Effect of Chemistry and Processing on Sinter-Hardening Performance of Non-Standardized Alloy Compositions

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Abstract

MPIF Standard 35 Grade FL-4800 base iron is an adaptable sinter hardenable base iron which can provide a fully martensitic structure on large cross section parts. This base material is used in a number of sinter hardenable alloy grades, but it typically used with increased levels of graphite and copper. This work will explore utilizing this base iron in several compositions outside of those described in the standard. Mechanical properties on both test bars and parts were explored.

Introduction

With the evolution of the powder metallurgy (PM) industry and with ever increasing focus on costs, consistency, product lifecycles and always - properties, a push towards a high strength material system with good reliability is always ongoing. Two of the most substantial improvements that can be made to the mechanical properties of a PM part are by compacting to higher density and through use of enhanced sintering and heat treating techniques to achieve an improved microstructure.

Through advancements in equipment technology, the ability to modify the cooling rate of sintered parts in-situ has been commercialized. The use of rapid cooling furnace units has become commonplace in many PM furnaces and allows for increased product cooling rates directly in the furnace. This capability, combined with tailored material compositions with increased hardenability, allows for a martensitic structure to be formed without the need of a secondary heat treatment process. With this advancement and its positive attributes including fewer processing steps, lower part distortion, and lower costs, sinter-hardening has been widely adopted in the industry over the past few decades [1-9].

Hardenability is a general material property term used to quantify a given material's ability to transform to martensite upon cooling from an austenitic state. This is typically achieved either through direct cooling within a furnace from sintering temperatures, or through secondary heat-treat operations. Common steel alloying elements such as carbon and those shown in Figure 1 can affect the required critical cooling rate required to achieve a martensitic structure. However, these elements must be balanced as they each have secondary impacts on material processing and handling requirements.

	Hardenability Factor	Effect on Compressibility	Affinity for Oxygen
Higher	Manganese	Copper	Manganese
	Chromium	Nickel	Chromium
	Molybdenum	Chromium	Nickel
	Copper	Manganese	Molybdenum
Lower	Nickel	Molybdenum	Copper

Figure 1: Ranking of alloying elements in prealloyed PM materials for various effects.

Various PM base iron grades have been designed over time with changes in alloy concentrations, each targeted for different levels of hardenability. When looking at the lineup of products from Hoeganaes Corporation, alloyed options include Ancorsteel 2000, 4600V, 721SH and 737SH, listed in order of increasing hardenability. A comparison in Jominy hardenability for these grades is shown in **Error! Reference source not found.**. Each of these alloy systems leverage a combination of prealloyed Ni, Mo, Cu and Mn, and often use a secondary addition of copper powder to increase hardenability of the final powder premix.

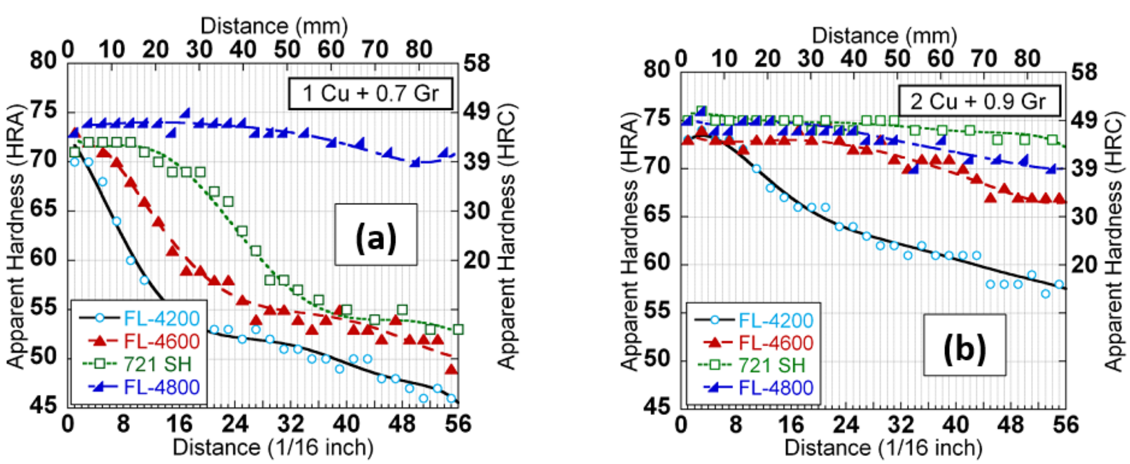

Figure 2: Jominy hardenability curves for common sinter-hardening PM alloys with (a) 1% Cu-0.7% graphite addition and (b) 2% Cu-0.9% graphite addition [3].

