P/M High Strength Magnetic Alloys

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Abstract:

Sintered P/M magnetic materials are characterized by good DC magnetic performance with relatively low yield and tensile strengths, typically the tensile strengths are less than 50,000 psi. This inherently low strength of the common magnetic alloys results from the use of pure iron or iron phosphorus alloys. This low strength often limits the potential applications for sintered P/M magnetic materials. Described in this paper are P/M alloys that have tensile strengths approaching 70,000 psi (480 MPa) in the as sintered condition with tensile ductility approaching 10% and having magnetic properties equal to the pure iron and / or iron phosphorus alloys. These alloys are intended for higher strength, magnetic applications. A comparison to the standard P/M magnetic alloys will be made.

Introduction:

The increasing demand for greater vehicle control during acceleration, braking, and accident avoidance maneuvers advanced the development of interactive torque management (ITM) systems. (1) These systems respond to numerous vehicle inputs in order to maintain vehicle stability over a wide range of driving situations. Key components of these systems include the torque transfer components, the electronic control module, and the electromechanical components that enable the variable torque transfer. The electromechanical components of these systems necessitate good magnetic performance to quickly activate the torque transfer system coupled with part to part consistency, wear resistance, and mechanical properties capable of withstanding assembly and usage in service. Given these property requirements coupled with restrictions in packaging and the continuous incentive to lower cost (with no compromise in quality) resulted in complex designs that fully exploit the advantages inherent with the powder metallurgy (P/M) process.

Sintered powder metallurgy electromechanical components typically are made from either pure iron or iron phosphorus alloys. These materials, pressed and sintered, possess good DC magnetic properties but applications opportunities maybe limited because of their low mechanical strength. In the case of pure iron MPIF Standard 35, cites a typical tensile strength of ~38,000 psi (260 MPa) at 7.30 g/cm³. The addition of phosphorus will increase the tensile strengths to ~62,000 psi (425 MPa) at 0.80 w/o phosphorus and at a sintered density of 7.3 g/cm³. (2)

Understanding the behavior of iron phosphorus P/M alloys begins with an understanding of the iron-phosphorus binary phase diagram. The iron phosphorus phase diagram exhibits a gamma loop indicating the coexistence of both alpha and gamma phases from ~0.3 w/o to ~0.6 w/o phosphorus at conventional sintering temperatures. Above 0.6 w/o phosphorus the sintering is done entirely in the alpha phase. (3) Alpha phase sintering results in enhanced sintering with the accompanying greater dimensional change, larger grain size (potentially lower strength), and the possibility of phosphorus segregation at the grain boundaries. (4) This phosphorus segregation is a significant problem in wrought steels resulting in an iron-phosphorus intermetallic forming in the grain boundaries and is accentuated by holding at temperature or slow cooling. P/M is unique in that the holding times at temperature are relatively short; however, higher levels of phosphorus accelerate the tendency for grain boundary segregation.

Alternatives to the use of iron phosphorus magnetic alloys are alloys containing silicon. Silicon increases the material’s resistivity thus increasing the permeability and lowering the coercive force. (5) The major drawback to the use of silicon is that high temperature sintering is required to homogenize the silicon addition. In work reported by Gegel etal, additions of both silicon (3 w/o) and phosphorus (0.45 w/o) produced magnetic alloys that exhibited permeability in excess of 5000. (6) Beyond the benefits of increased magnetic performance, silicon is a ferrite strengthener and has shown a positive effect on the strength and ductility of P/M materials. (7) The recent development of the Ancorloy MD series has demonstrated higher yield and tensile strengths with superior elongation at silicon levels ranging from 0.3 w/o to 0.6 w/o. Based on this work this study was performed to investigate the effects of relatively low levels of silicon (~0.6 w/o) on the magnetic and physical properties of P/M alloys both pure iron and based on MPIF FL4400 series materials.

