The Development of Engineered Binder-Treated Alternatives to Diffusion Alloyed Powders

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Abstract
Engineered binder-treated premixes have been developed as alternatives to diffusion alloyed powders. The binder-treated materials meet the chemical composition limits for diffusion alloyed materials listed in MPIF Standard 35, Materials Standards for P/M Structural Parts.

At an equivalent combined carbon content the binder-treated materials exhibit higher strength than the diffusion alloyed materials. When the combined carbon content of the binder-treated materials is reduced, to provide an equivalent strength level, the binder-treated materials match the tensile ductility and impact energy of the diffusion alloyed product.

The as-sintered and the quench-hardened and tempered performance of the new materials is reviewed and compared with diffusion alloyed materials of similar chemistry. These recently developed materials represent the first in a new family of high performance ferrous P/M materials.

Introduction
The first diffusion alloyed powder was developed in North America during the 1960's in an attempt to overcome the tendency for admixed powders to segregate and dust during handling [1, 2]. This diffusion alloyed powder was based on a direct reduced sponge iron powder and were given the name Ancoloy. Alloying additions mixed with the sponge iron powders were partially alloyed to the iron powder base in a diffusion annealing process.

Since the initial development of the Ancoloy powder, diffusion alloyed powders based upon both water atomized iron and water atomized prealloyed powders have been developed and marketed under the "Distaloy®" trademark. P/M materials based on diffusion alloyed powders exhibit a special combination of tensile strength, ductility, and impact energy in the as-sintered condition coupled with good response to heat treatment. Quench-hardened and tempered ferrous P/M materials based on diffusion alloyed powders even possess some ductility; a rarity in heat treated P/M materials.
The additional steps involved in producing diffusion alloyed powders result in a price premium for such products. Attempts at matching the combination of performance characteristics exhibited by materials based on diffusion alloyed powders have, until recently, met with no success. Even binder-treated hybrid alloys, based on prealloyed powders that use molybdenum as the principal alloy addition, fail to match the combination of performance characteristics possessed by materials based on diffusion alloyed powders [3]. They may meet or exceed one or more of the characteristics of the diffusion alloyed material but they do not match the combination of properties of the latter material.

Recently, however, two new powders have been developed that match and may even exceed the combination of performance characteristics exhibited by diffusion alloyed materials. As a tribute to their proud heritage, the new powders have been given the trade name of "Ancorloy™." The Ancorloy powders are supplied as binder-treated premixes and are made using a proprietary practice that does not include diffusion alloying. The two powders are the first members of a new family of Ancorloy products.

An excellent review of the development of the Ancorloy powders has been presented by Semel [4]. The balance of the present paper will be devoted to a direct comparison between two materials based on diffusion alloyed powders and their binder-treated analogs that are based on a proprietary practice.

Experimental Procedure

Premixes corresponding to MPIF material designations FD-0205 and FD-0405 were made using the appropriate diffusion alloyed powder base and additions of 0.6 w/o (weight %) graphite. Binder-treated premix analogs of these diffusion alloyed materials were prepared using a proprietary practice. The premix corresponding to FD-0205 was designated Ancorloy 2, and the one corresponding to FD-0405 was designated Ancorloy 4. All of the premixes were lubricated with 0.75 w/o of Acrawax C. The Ancorloy premixes matched the chemical composition of the corresponding diffusion alloyed materials and complied with the limits indicated in Table 1.

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

Tensile and impact properties of the various materials were evaluated in the as-sintered, sintered and tempered, and quench-hardened and tempered conditions. In some studies, samples were compacted to a desired green density while in others they were compacted at 415, 500, and 690 MPa respectively. Sintering was carried out at 1120°C in a Hayes pusher furnace for 30 minutes at temperature in a synthetic dissociated ammonia atmosphere.

The as-sintered and sintered and tempered tensile properties were based on as-pressed dog-bone specimens while the quenched and tempered properties were measured on machined round specimens conforming to ASTM E 8. The round specimens were polished parallel to the
tensile axis to a 1 µm RMS finish using metallurgical grade emery paper. The reported values are, in all cases, based on a minimum of three measurements and, in most cases, five measurements per condition.

