancorloys. The differences, however, were moderately small and while statistically significant are unlikely to be of much practical significance in most cases.

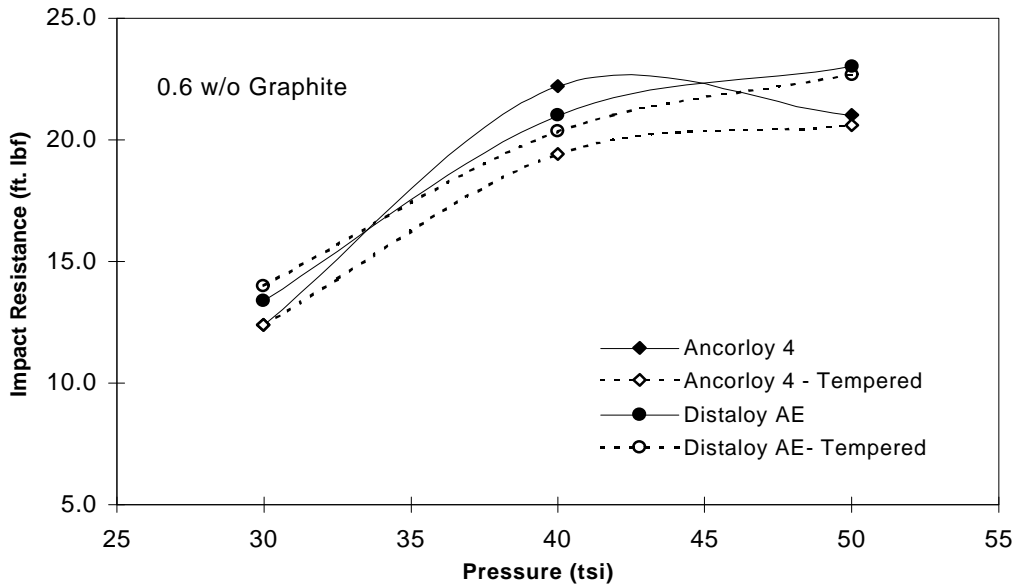


Figure 8b: Ancorloy 4 and Distaloy AE - Impact Resistance vs Compacting Pressure

Actually, impact resistance is usually found to vary inversely as the tensile properties, particularly the yield strength. Thus, in view of the large tensile property differences that were earlier seen with these premixes, it was anticipated that the impact differences between them would also be large. The fact that they weren't was significant. It represented a strong indication based on microalloying theory that the tensile differences were due primarily to grain refinement rather than to precipitation effects, (11). Subsequent comparative microstructural examinations supported this indication. Qualitatively, the Ancorloys had the finer structures in

each case. Thus, grain refinement should be added to the list of important differences that evidently exist between the Ancorloys and the Distalloys.

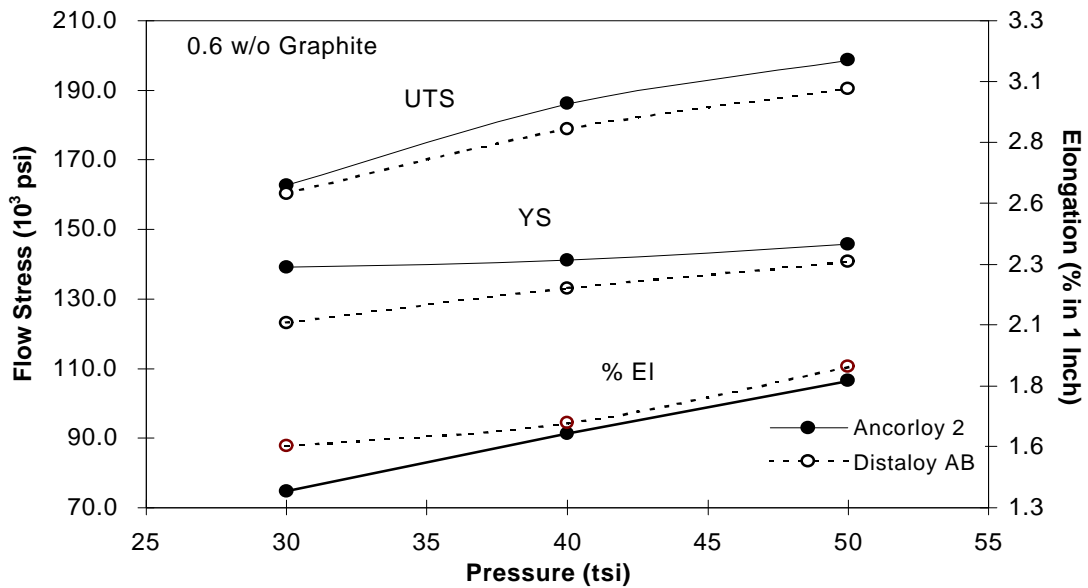


Figure 9a: Ancorloy 2 and Distaloy AB - Q&T Tensile Properties vs Compacting Pressure
Quenched And Tempered Tensile Properties. - The quenched and tempered tensile properties of the premixes including the yield, ultimate and elongation results are shown below in Figures 9a and 9b.