However, to truly optimize the system at hand, a marrying between powder composition, part geometry and weight, and furnace capability must be found. As is the case with smaller PM components and as shown previously [3], a leaner base iron may be capable when used in combination with copper to produce hardened parts without the need for the fully alloyed FLC-4805 / FLC2-4808 systems.

The following study will explore the impact of the removal of copper from the commonly used FL-4800 material systems and compare a range of mechanical properties along with PM shape making impacts when processed though the sinter-hardening process.

Experimental Procedure

Commercially available FL-4800 base iron material from Hoeganaes Corporation (Ancorsteel 737SH) was used to create four different compositions that are either Standard 35 recognized grades or modifications of grades. Nominal compositions along with the closest designations are shown in Table I. All mixes were produced using Asbury type 3203H graphite, -150 mesh Cu powder and 0.35% Ancorlube LV proprietary lubricant from Hoeganaes Corporation.

Table I: Nominal compositions of alloys used (Prealloyed unless noted*, non-standard designation**)

Mix Designation	Manganese (wt%)	Nickel (wt%)	Molybdenum (wt%)	Copper* (wt%)	Graphite* (wt%)
FL-4805	0.42	1.40	1.25	0.0	0.60
FL-4808**	0.42	1.40	1.25	0.0	0.90
FLC-4805	0.42	1.40	1.25	1.0	0.70
FLC2-4808	0.42	1.40	1.25	2.0	0.90

The produced samples were then split for a combination of laboratory material testing and production part performance testing.

Laboratory material testing consisted of compaction runs at both 6.95 and 7.15 g/cm^3 density and involved a mix of transverse rupture (TR) bars, dog-bone type tensile specimens and toroidal ring type specimens. All samples were sintered at either 1120°C (2050°F) or 1260°C (2300°F) in an Abbott continuous-belt furnace for 20 min at max temperature in a mixed atmosphere of 90% nitrogen and 10% hydrogen. Samples were cooled using an accelerated cooling unit where the cooling rates were approximately 1.6°C/s from austenitization temperature. Following sintering, all samples were tempered at 205°C (400°F) for one hour prior to subsequent testing.

TR bars were used in the determination of density, dimensional change, apparent hardness and transverse rupture strength following MPIF Standards 42, 44, 43 and 41 respectively. Dog-bone specimens were used in the determination of tensile properties according to MPIF standard 10 and the toroidal specimens were utilized as a secondary measure of break strength following the of MPIF standard 55 – Radial Crush Strength [10]. It should be noted that the use of Dog-bone type tensile bars are not optimal for use in hardened microstructures due to the shape effect having a negative impact on overall properties.

Machined round tensile specimens were not able to be completed in time for publication and are intended to be tested later as to provide a more optimal tensile strength comparison.

In parallel, short production runs were performed at APG in Ridgway, PA using a spur gear part geometry (**Figure 3**). This geometry was selected as to be able to investigate the impact of mix changes on both part crush strength along with size scatter. The spur gear was ~70 mm in size and was processed in an industrial sinter-hard furnace with accelerated cooling. Further, large cylindrical blanks were compacted with a diameter of 76.2 mm pressed to a range of OAL from 12.7 to 50.8 mm to investigate the effect on microstructure evolution.

Figure 3: Representative Spur Gear Part investigated.

Results and Discussion

Various material compositions utilizing the FL-4800 base iron were explored across multiple production locations, part geometries, and overall sample sizes. A range of key takeaways can be drawn when reviewing the material data gathered. Each section will explore different aspects of the material system comparisons along with underlying reasoning and key takeaways.

Material Evolution

The FL-4800 base iron and surrounding compositions are, first and foremost, designed to be used in a martensitic state. The high concentration of prealloyed Ni-Mo-Mn allows for the material to be transformed to a martensitic state either through a more traditional quench and temper (QT) process or through an accelerated cooling furnace (sinter-hardening) process. The additions of increasing graphite and copper further allow for larger parts to be processed in the sinter-hardening route, as the material becomes increasingly hardenable.