When applied, the after sintering tempering treatment was basically a stress relief at 177°C for 30 minutes in air.

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

Density checks of the specimens were conducted prior to testing by the immersion method described in ASTM B 328 and, typically, were limited to two specimens per condition.

Tensile testing was performed on a Tinius Olsen machine at a crosshead speed of 0.05 cm/min. The machine was equipped with a 25 mm extensometer and provided automated readouts of the 0.2% offset yield strength, ultimate tensile strength, and percentage elongation values.

Impact testing was performed at ambient temperature (approximately 20°C) using standard unnotched Charpy specimens in accordance with ASTM E 23. The specimens were compacted at 415, 550, and 690 MPa.

Apparent hardness values representing the as-sintered, and sintered and tempered condition were measured on the grip end-faces of the dog-bone tensile specimens prior to testing. For the quench-hardened and tempered condition, apparent hardness measurements were made on impact specimens prior to testing. All apparent hardness measurements were made using the Rockwell A scale (diamond indenter and 60 kgf load). The "A" scale has the convenience of covering the whole of the "C" scale and most of the "B" scale.

Rotating bending fatigue testing was performed on specimens conforming to the dimensions listed in reference 4. The specimens were machined from pressed and sintered blanks measuring 1 cm x 1 cm x 7.6 cm and polished parallel to their longitudinal axes to a 1 µm RMS finish. Fatigue determinations were limited to the as-sintered and the quench-hardened and tempered conditions for specimens compacted at 415 and 690 MPa. Typically, twenty-five specimens were used to estimate the fatigue endurance limit. Testing was conducted at 8,000 rpm with survival to 10⁶ cycles considered a runout. The stress levels used for testing were chosen according to the staircase method for estimating the fatigue endurance limit at the 90% survival value.

Results

The as-sintered densities of the various materials are illustrated in Figures 1a and 1b. The binder-treated premodels achieved sintered densities comparable to those of the corresponding diffusion alloyed materials. The compressibilities and dimensional change characteristics of the corresponding materials were quite similar.
The as-sintered and the sintered and tempered ultimate tensile strength data versus compaction pressure for the various materials are summarized graphically in Figures 2a and 2b. Tempering, or more precisely stress relieving, of the sintered specimens was performed because of the improvement in properties known to result from such a treatment for diffusion alloyed materials with graphite additions of 0.6 w/o and higher [5]. The ultimate strengths of the Ancorloy materials exceeded those of the diffusion alloyed materials in both the as-sintered and the sintered and tempered conditions at all three compaction pressures.
Figure 2a: Ultimate Tensile Strength versus Compaction Pressure for Ancorloy 2 and FD-0205

Figure 2b: Ultimate Tensile Strength versus Compaction Pressure for Ancorloy 4 and FD-0405

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

Figure 3a: Yield Strength versus Compaction Pressure for Ancorloy 2 and FD-0205

Figure 3b: Yield Strength versus Compaction Pressure for Ancorloy 4 and FD-0405

In contrast to the results for ultimate tensile strength and yield strength, the elongation of the Ancorloy materials was less than that of the diffusion alloyed materials. The data are presented graphically in Figures 4a and 4b.
Figure 4a: Elongation versus Compaction Pressure for Ancoroy 2 and FD-0205

Figure 4b: Elongation versus Compaction Pressure for Ancoroy 4 and FD-0405

Apparent hardness and unnotched Charpy impact energy data for the materials are shown graphically in Figures 5a and 5b, and Figures 6a and 6b respectively. The apparent hardness for the Ancoroy materials exceeds that of the diffusion alloyed materials for all process conditions. Tempering generally reduces the apparent hardness of the materials slightly. The diffusion alloyed materials had slightly higher impact energy values than their binder-treated analogs. However, the differences were moderate and, in most cases, unlikely to be of practical significance.
Figure 5a: Apparent Hardness versus Compaction Pressure for Ancorloy 2 and FD-0205

Figure 5b: Apparent Hardness versus Compaction Pressure for Ancorloy 4 and FD-0405