A word of caution about using standard test data for actual component performance. The preponderance of magnetic data presented in the literature was generated using standard toroidal magnetic specimens. (8,9,10) These specimens are readily prepared and analyzed. However, the standardized toroidal specimen sintered in R&D furnaces do not replicate the performance of complex P/M components with their associated density gradients, potential non-homogeneous microstructures, and production processing. (11) These unique characteristics of P/M parts dictate that the part design is robust to account for the potential variations inherent in the P/M processing. Beyond the magnetic performance requirements of the electromechanical component, the new part designs incorporated in the ITM systems place structural loads on the P/M part. Now the task of designing these components with all the inherent variations becomes even more complex. Thus the potential development of new materials and processing that have superior magnetic and physical properties to current materials may expand the application range for P/M magnetic alloys.

Experimental Procedure:

Ancorsteel 80P® (MPIF FY-8000) is a commercial material currently in use at Borg Warner in the production of electromechanical clutch systems. The initial stage of the experimental work investigated the effects of potential variations in both the phosphorus content and the sintering conditions. The phosphorus content was varied from 0.72% to 0.88% using Ancorsteel 1000C® as the base iron. Toroids (2.00 inch OD [50.8 mm] x 1.66 inch ID [42.2 mm] x .25 inch OAL [12.7 mm]) and tensile specimens (per MPIF standard #10) were compacted to a nominal density of 7.05 g/cm^3 using admixed Acrawax as the lubricant. Sintering was done at 2050 °F (1120 °C) in the following atmospheres: 75 v/o hydrogen with 25 v/o nitrogen, 36 v/o hydrogen with 64 v/o nitrogen, 3 v/o hydrogen and 97% nitrogen, and lastly less than 1% v/o hydrogen with the balance nitrogen. Sintering was done in both a laboratory pusher furnace and a production 24-inch [610 mm] belt furnace. After sintering, the toroid specimens were measured and subsequently wrapped with 80 primary and 80 secondary turns of lacquered copper wire (#22 wire). Magnetic testing was performed using an OS Walker AMH 20 Hysteresisgraph at both 15 Oersteds and 25 Oersteds drive field. All tensile specimens were tested in the as-sintered condition.

The objective of this initial study was to establish a baseline of data for the standard production material. Sintering in both an R&D pusher furnace and a production furnace gave a broad range of magnetic and physical properties to which future material developments could be compared. This first part of the study investigated the normal variations expected with the 0.80 w/o phosphorus alloy and assessed potential problems potentially encountered during routine production.

Following the initial work, the second step in the experimental program was the development of enhanced materials and processing that would provide equivalent or greater magnetic and physical properties characterized in step one. Again toroidal specimens and tensile specimens were compacted over a range of pressures from 30 tsi (415 MPa) to 50 tsi (690 MPa). All sintering was done in a laboratory belt furnace using 75 v/o hydrogen and 25 v/o nitrogen for 30 minutes at temperatures of 2050 °F (1120 °C) and 2300 °F (1260 °C). Magnetic testing was performed on an AMH 20 Hysteresisgraph using 80 primary and 80 secondary turns. The range of alloys tested is presented in Table 1. All premixes were prepared using 0.75 w/o Acrawax as a lubricant.

Table 1
Chemical Composition of Materials Tested

Premix ID	Base Iron	Phosphorus Content (w/o)	Silicon Content (w/o)	Carbon (w/o)
A	FL-4400	0.45	0.0	0.0
B	FL-4400	0.80	0.0	0.0
C	FL-4400	0.80	0.60	0.0
D	FL-4400	0.45	0.30	0.0
E	FL-4400	0.45	0.60	0.30
F	F-0000	0.45	0.0	0.0
G	F-0000	0.80	0.0	0.0
H	F-0000	0.80	0.60	0.0

Results:

Part 1: Review of Current Production Material

In the first part of this study, the effects of phosphorus level and sintering atmosphere were evaluated on a FY-8000 material. Table 2 presents the effect of different sintering atmospheres on both the sintered density and dimensional change of the four initial blends evaluated. As expected, the 75-v/o-hydrogen atmosphere resulted in the highest sintered density and the largest shrinkage. Interestingly, the <1% v/o hydrogen atmosphere showed nearly identical sintered density and dimensional change to the highest hydrogen atmosphere. The reasoning for this nearly identical behavior can be explained by residual elements present after the four different sintering trials. The <1% hydrogen showed the lowest carbon content of the atmospheres evaluated; thus promoting the maximum shrinkage from the ferrophosphorus addition (Table 3). Note: Table 3 presents the results for the 0.80% phosphorus condition, the results for the remaining phosphorus levels were similar.