In addition to the work completed by Sokolowski et al. [2], the J-depth of a material meeting FL-4805 was measured. When austenized at a temperature of 950°C (1750 °F), which was shown in the previous study as being required to fully maximize the hardenability of these alloy systems, the FL-4805 material was found to have the lowest hardenability of the products at a J-depth of 21, which represents a distance of 33 mm from the quenched end.

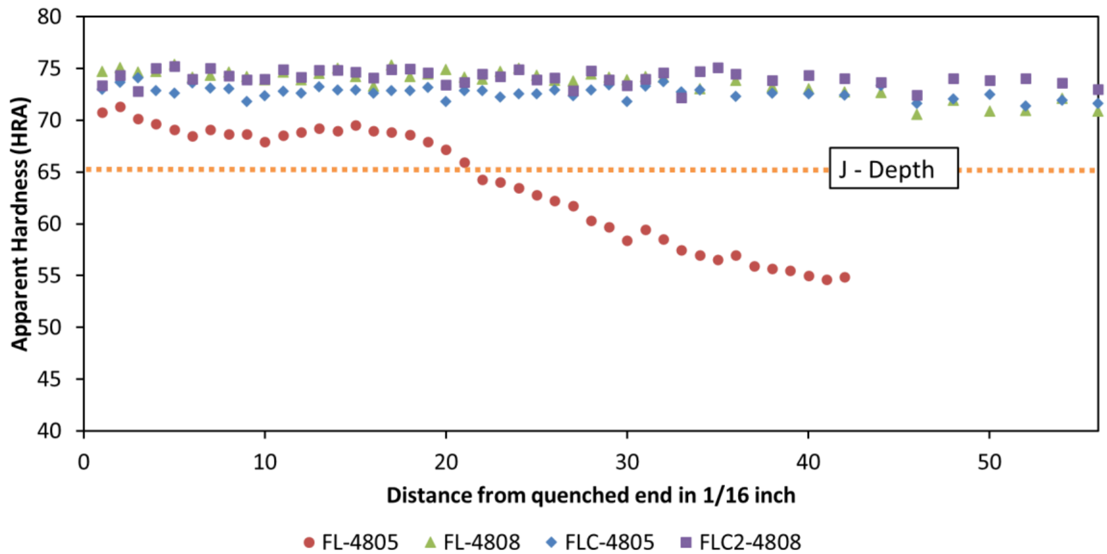

Figure 4: J-Depth of a series of FL-4800 based material compositions austenized at 950°C at a density of 7.0 g/cm^3.

While the FL-4805 type material was found to have the lowest J-depth hardenability of the group, the observed hardenability (J-depth - 21) in overall terms is still higher than most other commonly utilized PM compositions and is closely aligned with the FL-5305 type material according to MPIF Standard 35 [10]. As such, while not commonly utilized nor formally designated as a sinter-hardened steel designation in MPIF, with optimized processing, the material is still capable.

More typically, the FL-4805 type material, as designated in the MPIF Standard 35, is shown in the quench and temper (Q&T) heat treated state. Under this condition, and in contrast to that of FLC-4805 and FLC2-4808 processed through sinter-hardening, large cylindrical samples of 50.8mm (2") in height and 76.2mm (3") in diameter were compared of these various material grades. Adopting the procedure shown in McQuaig et al. [11] the hardness profile of the cross section of the cylindrical specimens was compared. At this large specimen size, the leaner FL-4805-QT specimen had a similar hardness profile to that of the highly alloyed FLC2-4808 sample and produced a consistently higher hardness product than that of the FLC-4805 product (Figure 5).

