Method to Reduce Die Wear Caused by Abrasive Hard Particle PM Additives

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ABSTRACT

Hard particle additions are common in the PM industry in standard MPIF materials such as FY-4500 and FS-0300. These additives, especially important in sintered soft magnetic materials, are used to introduce alloying elements such as phosphorus and silicon to PM premixes. The drawbacks of these abrasive additives include lower compressibility and increased wear of compaction tooling, leading to poor surface finish on the compacted green parts and premature failure of punches, dies and core rods. Using an enhanced lubricant system, these negative effects can be substantially reduced, extending tool life and improving part quality. While the FY-4500 material system has been studied previously, this enhanced lubricant system can be applied to other hard particles common in the PM industry.

INTRODUCTION

MPIF standard FY-4500 and FS-0300 materials are used primarily for soft magnetic applications requiring high DC magnetic permeability and low coercive force, such as linear actuators, speed sensors, and solenoid valves.[1] Typical production practice uses high purity iron base powder with premix additives to achieve these materials. Intermetallic compounds such as Fe_2P or Fe_3P are used to produce 0.45% phosphorus in FY-4500[2] and various ratios of Fe-Si are used to produce 3.0% silicon in FS-0300. These intermetallic additives are ground to particle sizes below 30 micrometers to allow for uniform distribution in the premix material. Since magnetic properties rely heavily on structure-sensitive properties, the diffusion of these intermetallics during sintering is of the utmost importance. To obtain a high magnetic permeability and low coercive force, alloying should be as uniform as possible, where phosphorus or silicon is distributed amongst the iron matrix. In addition, interstitial impurities need to be kept to a minimum as required by MPIF Standard 35 for Soft Magnetic Alloys (C < 0.03%, O < 0.10%, and N < 0.01%).[3]

A major drawback of ferrophosphorus and ferrosilicon additives are their extremely high hardness values, well above typical base iron powder. Compared to base iron with a Hardness Vickers Number (HVN) of 100, intermetallic compounds described here have HVN of ≥ 1000. The impact of second phase hard particles on PM techniques is significant for tool wear potentially leading to breakage. Often, fine additives build-up between punches and the die body, which results in accelerated tool wear, especially when these additives are hard and abrasive. Not only are the punches and dies affected, but additional tooling members that interact with the powder throughout the compaction cycle, such as core rods, feed shoe components, plates, etc. The repair or altogether replacement can significantly increase cost and down time during a production run of these materials.

Previous work presented by Hanejko et al.[4,5] evaluated the effect of chemically bonded FY-4500 premixes with and without the enhanced lubrication system. Compaction trials used a Dorst TPA 140 mechanical press to compact approximately 25,000 pieces with cylindrical geometry using both standard FY-4500 and enhanced FY-4500. Parts were compacted at a press rate of 700 parts per hour with a compaction pressure of 480 MPa to a part density of 6.95-7.05 g/cm^3 with no heating of the die. The tooling and parts were analyzed throughout the study for wear of punches and core rod, part temperature and flashing, as well as surface scoring. Significant scoring was found on the OD of parts from standard FY-4500 and minimal scoring on the OD from enhanced FY-4500, shown in Figure 1. In addition, results from enhanced FY-4500 indicated ~75% lower wear on the core rod and top punch, 8 °C (15 °F) lower ejection temperature, and no tooling issues.[4,5] Hanejko et al. presented numerous advantages to the enhanced lubrication system when applied to FY-4500 materials, using Fe_3P additives.

Components made from the phosphorus alloys exhibit a good combination of tensile strength, ductility, and impact absorption energy. The particle size of the added ferrophosphorus is important as it has a significant effect on these properties. The ferrophosphorus powder should be finer than 20 micrometers and preferably should have a median particle size close to 10 micrometers. Comparison of two ferrophosphorus additives is completed throughout this study for MPIF FY-4500 materials, using Fe_3P and Fe_2P, both previously described as abrasive additives. An enhanced lubrication system can be applied to help isolate the ferrophosphorus additions from the tooling and substantially improve compaction conditions. This study illustrates the application of the enhanced lubrication system on two hard additives, showing it to be successful in reducing die wear issues for PM production. Enhanced FY-4500 has no effect on processing conditions or material properties, such as apparent density, flow rate, compressibility, mechanical strength, ductility, or magnetic properties. This study also presents a larger compaction trial at Hoeganaes Corp. on ~1,000 parts and a production trial at Phoenix Sinter Metals on ~6,000 parts to further confirm the success of the enhanced lubricant system in PM production.