Table 2
Effects of Sintering Atmosphere on Sintered Density And Sintered Dimensional Change

Phosphorus Level (%)	75 v/o Hydrogen, g/cm³,(%)	3 v/o Hydrogen, g/cm³,(%)	36 v/o Hydrogen, g/cm³,(%)	<1 v/o Hydrogen, g/cm³,(%)
0.80	7.17 (-0.29)	7.13 (-0.16)	7.13 (-0.17)	7.14 (-0.27)
0.72	7.15 (-0.22)	7.11 (-0.11)	7.11 (-0.11)	7.13 (-0.22)
0.88	7.17 (-0.32)	7.13 (-0.23)	7.12 (-0.17)	7.13 (-0.28)
0.45	7.09 (-0.01)	7.07 (+0.03)	7.06 (+0.06)	7.07 (+0.04)

(Dimensional Change is shown in parenthesis)

Table 3
Residual Element Analysis Resulting from the Varying Sintering Conditions

Phosphorus Level (%)	Atmosphere (%Hydrogen)	Carbon (%)	Oxygen (%)	Nitrogen (%)
0.80	75	0.02	0.035	0.001
	3	0.01	0.065	0.004
	36	0.02	0.035	0.002
	<1	0.01	0.050	0.002

The tensile properties of the initial materials evaluated are shown as Table 4. The nominal 0.80 w/o phosphorus addition showed a tensile strength of ~60,000 psi (415 MPa) for all hydrogen atmospheres greater than 3%. At the <1% level, the tensile and yield strengths dropped off dramatically to approximately 50,000 psi (340 MPa). Additionally, the elongation showed a precipitous decrease from a high of ~10% to less than 1% for the 0.88 w/o phosphorus addition. The higher phosphorus additions are the most sensitive to sintering atmosphere; however, the 0.45 w/o phosphorus does not show the same sensitivity.

Table 4
Tensile Properties of Initial Materials Evaluated

Material	Sintering Atmosphere	Yield Strength (1000 psi / MPa)	Tensile Strength (1000 psi / MPa)	Elongation (%)
0.80% Phos	75% Hydrogen	52.2 / 357	67.8 / 464	9.7
	36% Hydrogen	50.5 / 345	64.3 / 440	7.8
	3% Hydrogen	49.7 / 340	64.4 / 441	9.0
	<1% Hydrogen	49.3 / 337	56.1 / 384	2.7
0.88% Phos	75% Hydrogen	53.8 / 368	69.3 / 475	8.9
	36% Hydrogen	53.1 / 364	69.0 / 473	8.4
	3% Hydrogen	53.3 / 365	67.5 / 462	8.6
	<1% Hydrogen	51.6 / 353	53.1 / 364	0.7
0.72% Phos	75% Hydrogen	47.5 / 325	63.6 / 436	10.1
	36% Hydrogen	47.9 / 328	63.3 / 434	9.9
	3% Hydrogen	46.3 / 317	60.2 / 412	8.3
	<1% Hydrogen	46.5 / 318	54.1 / 371	4.1
0.45% Phos	75% Hydrogen	36.5 / 250	51.6 / 353	10.8
	36% Hydrogen	38.5 / 263	53.0 / 363	11.3
	3% Hydrogen	35.7 / 244	50.4 / 345	10.2
	<1% Hydrogen	35.5 / 243	49.7 / 340	10.1

The magnetic properties at 15 Oersteds are summarized in Table 5. The magnetic results for the 3% hydrogen and <1.0% hydrogen sintering atmosphere are superior to the other results. The reason for this result is the carbon content of the test specimens. Inadequate burn-off of the lubricant in the 36% and 75% hydrogen atmospheres resulted in residual carbon in the test samples and consequently lowered the magnetic performance. There is not a significant difference in magnetic performance over the range of phosphorus evaluated in this part of the study. Generally, the magnetic properties shown in Table 5 are lower than the values cited in MPIF Standard 35 (in particular, the values for the 75 v/o and 36 v/o hydrogen atmospheres). These lower properties are a direct result of the residual carbon present in these samples. This illustrated the care required to complete remove the lubricant from the magnetic component during manufacture.