A careful review of these findings will show that the trends which they indicate resemble the earlier findings in direction but not in magnitude. The yield and ultimate strength values of the Ancorloys generally exceeded those of the Distalloys while the reverse was true of the elongation values. However, the relative magnitudes of the differences were not nearly as great as previously. The yield strength improvements were again the largest but were typically less than 10% overall. In the case of the ultimate strength, the findings were mixed varying from

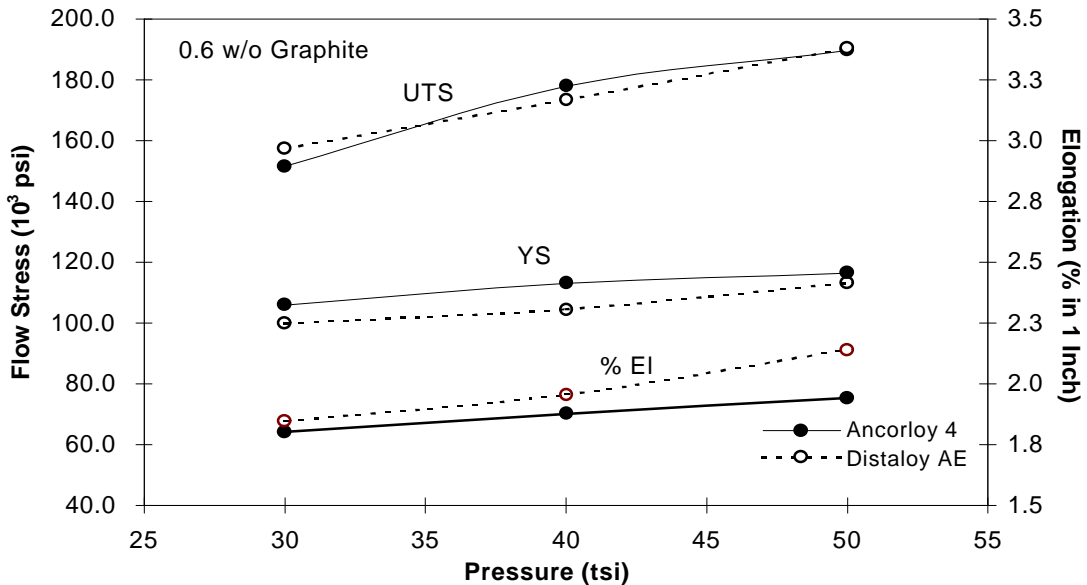


Figure 9b: Ancorloy 4 and Distaloy AE - Q&T Tensile Properties vs Compacting Pressure

essentially no improvement in the Ancorloy 4 to about a 5% increase in the Ancorloy 2. The elongation differences were likewise small and in fact really too small to be of much practical value. Significantly, however, the inverse relationship with the yield strength was nevertheless preserved. For example, it was especially apparent in Figure 9a where the yield strength and elongation curves are virtually mirror images of each other.

Quenched And Tempered Impact Properties. - The quenched and tempered impact properties of the premixes along with the average hardness values of the impact specimens are shown below in Figures 10a and 10b.

According to these findings, the quenched and tempered impact resistance of the Ancorloys was reasonably the same as that of the Distalloys. Although some of the trends in the data tended to favor the Distalloys, the magnitudes of the indicated differences were too small to be of material value. Interestingly, the data in the figures also showed that the apparent hardness values in each case were virtually identical and hence reflected the near parity that was earlier seen in the quenched and tempered ultimate strengths. As a point of reference, 70 HRA is about equal to 39 HRC.