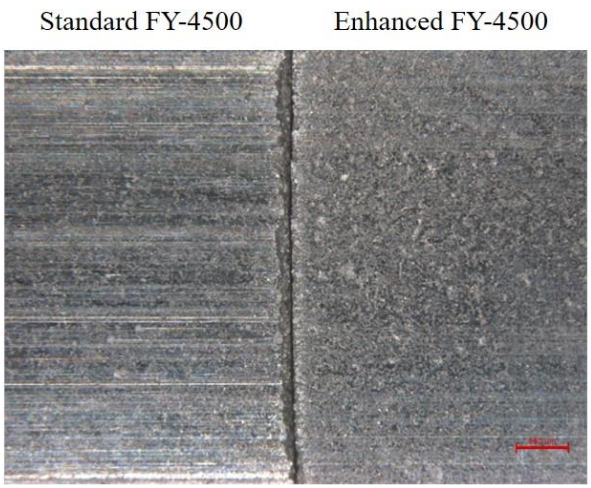

Figure 1: Outer diameter surface of standard FY-4500 (left) showing significant scoring compared to enhanced FY-4500 (right) with minimal scoring.[5]

EXPERIMENTAL PROCEDURE

Commercially available powder from Hoeganaes Corporation, Ancorsteel 1000B was used as the base iron material to produce the FY-4500 mixes tested in this study. Mixes described in this study used 0.45% nominal phosphorus, added via a ferrophosphorus additive, either Fe_2P or Fe_3P, and 0.75% Acrawax C lubricant. In this study, standard FY-4500 is used to denote material using the standard lubricant system described previously, while enhanced FY-4500 is used for material with the enhanced lubricant system. Of note, all mixes utilize 0.75% Acrawax as the primary lubricant. Transverse rupture (TR) strength bars were compacted to green densities of 7.0 and 7.2 g/cm^3 to determine the static mechanical properties of each mix. Magnetic toroids were compacted to sintered densities of 6.9 and 7.1 g/cm^3 to measure effect of density and sintering conditions on magnetic properties. All test bars and toroids were sintered in an Abbott continuous-belt furnace at 1120 °C (2050 °F) for 20 minutes at temperature in a mixed atmosphere of 25 volume % nitrogen and 75 volume % hydrogen, nominally dissociated ammonia (DA). The sintered density, dimensional change, and apparent hardness were determined on TR bars following MPIF Standards 42, 43, and 44. TR strength testing adhered to MPIF Standard 41.[6] The sintered density was measured on toroid geometries to be used for magnetic testing purposes. Toroids were wound and tested using an KJS Associates SMT700 Soft Magnetic Tester. Direct current (DC) magnetic permeability, coercive force, and magnetic flux density were measured at 1200 A/m according to MPIF Standard 35 for Soft-Magnetic Alloys.[3]

RESULTS AND DISCUSSION

Powder properties comparing standard FY-4500 and enhanced FY-4500 using both ferrophosphorus additive types are presented in Table 1. Apparent density and Hall flow rate are unaltered from the standard to enhanced materials, indicating no changes are seen at the macro level for powder testing.

Table 1: Powder properties for standard FY-4500 using two ferrophosphorus additives, Fe_3P and Fe_2P, as well as enhanced FY-4500 using the same additives

Mix Designation	Additive Designation	Apparent Density (g/cm^3)	Flow (s/50g)
Standard FY-4500	**Fe_3P**	3.21	31
	Fe_2P	3.17	31
Enhanced FY-4500	**Fe_3P**	3.20	32
	Fe_2P	3.16	31