Table 5
Magnetic Properties of MPIF FY-8000 Material

Material	Sintering Atmosphere	Max Perm	Hc @ 15 Oe (Oe)	Induction at 15 Oe (kG)	Br at 15 Oe (kG)
0.80% Phos	75% Hydrogen	2000	1.86	11.63	7.15
	36% Hydrogen	2375	1.77	11.91	8.30
	3% Hydrogen	3550	1.47	12.72	11.02
	<1% Hydrogen	3420	1.46	12.62	11.03
0.88% Phos	75% Hydrogen	1960	1.80	11.64	7.09
	36% Hydrogen	2230	1.77	11.85	8.02
	3% Hydrogen	2350	1.66	12.05	8.68
	<1% Hydrogen	3230	1.36	12.57	8.02
0.72% Phos	75% Hydrogen	1900	1.86	11.55	7.11
	36% Hydrogen	2180	1.78	11.75	8.14
	3% Hydrogen	3125	1.47	12.52	10.83
	<1% Hydrogen	3630	1.47	12.52	10.84
0.45% Phos	75% Hydrogen	1825	2.00	11.40	7.70
	36% Hydrogen	1950	1.99	11.45	8.27
	3% Hydrogen	2060	1.78	11.82	9.27
	<1% Hydrogen	2600	1.77	11.91	10.27

Occasionally, a problem encountered with P/M parts is cracking resulting from the press fitting of the P/M component onto a steel shaft. A method chosen to evaluate the damage tolerance during the assembly operation was to measure the radial crush strength and radial strain to failure of the 4 materials. After completing the magnetic testing, the toroids were stripped of the primary and secondary windings and tested via radial crush (12). During testing the maximum load at failure was used to determine the radial crush strength and the radial strain was recorded by the following calculation:

$$\text{Radial strain} = (\text{OD}_{\text{initial}} - \text{OD}_{\text{final}}) / \text{OD}_{\text{initial}}$$

Table 6 is a summary of the radial crush strength and radial strain as a function of the material type and sintering atmosphere. The low hydrogen atmosphere significantly reduces the radial strain at fracture for the 0.72 w/o, 0.80 w/o, and 0.88 w/o phosphorus materials. The 0.45 w/o phosphorus material was not as adversely effected. The deformation of the toroids at failure correlates with the tensile elongation. Specifically, as the hydrogen content of the atmosphere increases, the tensile elongation and radial strain to failure also increases. Thus future testing of radial crush was eliminated.

Table 6
Radial Crush Strength and Radial Strain

Material	Sintering Atmosphere	Radial Crush Strength (1000 psi / MPa)	Radial Strain (%)
0.80% Phos	75% Hydrogen	128 / 877	0.13
	36% Hydrogen	122 / 836	0.11
	3% Hydrogen	129 / 884	0.13
	<1% Hydrogen	109 / 747	0.03
0.88% Phos	75% Hydrogen	127 / 870	0.08
	36% Hydrogen	132 / 904	0.11
	3% Hydrogen	131 / 897	0.08
	<1% Hydrogen	101 / 692	0.01
0.72% Phos	75% Hydrogen	117 / 801	0.11
	36% Hydrogen	120 / 822	0.13
	3% Hydrogen	120 / 822	0.13
	<1% Hydrogen	105 / 719	0.05
0.45% Phos	75% Hydrogen	107 / 732	0.26
	36% Hydrogen	99 / 678	0.20
	3% Hydrogen	101 / 691	0.18
	<1% Hydrogen	114 / 781	0.29

Part 2: Development of High Strength Magnetic Materials

Once the mechanical properties of the current production materials were documented, the second part of the testing was intended to develop material systems and processing that would produce mechanical properties superior to the FY-8000 material with equivalent magnetic performance. Table 1 is a summary of the compositions evaluated. Graphite was added to Mix E to evaluate the potential for obtaining higher strength and to determine the potential loss in magnetic performance. The magnetic property test results of these materials is presented in Table 7 and Table 8.