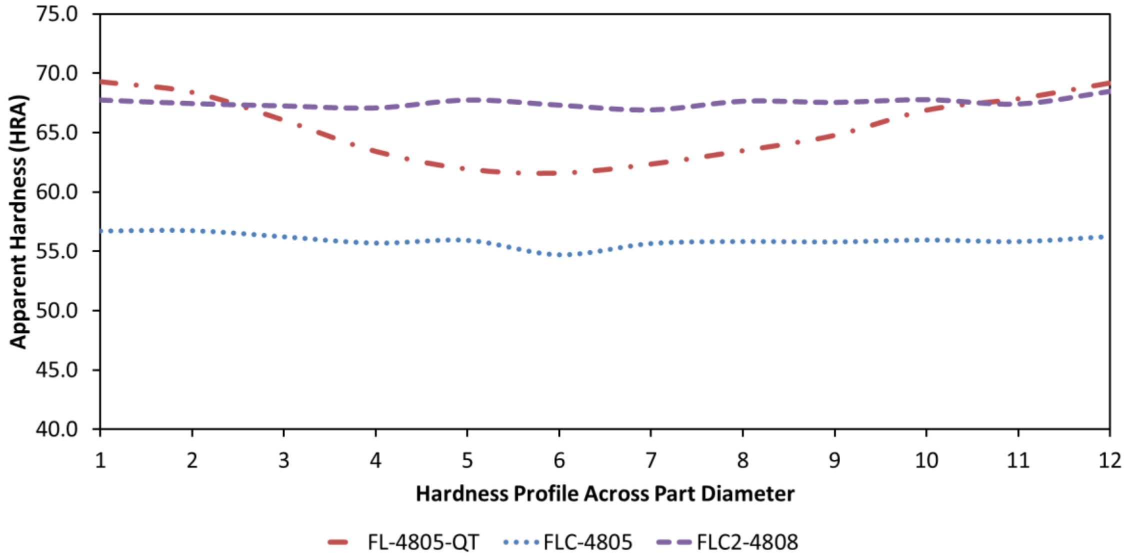

Figure 5: Hardness profile of 76.2 mm diameter cylindrical samples at center line.

Overall, while the FL-4805 sample showed the lowest hardenability of the four mixes produced, given a sufficient cooling rate, the material is still highly capable of producing a martensitic structure and leveraging the benefits of this hardened structure in operation.

In contrast to changing the actual cooling rate and/or processing route of the parts, part size is the other major determining factor in determination of observed cooling rate and microstructure transformation. As it has been widely noted and leveraged over the years, smaller parts can be modified away from highly alloyed chemistries to leaner alloy systems [3]. The same methodology can be held true when leaning from the highly alloyed FL-4800 based systems containing high graphite and copper when moving to the lower alloyed FL-4805 type product, as long as the martensitic structure is maintained.

Strength Comparison of Martensitic Parts

While different combinations of FL-4800 base iron and additions of graphite and copper can affect the overall hardenability of the compacted component, the material property differences of the various compositions can be negated with a full transformation to martensite.

Processed samples compacted and sintered to a common density of 6.90 g/cm^3 were produced from the four denoted compositions. After sintering at 1120°C (2050°F) with accelerated cooling, a range of material properties were then investigated as shown in Table II. When looking at the material properties ranging from TRS to UTS, the FL-4808 material was found to consistently have the lowest measured strength but the highest apparent hardness. Alternatively, the leanest material (FL-4805) was found to have much more similar properties to that of the copper rich alloys than to the graphite rich FL-4808 type sample. Further, the TRS values measured in the samples are all more than that for the respective book values shown in Standard 35. UTS values were also found to be similar when comparing these compositions but were well under book values, as expected, as the measurements shown were taken on dogbone type specimens which is not in line with best practices. Machined round tensile specimens were not able to be completed in time for publication and are intended to be tested later.

Table II: Mechanical Property Comparison of samples sintered at 1120°C.

Mix	**Sinter Density (g/cm^3)**	**TRS (MPa)**	**Radial Crush (MPa)**	**UTS (MPa)**	**Apparent Hardness (HRA)**
FL-4805	**6.9**	**1500**	**1225**	**750**	**64.6**
FL-4808		**1075**	**1125**	**700**	**68.5**
FLC-4805		**1575**	**1350**	**725**	**66.6**
FLC2-4808		**1650**	**1400**	**750**	**67.8**

This trend of collapsing differences between the mix compositions is further evident when the samples were sintered at an elevated temperature of 1260°C, where the FL-4805 had the highest percentage increase in material properties across the measured values (Table III).

Table III: Mechanical Property Comparison of samples sintered at 1260°C.