Ejection characteristics comparing both ferrophosphorus additives for standard and enhanced FY-4500 are represented in Table 2, using a compaction pressure of 550 MPa to achieve a 7.0 g/cm^3 green density. Higher stripping pressures are seen for standard FY-4500 regardless of the additive used. A significant decrease in stripping pressure is measured with the enhanced FY-4500 samples, indicating less force is required to begin ejection of the part. Likewise, a decrease in sliding pressure is seen for the enhanced FY-4500 material for each additive. The lower sliding pressure correlates to less force required to continue the ejection process and remove the part completely from the die. Green strength did not change significantly from the two material types, also shown in Table 2, for 7.0 g/cm^3 green densities. Complete compressibility curves were generated for each mix as well, as shown in Figure 2. Neither the lubricant system nor additive type was found to influence material compressibility over the range of pressures tested. This indicates other hard abrasive additives can benefit from the enhanced lubricant system, such as ferrosilicon not presented in this study.

Table 2: Ejection characteristics and green strength for standard FY-4500 and enhanced FY-4500 using two ferrophosphorus additives, Fe_3P and Fe_2P, with a compaction pressure of 550 MPa

Mix Designation	Additive Designation	Stripping Pressure (MPa)	Sliding Pressure (MPa)	Green Strength (MPa)
Standard FY-4500	**Fe_3P**	39	29	19
	Fe_2P	36	24	17
Enhanced FY-4500	**Fe_3P**	30	26	19
	Fe_2P	29	15	17

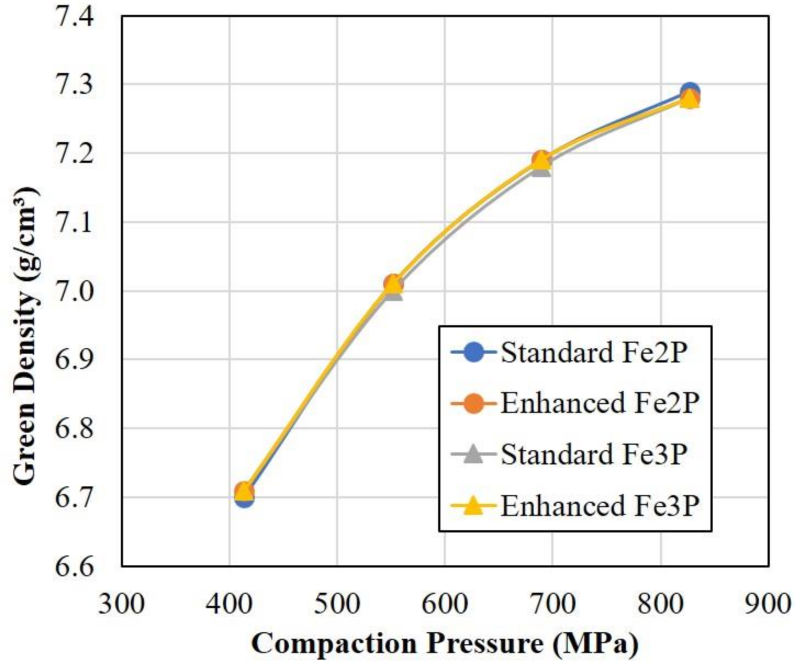

Figure 2: Compressibility curve for standard FY-4500 and enhanced FY-4500 using Fe_2P and Fe_3P additives

In addition to improving compaction conditions, it is essential that introducing a new lubricant system will have minimal impact on final component properties including mechanical and magnetic performance. To test mechanical properties, FY-4500 materials were compacted using each lubricant system and the Fe_3P additive, which is standard in the PM industry. Each mix was compacted to two green density levels and sintered at 1120°C in a DA atmosphere. A slight increase in dimensional change was found for the enhanced FY-4500 material at both density levels, but no significant change in TR strength or apparent hardness was observed, shown in Table 3.