The magnetic performance of the FL-4400 material with 0.45 w/o phosphorus (material A) was nearly equivalent to the best results obtained in Part 1. Increasing the phosphorus level to 0.80 w/o (using FL-4400) improved the maximum induction and lowered the coercive force relative (sintering at 2050 °F (1120 °C)). Additions of up to 0.6 w/o silicon (materials C&D) did not show any significant improvement in magnetic performance. Sintering at 2300 °F (1260 °C) did improve the magnetic properties of all materials tested. Permeability in excess of 5000 was measured for 0.80 w/o phosphorus and 0.60 w/o silicon using both F-0000 and FL-4400 base irons. These results are similar to the results reported by Gegel. The addition of 0.3 w/o silicon (material D) did not produce any significant increase in magnetic performance.

Table 7
Magnetic Properties of Test Materials Sintered at 2050 °F (1120 °C)

Material	Density (gm/cm³)	Max Perm	Hc (Oe)	Induction at 15 Oe (kG)	Induction at 25 Oe (kG)
A	6.63	2825	1.55	10.1	10.7
	7.12	3750	1.47	12.8	13.4
B	6.74	3300	1.40	11.1	11.4
	7.21	3725	1.40	13.0	13.5
C	6.71	3000	1.37	10.4	10.9
	7.13	3325	1.42	12.1	12.7
D	6.73	1575	1.88	9.5	10.6
	7.10	2000	1.78	10.9	12.2
E	6.94	455	3.75	5.4	7.18
F	6.72	3050	1.46	10.4	11.0
	7.16	3950	1.48	12.6	13.2
G	6.77	3525	1.31	11.0	11.6
	7.20	4500	1.32	13.1	13.6
H	6.72	3230	1.31	10.5	11.1
	7.15	3675	1.32	12.3	12.9

Table 8
Magnetic Properties of Test Materials Sintered at 2300 °F (1260 °C)

Material	Density (gm/cm³)	Max Perm	Hc (Oe)	Induction at 15 Oe (kG)	Induction at 25 Oe (kG)
B	6.97	4125	1.21	12.3	12.8
	7.33	4325	1.13	13.9	14.4
C	6.90	4475	1.14	11.9	12.4
	7.25	5200	1.09	13.3	13.9
D	6.96	3650	1.22	11.8	12.5
	7.21	3375	1.26	12.3	13.2
E	6.91	500	3.18	5.7	7.3
F	6.82	3875	1.28	11.7	12.1
	7.25	5050	1.23	13.6	14.1
G	6.88	4100	1.14	12.0	12.5
	7.27	5075	1.08	13.9	14.3
H	6.80	4725	1.10	11.5	12.0
	7.18	5550	1.04	13.2	13.7

Physical Property Testing

The tensile properties of the various materials investigated are presented as Table 9 and Table 10. FY-4500 and FY-8000 were tested as standards for comparison to the new material systems. FY-4500 exhibited yield strengths ranging from ~28,000 psi (190

MPa) to ~37,000 psi (255 MPa) depending on the sintered density and sintering condition. Tensile strengths ranged from a low of ~39,000 psi (265 MPa) to a high of ~58,000 psi (395 MPa). What was remarkable about the Ancorsteel 45P was the level of elongation achieved (up to 20%) with high temperature sintering. Sintering the FY-4500 material at 2050 °F (1120 °C) produced tensile elongation in excess of 7% for the density range evaluated. FY-8000 produced yield strengths approaching 54,000 psi and tensile strengths approaching 60,000 psi (415 MPa) at 7.39 gm/cm and sintering at 2300 °F (1260 °C). However, the tensile elongation was significantly reduced relative to the FY-4500.

Table 9
Tensile Properties of Materials Sintered at 2050 °F (1120 °C)

Material	Density, g/cm³	YS, 1000 psi	TS, 1000 psi	Elongation, %	Hardness, HRB
A	6.72	35.0	46.0	6.7	50
	6.98	40.3	56.0	7.1	61
	7.14	44.5	62.4	7.2	68
B	6.86	41.7	51.1	5.0	59
	7.12	48.0	59.4	5.6	69
	7.29	52.2	65.4	8.0	75
C	6.82	39.8	47.2	3.5	61
	7.08	45.7	54.4	3.9	70
	7.23	49.4	59.4	4.3	76
D	6.80	38.2	50.0	5.1	56
	7.05	43.7	60.3	7.8	66
	7.22	47.0	66.3	9.0	73
E	6.60	39.4	55.0	2.3	66
	6.86	45.5	64.8	2.9	74
	7.03	49.8	72.8	3.0	81
F	6.86	27.6	38.6	7.4	38
	7.11	31.5	46.5	10.2	49
	7.25	33.5	50.4	11.1	58
G	6.89	39.7	43	1.1	58
	7.14	46.5	50.7	1.5	67
	7.28	49.6	53.5	1.4	71
H	6.86	38.1	40.1	0.7	58
	7.08	42.8	45.2	0.7	69
	7.22	46.3	49.1	1.0	74