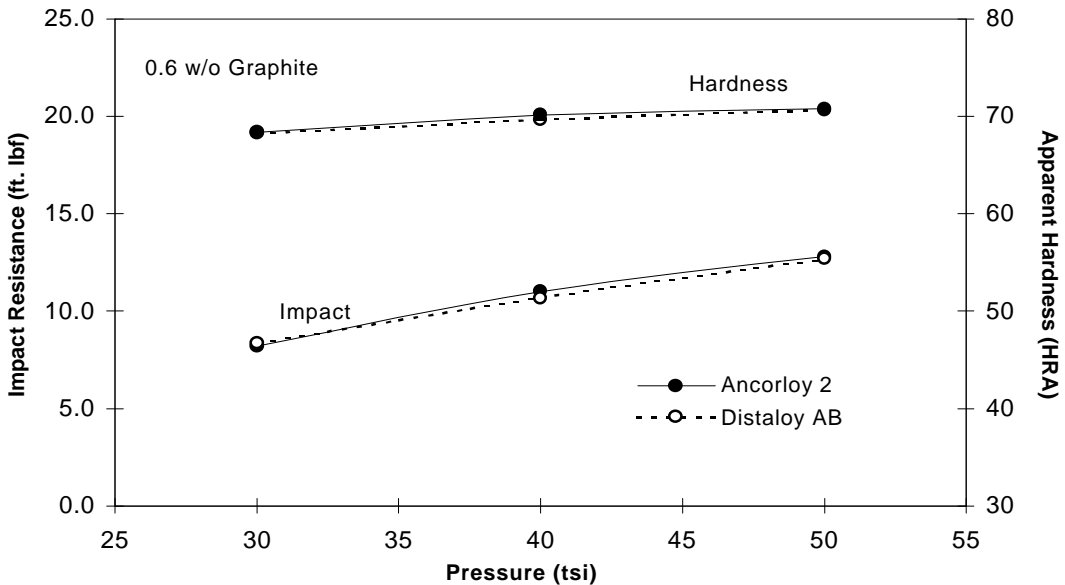


Figure 10a: Ancorloy 2 and Distaloy AB - Q&T Impact and Apparent Hardness vs Compacting Pressure

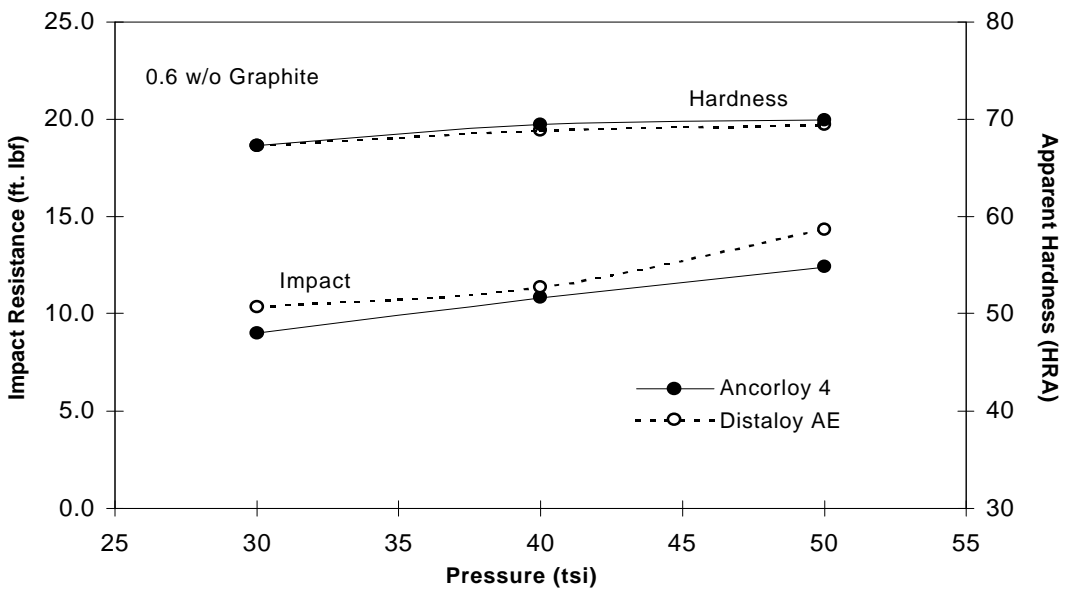


Figure 10b: Ancorloy 4 & Distaloy AE - Q&T Impact and Apparent Hardness vs Compacting Pressure

Notably, the impact findings here were very like the quenched and tempered tensile findings in that each data set indicated the same general trends vis-à-vis the Ancorloys versus the Distalloys that were indicated in the corresponding as-sintered and sintered and tempered data sets. The major distinction between them was in the magnitudes of the relative differences that were indicated. The quenched and tempered differences were by far the smaller of the two. The fact that they were is thought to represent clear-cut evidence to the effect that whatever it is that's lacking in the Distalloys relative to the Ancorloys is apparently amenable to processing. However, in order to implement this possibility, it will also be evident in view of the gross differences which exist between simple sintering and quench and tempering that what will be

required in terms of actual processing is not only likely to be technically challenging but relatively expensive as well.