Table 3: Sintered properties of TR samples compacted using each lubricant system and sintered in a DA atmosphere at 2050 °F, using Fe_3P additive

Mix Designation	Green Density (g/cm^3)	Dimensional Change (%)	TRS (MPa)	Apparent Hardness (HRA)
Standard FY-4500	7.00	0.04%	118	31
	7.20	0.06%	140	34
Enhanced FY-4500	7.00	0.05%	117	30
	7.20	0.08%	143	33

MPIF FY-4500 magnetic requirements are described in detail in MPIF Standard 35,[3] where coercive force and relative maximum permeability are primarily affected by the sintering conditions, while maximum flux density is a factor of chemistry and sintered density. Standard FY-4500 and enhanced FY-4500 compare well for magnetic properties tested at an applied field of 1200 A/m, as shown in Table 4. As to be expected, higher density correlated to higher magnetic permeability and flux density. No significant differences were found for either of the materials tested. Magnetic toroids were tested using the same mixes as above, utilizing Fe_3P as the additive and sintering in a DA atmosphere.

Table 4: Magnetic properties tested at an applied field (H) of 1200 A/m, comparing toroids compacted to two density levels using standard and enhanced FY-4500

Mix Designation	**Standard FY-4500**		**Enhanced FY-4500**	
Sintered Density	***6.9 g/cm³***	***7.1 g/cm³***	***6.9 g/cm³***	***7.1 g/cm³***
Coercive Force (A/m)	115	110	110	110
Relative Maximum Permeability	3350	3800	3400	3750
Maximum Flux Density (T)	1.2	1.3	1.2	1.3
Residual Induction (T)	1.0	1.1	1.0	1.1

An important aspect of the enhanced lubricant system is that no changes are seen in powder properties, compressibility, mechanical strength, or magnetic properties. Powder properties were found to be unaffected by the implementation of the enhanced lubrication system for either of the ferrophosphorus additives presented in this study. A constant apparent density, flow rate, and compressibility for standard and enhanced FY-4500 materials indicated that no significant adjustments should be necessary for powder or part specifications in production. Especially important for soft magnetic applications is that magnetic properties be unaffected by alterations to the material system. This study exemplifies that no significant difference in magnetic properties was evident using the enhanced lubrication system. Transferring current production parts using standard FY-4500 to enhanced FY-4500 is therefore possible due to powder transfer, die fill, and overall part geometry and performance remaining unchanged.

As part of this study, a short compaction trial was performed on VVT stator components. Both standard FY-4500 and enhanced FY-4500 materials were used for the same compaction conditions utilizing the same press set-up for a short compaction run of ~1,000 parts. The change in lubricant system was found to have no effect on necessary press settings or achievable part density. Part temperature was measured every 50 parts and the results are shown in Figure 3. Interestingly, it was found that temperature increased more rapidly when using the standard FY-4500 material compared to the enhanced FY-4500 mix. This points to a lowering of the frictional force generated when using the enhanced lubrication system and helps to verify some of the previous laboratory results.

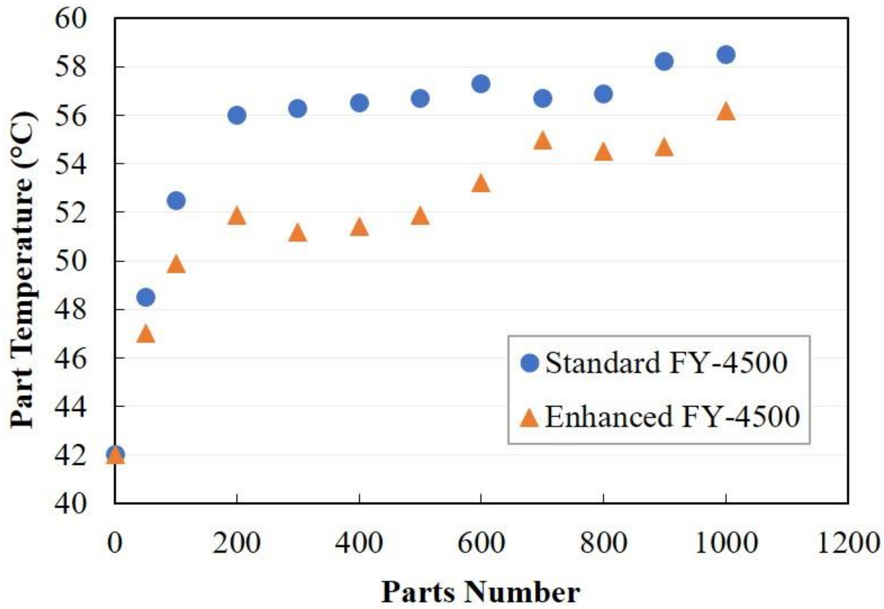

Figure 3: Part temperature measured every 50 parts for a short compaction trial on VVT stator components