Utilizing FL-4400 as the base iron and adding sufficient ferrophosphorus to achieve 0.45 w/o phosphorus increased both the yield and tensile strengths relative to FY-4500 without any degradation in the tensile elongation. The average increase in the yield and tensile strength was ~20% relative to the FY-4500. Interestingly, the yield strength of the FL-4400 with 0.45 w/o phosphorus was only 10% lower than the FY-8000; however, the tensile strength was higher at the 40 and 50 tsi (550 to 690 MPa) compaction levels. More importantly, the tensile elongation of the FL-4400 with 0.45 w/o phosphorus was the same as the FY-4500 or ~7%. Thus, the FL-4400 with the 0.45 w/o phosphorus would be more damage tolerant relative to the FY-8000 at nearly the same strength level.

Adding 0.80 w/o phosphorus to the FL-4400 did produce ~ a 5% increase in both yield and tensile strength relative to the standard FY-8000. However, the tensile elongation did not show the same degradation as experienced with standard FY-8000. This fact was unexpected because all the test samples were sintered at the same time using a continuous belt high temperature-sintering furnace in a 75v/o-hydrogen atmosphere.

Table 10
Tensile Properties of Materials Sintered at 2300F °F (1260 °C)

Material	Density, g/cm³	YS, 1000 psi	TS, 1000 psi	Elongation, %	Hardness, HRB
B	7.09	48.2	62.5	12.2	69
	7.28	53.0	72.9	12.5	77
	7.42	56.0	72.0	6.5	81
C	7.01	49.9	62.1	6.6	70
	7.22	54.5	70.5	8.8	79
	7.35	57.0	68.1	4.2	82
D	6.93	39.6	55.7	6.2	61
	7.17	45.5	63.3	8.9	71
	7.32	48.4	69.0	9.9	77
E	6.66	43.6	63.0	2.6	71
	6.91	48.6	73.0	3.3	78
	7.07	52.4	83.4	3.6	84
F	6.99	31.8	46.4	11.6	47
	7.23	34.9	53.5	16.0	58
	7.38	37.9	58.4	19.7	64
G	7.03	44.2	52.5	3.3	66
	7.27	49.4	57.8	3.1	73
	7.39	53.6	59.0	1.9	78
H	6.96	44.8	48.7	1.3	67
	7.19	51.4	56.0	1.7	76
	7.30	54.1	59.7	2.1	80

Additions of up to 0.60 w/o silicon into both the FL-4400 with 0.80 w/o phosphorus and FY-8000 did not substantially increase the yield or tensile strengths of either material. The only effect observed was a lowering of the tensile elongation. Again, the FL-4400 with 0.80 w/o phosphorus exhibited higher elongation relative to the FY-8000.

Material D containing FL-4400 with 0.60 w/o silicon, 0.45 w/o phosphorus and 0.30 w/o graphite did show high sintered strength with tensile strengths approaching 83,000 psi after sintering at 2300 °F (1260 °C). The properties after sintering at 2050 °F (1120 °C) were comparable to the FL-4400 with 0.80 w/o phosphorus. Thus the addition of graphite did provide the increase in strength as expected; however, the resulting loss in magnetic performance made this material unacceptable as a possible electromagnetic clutch material.

Discussion:

The objective of this experimental work was the potential development of new magnetic materials that exhibited higher strength without any loss in magnetic performance. It was demonstrated that adding phosphorus to a FL4400 prealloy powder produces increases in the yield strength and tensile strength without any loss in magnetic performance. Specifically, FY-4500 and FL-4400 with 0.45 w/o phosphorus both exhibit permeability ranging from ~3000 to ~5000 depending on sintering conditions and sintered density. The advantage of utilizing the FL4400 as the base iron is a 20% increase in yield and tensile strength relative to the A1000C base iron. This increased strength is a result of the ferrite strengthening achieved with the molybdenum-prealloyed iron.