Fatigue Properties. - The fatigue properties in the as-sintered and quenched and tempered conditions of the Ancorloys are shown below in Tables 6a and 6b. Also shown in the tables are the corresponding sintered densities and endurance to ultimate strength ratios. Owing to the substantial time requirements that are generally needed for these tests, comparative studies of the fatigue properties of the Distalloys were not conducted.

A review of the data in these tables will show that the effects of processing and composition which they indicate are reasonably in accord with expectation but are not without some anomalies and concerns. For example, the data generally show that the survival stress

Table 6a: As-sintered Fatigue Properties of Ancorloy 2 and Ancorloy 4

Premix ID	Compacting Pressure		Sintered Density g/cm ³	99.9% Endurance Limit		Endurance Ratio
	tsi	(MPa)		10 ³ psi	(MPa)	
Ancorloy 2	30	(413.8)	6.96	26.1	(180.0)	0.29
	50	(689.7)	7.23	40.7	(280.7)	0.36
Ancorloy 4	30	(413.8)	7.00	32.6	(224.8)	0.30
	50	(689.7)	7.28	36.6	(252.4)	0.29

increased both with increasing compacting pressure and cooling rate subsequent to sintering and that the Ancorloy 4 values were typically greater than the comparably processed Ancorloy 2 values. However, the latter differences were generally not as large as might be expected given the compositional differences involved and there was at least one instance where the indicated relationship was reversed.

Table 6b: Quenched and Tempered Fatigue Properties of Ancorloy 2 and Ancorloy 4

Premix ID	Compacting Pressure		Sintered Density g/cm ³	99.9% Endurance Limit		Endurance Ratio
	tsi	(MPa)		10 ³ psi	(MPa)	
Ancorloy 2	30	(413.8)	6.95	58.5	(403.4)	0.36
	50	(689.7)	7.23	67.5	(465.5)	0.34
Ancorloy 4	30	(413.8)	7.01	60.6	(417.9)	0.40
	50	(689.7)	7.28	68.9	(475.2)	0.36

Inconsistencies or anomalies of the latter sort, of course, are not unusual in limited studies of this type. However, in this particular instance, they are very probably significant. Apart from the highly statistical nature of the fatigue test, there is also the very good possibility here of the haphazard influence of residual stresses on the findings as well. Both the likely existence and significance of this influence has already been demonstrated in the case of the as-sintered condition and given the fact that it was necessary to center grind the quenched and tempered specimens to final size after tempering, residual stresses no doubt existed and may have been significant in these cases as well. Of course, the obvious implication is that the specimens should have been submitted to a stress relief anneal just prior to testing. However, as far as

known, this is not commonly done and one of the general aims of the study, of course, was to provide information which would be comparable with common practice. Thus, suffice to say that while the present findings meet this particular criterion and are otherwise the best that the broad scope of the study would justify, it may well be that they mask important effects and are not the best of what the Ancorloys have to offer.

In any case, returning to the data in Tables 6a and 6b, the endurance ratios that are shown provide the means to make a general, albeit qualitative, comparison of the fatigue behavior of the Ancorloys versus that of other P/M compositions of interest including the Distalloys. Notice, in particular, that there is reasonable parity between the several values of the ratio that are reported in each table. Thus, in Table 6a the overall average of the ratio representing the as-sintered condition is 0.31 while in Table 6b, the value representing the quenched and tempered condition is 0.37.

Comprehensive comparisons of the rotating bending fatigue properties of the Distalloys as well as of several other P/M compositions of general industrial importance have been reported in the open literature, (12, 13). Interestingly, a review of these findings showed that for the Distalloys in the as-sintered condition, the average of the ratios reported over a wide variety of graphite contents and densities was coincidentally also precisely 0.31. Thus, given this and the present findings to the effect that the as-sintered ultimate strengths of the Ancorloys typically exceeded those of the Distalloys by anywhere from 5 to 15%, it appears reasonable to conclude that this will also be the case with the as-sintered fatigue strengths as well. In the case of the quenched and tempered condition, the situation was more nebulous. The available data were largely limited to one study and were based on the 90% rather than the 99.9% survival values as in the present case, (14). Moreover, the endurance ratios reported for the Distalloys were suspiciously high, typically being in excess of 0.5, and it was speculated that they were flawed due to erroneously low ultimate strengths. Thus, the significance of a comparison with the present value of 0.37 is in doubt. On the other hand, of the several quenched and tempered compositions that were included in this particular study, the Distalloys were cited as having exhibited three of the four highest fatigue strength values that were observed. Significantly, only one of these values was higher than the two highest values indicated above for the Ancorloys. Thus, in the case of the quenched and tempered condition, it seems reasonable to speculate that the Ancorloys are at least the equivalent of the Distalloys and as such may be expected to rank with the best of what the P/M industry has to offer in terms of fatigue properties.