Mix	**Sinter Density (g/cm^3)**	**TRS (MPa)**	**Radial Crush (MPa)**	**UTS (MPa)**	**Hardness (HRA)**
FL-4805	**6.9**	**1975**	**1475**	**875**	**64.6**
FL-4808		**1525**	**1300**	**700**	**68.5**
FLC-4805		**1925**	**1550**	**875**	**66.6**
FLC2-4808		**1925**	**1550**	**900**	**67.8**

Alloy Comparisons

The wide use of copper-containing alloys in the PM industry is a continuing challenge to the ability to reuse PM steel in scrap recycling. PM scrap is often specifically called out as a reason for rejecting scrap steel loads at both wrought and powder steel producers due to copper's inability to be removed during melting and production and its adverse effect on material processing such as hot shortness and increased compressibility for powder.

As shown in tables Table II and Table III, the beneficial effects of copper within the product, while present, are minimal when compared against the lower graphite containing FL-4805 product in a martensitic state. This is further mitigated if sintering at elevated temperatures.

As such, since the FL-4805 and FL-4808 materials are not leveraging copper as an alloy constituent, these offer both, a more recyclable option and a more DC stable solution when processed to a fully martensitic state. By removing the addition of admixed copper which alloys though a liquid transformation, spreading and diffusion method, when measured on larger parts the part size variation of the copper free compositions was approximately 60-65% of the values in comparison to the FLC compositions.

However, this cannot be uniformly assumed and the common FLC-4805 and FLC2-4808 compositions may still be required for full transformation in larger sample sizes which provides the primary strength of the components. Larger spur gears were produced and sintered under a situation where the effective cooling rate was not sufficient for the transformation of a martensitic structure across the range of materials investigated. Here, the FL-4805, which was shown to have the lowest hardenability in comparison to the other products, only produced a primary bainitic structure with martensite (Figure 6A). As such, when the gears were tested for strength, those produced from the FL-4805 composition were lower strength than the fully martensitic alternatives with the exception of the FL-4808 samples.