The quench-hardened and tempered tensile properties of the various materials are shown graphically in Figures 7a and 7b. The yield and ultimate strength values for the Ancorloys generally exceeded those of the diffusion alloyed materials. However, the magnitude of the difference was not great. The yield strength improvements typically were less than 10% overall. The ultimate strength of the material based on Ancorloy 4 was similar to that for the corresponding diffusion alloyed material while that for Ancorloy 2 was about 5% higher than its counterpart. The differences in elongation were too small to be of practical significance.
Figure 6a: Unnotched Room Temperature Charpy Impact Energy versus Compaction Pressure for Ancorloy 2 and FD-0205

Figure 6b: Unnotched Room Temperature Charpy Impact Energy versus Compaction Pressure for Ancorloy 4 and FD-0406

Room temperature, unnotched Charpy impact energy data and apparent hardness values are summarized in Figures 8a and 8b. The impact energy data for the corresponding grades are very comparable.
Figure 7a: Quench-Hardened and Tempered Tensile Properties of Ancorloy 2 and FD-0205

Figure 7b: Quench-Hardened and Tempered Tensile Properties of Ancorloy 4 and FD-0405

Rotating bending fatigue data for the Ancorloy materials are summarized in Figure 9. The data are for samples compacted at 415 MPa and 690 MPa for both the as-sintered and the quench-hardened and tempered condition. Also included in the graph are data for corresponding diffusion alloyed materials; these data were interpolated from MPIF Standard 35 (1997 Edition).

Discussion

In the as-sintered and the sintered and tempered condition, the ultimate tensile strengths, yield strengths, and apparent hardness values of the Ancorloy materials are higher than for the
corresponding diffusion alloyed materials with the same graphite addition (0.6 w/o). In contrast to this, the tensile elongations of the diffusion alloyed materials are greater than those of the Ancorloys. While the elongations of the Ancorloy materials improve after a stress relief tempering treatment, they are still lower than those of the diffusion alloyed materials.

Figure 8a: Quench-Hardened and Tempered, Unnotched Room Temperature Charpy Impact Energy and Apparent Hardness versus Compaction Pressure for Ancorloy 2 and FD-0205

Figure 8b: Quench-Hardened and Tempered, Unnotched Room Temperature Charpy Impact Energy and Apparent Hardness versus Compaction Pressure for Ancorloy 4 and FD-0405

The results appear to indicate the existence of an inverse relationship between yield strength and elongation and therefore are consistent with an effect that is ordinarily to be expected. A relationship of the form: Yield Strength = k \cdot e^{-c \cdot \% \text{Elongation}}, where k and c are constants was
suggested by Samel [4]. When the yield strength and elongation data were plotted it was found that the resultant trendlines appeared to confirm such a relationship. For example, the trendlines for the as-sintered condition and a compaction pressure of 550 MPa are illustrated in Figures 10a and 10b.

![Graph showing fatigue limit vs. compaction pressure for different conditions](image)

**Figure 9:** Rotating Bending Fatigue Limit for Ancoroy Materials Compacted at 415 MPa and 690 MPa for the As-Sintered and the Quench-Hardened and Tempered Condition. The Data are Compared with Data for Diffusion Alloyed Materials - Based on MPIF Standard 35.

Also shown in each graph is the least squares equation of the respective trendline along with the squared value of the corresponding correlation coefficient, R. Each of the R² values is in excess of 0.9. It is therefore unlikely that the indicated trends are chance relationships. The data therefore support the idea of an inverse relationship between yield strength and elongation.

The unnotched, room temperature impact energy values, in the as-sintered and the sintered and tempered condition, are slightly higher for the diffusion alloyed materials. However, the values for the Ancoroy materials are, in practical terms, quite similar to those of the diffusion alloyed samples. In fact, with the observed disparities in the tensile strengths of the respective materials, greater differences in impact performance might have been expected.

In view of these findings it seemed likely that the Ancoroy and diffusion alloyed materials should exhibit equivalent elongations at equivalent yield strengths. Tensile specimens of the Ancoroy materials were prepared, therefore, with graphite additions of 0.45 w/o at compaction pressures of 415, 550, and 690 MPa. In both the as-sintered and the sintered and tempered conditions. The results of the tensile testing are summarized in Figures 11a and 11b, and 12a and 12b.