SUMMARY AND CONCLUSIONS

Premixes of standard FD-0205 and FD-0405 compositions of the diffusion alloyed steels, represented by Distaloy AB and Distaloy AE, were compared with binder treated analogs thereof, called Ancorloy 2 and Ancorloy 4. The studies included comparisons of the powder, green and standard sintered properties of the premixes and of the effects of various compaction pressures in the range of 30 to 50 tsi on the resulting tensile, impact and fatigue properties in the as-sintered, sintered and tempered and quenched and tempered conditions.

The powder and green property comparisons generally showed the Ancorloy premixes as having increased apparent densities and substantially improved flow rates and compressibilities but lower green strengths than the Distalloys. The differences in each case were directly attributable to the inherent processing differences that were involved in the manufacture of the premixes. The flexibility of the binder treatment process to alter the properties of the Ancorloy premixes to suit a particular need, especially as regards green strength, was briefly noted.

The standard sintered property comparisons indicated the Ancorloys to be essentially equivalent to the Distalloys as regards transverse rupture strength and dimensional change. The respective values that were reported were within 5000 psi and 0.05% in each case.

In the tensile property comparisons, the Ancorloys exhibited significantly improved yield and ultimate strength values but decreased elongations versus the Distalloys in all three conditions of processing. The largest relative strength improvements were in the as-sintered and sintered and tempered conditions. The increases were typically from 15 to 20% in yield strength and from 5 to 15% in ultimate strength. In the quenched and tempered condition, the increases ranged from 5 to 10% in yield strength and were ordinarily no better than about 5% in ultimate strength. The elongation decreases mentioned were of the same relative magnitude as the yield strength increases and it was noted that the strain hardening characteristics indicated in the data suggested that the two properties were inversely related. Subsequently, evidence was presented that both supported the existence of such a relationship and indicated that at equal yield strengths, the Ancorloys can generally be expected to exhibit equivalent or slightly better elongations than the Distalloys.

In the impact property comparisons, the findings were generally mixed. Although more of the individual Distalloy values in each of the three conditions of processing were positive of the corresponding Ancorloy values than visa versa, none of the differences were large enough to be regarded as significant. Thus, as a practical matter, it was concluded that the Ancorloys were essentially equivalent to the Distalloys in impact resistance. According to microalloying theory, an important implication of this finding was that the very substantial yield strength improvements of the Ancorloys versus the Distalloys were due principally to differences in grain size rather than to precipitation effects. Subsequent metallographic examinations confirmed that the microstructures of the Ancorloys were qualitatively much finer than those of the comparably processed Distalloys.

The hardness comparisons in the data generally reflected the ultimate strength results. The major differences were in the as-sintered and sintered and tempered conditions where the relative increases in the Ancorloy versus the Distalloy values typically ranged from 5 to 15%. The hardness findings were also of interest to indicate the nature of the changes that were occurring during tempering subsequent to sintering. The data showed that while the hardness of both the Ancorloys and the Distalloys either remained the same or decreased slightly on tempering, all of the other properties of interest generally increased. Thus, the primary function of the tempering treatment appeared to be residual stress relief. The stresses were thought to have arisen adventitiously in response to incidental cooling rate differences after sintering and otherwise to be a consequence of the tendency of the present compositions to precipitate low temperature transformation products even at moderate cooling rates.

The results of limited RBF fatigue studies of the Ancorloys in the as-sintered and quenched and tempered conditions were presented. Based on the endurance ratios indicated in the findings, comparisons with published data on the Distalloys suggested that the Ancorloys can be expected to exhibit the same relative improvements in fatigue strength versus the Distalloys as have been shown to exist in the ultimate strength. In addition, both the findings of the fatigue study as well as of the larger study in general hinted broadly at the likelihood of adverse effects due to the presence of residual stresses. Thus, a more comprehensive investigation which systematically addresses this possibility may well show that both the fatigue properties reported here as well as those quoted in the open literature for these compositions have significantly underestimated the true values.

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