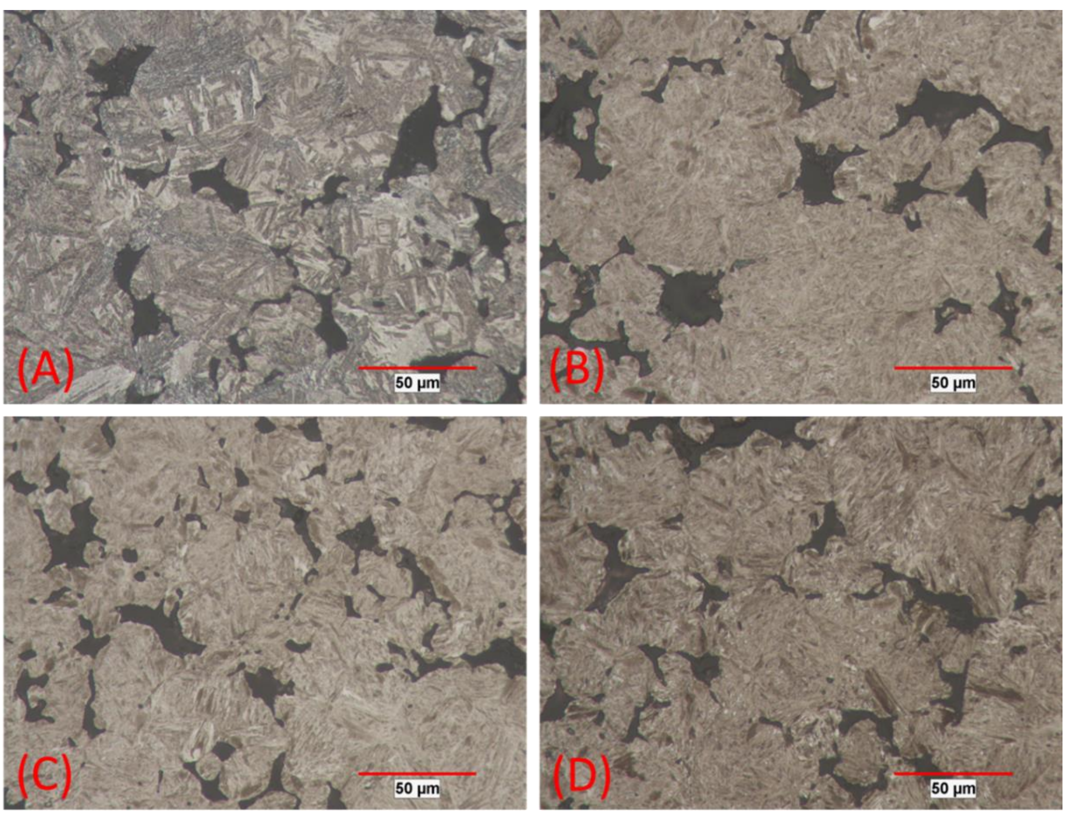

Figure 6: Microstructure of Spur Gears: A) FL-4805, B) FL-4808, C) FLC-4805, D) FLC2-4808.

Due to the high carbon content of the FL-4808 material without the presence of any copper, the strength was negatively impacted from the additional carbon content. While this sample was found to have the highest overall hardness, this proved detrimental to strength, but would be the best option for wear properties. Figure 7 shows the effect of sintered carbon content on strength in standard FL-4800 base iron + graphite premixes with no copper compared to the highly alloyed FLC2-4808 alternative as a baseline. All samples shown here were fully martensitic with the exception of the lowest carbon content sample (0.39%), which had a mixed structure.

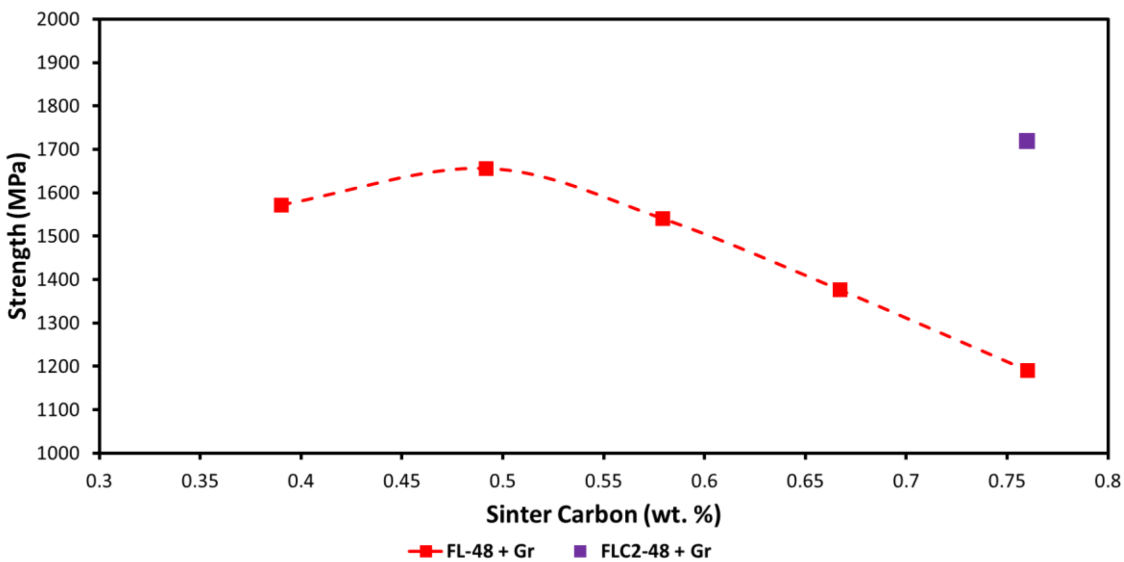

Figure 7: TRS Strength comparison of FL-48 base iron with various carbon contents vs FLC2-4808.

Conclusions

As a result of the experimental work performed during this study, the following observations were made:

- FL-4805, FL-4808, FLC-4805 and FLC2-4808 materials are all able to produce a fully martensitic structure when adequately cooled in a sinter hard furnace.
- FL-4805 material had the lowest hardenability in comparison to the other grades but when fully transformed had mechanical properties similar to the more commonly used copper containing systems.
- FL-4805 when fully transformed in the sinter-hard process has mechanical properties aligned with the MPIF book values noted for the quench and temper process.
- FL-4808 had the lowest strength but had the highest hardness of all other systems investigated
- The removal of copper in the FL-4805 / 4808 system is beneficial for both material recyclability and DC consistency

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