The reduced graphite addition (0.45 w/o) in the Ancoroy materials resulted in yield strength values equivalent to those of the diffusion alloyed materials with 0.6 w/o graphite (Figures 11a...
and 12a). At an equivalent yield strength, the Ancorloy materials have comparable elongation values to the diffusion alloyed materials (Figures 11b and 12b).

![Graph showing relationship between yield strength and elongation for Ancorloy 2 and FD-0205 samples compacted at 550 MPa.](image)

Figure 10a: Relationship Between the As-Sintered Yield Strength and Elongation for Ancorloy 2 and FD-0205 Samples Compacted at 550 MPa

![Graph showing relationship between yield strength and elongation for Ancorloy 4 and FD-0405 samples compacted at 550 MPa.](image)

Figure 10b: Relationship Between the As-Sintered Yield Strength and Elongation for Ancorloy 4 and FD-0405 Samples Compacted at 550 MPa

In the as-sintered condition, the rotating bending fatigue limit for both Ancorloy 2 and Ancorloy 4 materials improves with increased compaction pressure (Figure 9). In the quench-hardened and tempered condition, the fatigue limits are significantly higher. However, while the values for Ancorloy 4 are higher than for Ancorloy 2 at both compaction pressures, the differential is not great considering the difference in the chemical composition of the two materials.
Figure 11a: 0.2% Offset Yield Strength versus Compaction Pressure for Ancorloy 2 and FD-0205 Materials with Equivalent Yield Strength

Figure 11b: Elongation versus Compaction Pressure for Ancorloy 2 and FD-0205 Materials with Equivalent Yield Strength

Because of time constraints, fatigue testing of the corresponding diffusion alloyed materials was not carried out in the present study. However, the results from prior studies at our laboratory confirmed that the data for the Ancorloy materials were at least comparable to that for the diffusion alloyed materials [8-8]. For comparison purposes, data from MPIF Standard 35 for P/M Structural Parts (1997 Edition) have been added to the bar charts in Figure 9. The Ancorloy materials are equivalent to, and in some instances better than, the diffusion alloyed materials.
However, the heat treated Ancorloy samples were tempered at 200°C while the heat treated diffusion alloyed materials in Standard 35 were tempered at 177°C and this may explain some of the difference.

Figure 12a: 0.2% Offset Yield Strength versus Compaction Pressure for Ancorloy 4 and FD-0405 Materials with Equivalent Yield Strength

Figure 12b: Elongation versus Compaction Pressure for Ancorloy 2 and FD-0205 Materials with Equivalent Yield Strength

After quench-hardening and tempering, for samples with a 0.6 w/o graphite addition, the ultimate tensile strengths, yield strengths, elongations, apparent hardness values, and impact energies of the Ancorloy and diffusion alloyed materials are very similar (Figures 7a, 7b, 8a, and 8b).
Therefore it would appear that, in martensitic microstructures, Ancorloy and diffusion alloyed materials are comparable when they have the same graphite addition.

Conclusions

Engineered binder-treated premixes have been developed as alternatives to diffusion alloyed powders. The new materials have been given the tradename of "Ancorloys". In the as-sintered as well as the sintered and stress relieved condition, Ancorloys exhibit higher ultimate tensile strength, yield strength, and apparent hardness than diffusion alloyed materials of similar chemistry with the same graphite addition. However, the elongation of the diffusion alloyed materials is greater than that of the Ancorloys. While the impact energy of the diffusion alloyed materials is slightly greater than that of the Ancorloys the difference, in most instances, is unlikely to be of practical significance.

An inverse relation has been demonstrated, in the as-sintered condition, between the yield strength and elongation of the materials. At comparable levels of yield strength the materials have equivalent values of tensile elongation.

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

The rotating bending fatigue performance of the Ancorloy materials appears to be at least comparable to that of the corresponding diffusion alloyed materials and there are some indications that it may be better. A more comprehensive study needs to be conducted.

References