As a final portion of this study, a production trial was performed at Phoenix Sintered Metals comparing their standard FY-4500 material to a 500-pound sample of enhanced FY-4500, that was provided. Due to the abrasive nature of the Fe_3P additive in the FY-4500 material, issues with tool wear, surface finish, and "picking" on the parts had been observed consistently in part production, leading to excess scrap rates. The geometry of the punch face experiencing the greatest number of issues is shown in Figure 4.

Figure 4: Punch geometry for production trial at Phoenix Sintered Metals

When testing the enhanced FY-4500 sample, a total of 6,000 parts were run and examined for commonly noticed production defects. No issues were reported. Immediately following this trial, without any changes to the press or tooling set-up, the material was switched back to their standard FY-4500. Within several hundred parts, there were again occurrences of material missing on the outer diameter of the parts due to sticking to the punch, as shown in Figure 5A below. A part produced with the enhanced FY-4500 material is shown in Figure 5B for comparison. Improved lubrication allows for substantially less friction during production runs, yielding better part surfaces.

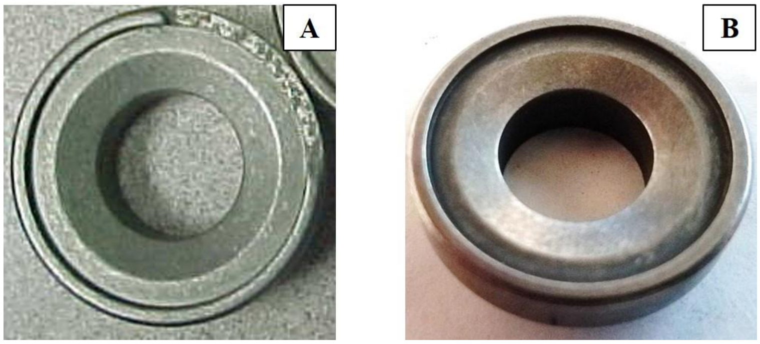

Figure 5: Images of parts compacted with standard FY-4500 (A) and enhanced FY-4500 (B)

There are obvious cost savings associated with reducing abrasiveness of Fe_3P particles or any hard additives for that matter, including lowering part scrap rates and extending life of the tooling and press components. But additional indirect costs must be considered as well. Repairing or replacing tooling as it wears out also results in longer press down time, reduced plant efficiency, and more man-hours required. This has potential for trickle-down effects, such as forcing employers to pay for extra shifts and possible overtime. Reduced press utilization can lead to customer requirements for additional inventory or rush shipments of parts, which have their own associated cost implications. At a time when PM part costs are being reduced to compete with other manufacturing methods, utilizing innovative material technology options can provide a huge advantage.

CONCLUSIONS

An enhanced lubrication system has been developed and applied to hard ferrophosphorus additives to help reduce die wear significantly without sacrificing powder or part properties. From this study, the following observations have been made:

- Enhanced FY-4500 provides a substantial improvement when compacting hard particle additives in terms of reduced ejection pressures, lower heat generation from frictional forces, and lower wear on tooling members.
- There was no substantial difference in powder properties, compressibility, static mechanical properties, or magnetic performance between the standard FY-4500 and enhanced FY-4500.
- A short compaction trial showed additional heat generation during compaction of just 1,000 VVT stator parts with the standard FY-4500 compared to the enhanced FY-4500.
- A small production trial with the enhanced FY-4500 was performed and found to reduce the occurrence of “picking” on the edges of parts. This allows for fewer production issues, tooling changes, and scrap parts.
- Other early production trials have also agreed well with laboratory data, showing approximately three times tool life upon use of the enhanced FY-4500 compared to standard lubricant systems.

Future work for this study will incorporate the enhanced lubricant system in conjunction with other hard additives such as ferrosilicon.

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