A similar trend was observed at the 0.80 w/o phosphorus level; although the increase in strength was not as dramatic as at the 0.45 w/o phosphorus level. It was interesting to note that the yield strength of the FL-4400 with 0.45 w/o phosphorus was only 10% lower than the FY-8000 at comparable densities, without the corresponding loss in ductility or damage tolerance capability.

It is important to note that the yield strength and tensile strength of the FL-4400 with 0.45 w/o phosphorus at 6.8 g/cm³ is nearly the same as the FY-4500 at 7.2 g/cm³, both materials sintered at 2050 °F (1120 °C). Thus, with the current trend of more complex part designs and the potential for greater non-uniformity of density within a part, the FL-4400 has higher strength levels at lower part densities.

Increasing the phosphorus to 0.80 w/o for both alloy bases did produce improvements in strength but the results achieved with the FL-4400 were <10% improvement in the strength levels. However, the critical aspect of the alloy base is the higher ductility inherent with the molybdenum steel base relative to pure iron. The FY-8000 showed a significant reduction in elongation relative to the FY-4500; whereas, the reduction in tensile ductile using the FL-4400 base was less severe. The other issue with the FY-8000 material was the variability of the tensile performance. In the first stage of this experimental work, the loss in ductility was observed only at the low levels of hydrogen in the sintering atmosphere. However, in the second part of the study, the loss in ductility was observed in a 75-v/o-hydrogen atmosphere under laboratory sintering conditions. Thus the potential production variability can lead to potential varying final product performance variations.

This embrittlement behavior observed with the FY-8000 is similar to the temper embrittlement observed in wrought steels. In wrought steels, molybdenum is added to reduce this effect. (13) Molybdenum when added to steel has a strong attraction for the phosphorus thus preventing phosphorus segregation at the grain boundaries. (14) Thus, in the present study, the FL-4400 steel maintains the beneficial effect that phosphorus has on the magnetic properties with a corresponding increase in the yield and tensile strengths but minimizes the risk of embrittlement.

One additional aspect of magnetic clutches is often the wear resistance of the part when it is in contact with the lock up component. Too soft a material may lead to excessive wear of the magnetic component. To overcome this wear, the wear surface of the P/M part will be surfaced hardened. Using FL-4400 as the base for these magnetic clutches does increase the apparent hardness of the P/M materials. However, the increase in hardness is only minor. Incorporating silicon into the material and high temperature sintering does raise the hardness ~10 HRB. It is unknown if this increase in hardness will be sufficient to eliminate the surface hardening of these components. This will be investigated in the future work.

Conclusions:

From this study the following conclusions can be reached:

1.) FY-8000 magnetic material has tensile strengths approaching 60,000 psi; however, the variability in elongation is a result of phosphorus segregation and can result in tensile elongation variations from ~5% to less than 1%.
2.) Substituting FL-4400 as a base for the 0.45 w/o phosphorus addition produced ~20% increase in the yield and tensile strength with no loss in magnetic performance or tensile elongation when compared to comparably sintered FY-4500. The FL-4400 material was ~10% lower in yield strength relative to FY-8000 but had equivalent tensile strength.
3.) Use of the FL-4400 with 0.80 w/o phosphorus produced tensile strengths of ~70,000 psi (480 MPa) with no significant loss in tensile elongation. The presence of the molybdenum prevents phosphorus segregation and subsequent embrittlement.
4.) As expected, additions of small amount of graphite did raise the yield and tensile strengths but was accompanied with an unacceptable loss in magnetic performance thus these materials are unacceptable for high quality magnetic applications.
5.) Substituting FL-4400 for the pure iron in these magnetic grades resulted in only a minor decrease in green and sintered density over the compaction pressures studied.
6.) Additions of silicon up to 0.60 w/o did improve the magnetic performance when sintered at 2300 °F (1260 °C) but had only a minor increase in sintered tensile properties and a reduction in tensile ductility.

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