Influence of Alloy Selection on Manufacturing Precision PM Components

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Abstract

The prevailing alloy of choice for manufacturing Powder Metallurgy (PM) parts is based on a mixture of Fe-Cu-C for numerous reasons. Paramount of these reasons is its relatively low cost and when combined with the ease of sintering this material system, it’s difficult to justify the use of other material systems in its place. However, with the growing demand to drive tolerance levels of parts, in particular motor components, to more stringent levels of accuracy, Fe-Cu-C reaches a limitation. Variation in Cu concentration will locally impact dimensional behavior and can lead to distortion. This is a common occurrence due to the susceptibility of Cu particulates to segregate within a premix during handling and as a result can require secondary processing, such as sizing or machining, to correct. This study reviewed the capability of manufacturing sprockets with a typical FC-0205 type composition and compared against a Cu-free material system based on prealloyed molybdenum (Mo) steel. The results of this effort indicate a prealloyed Mo steel can provide a more consistent product over a Cu containing material in terms of weight stability and dimensional accuracy throughout the multiple processing steps employed.

Introduction

PM part producers are increasingly under pressure to improve part to part dimensional consistency for meeting stringent tolerance and accuracy guidelines. The burden to achieve high precision is necessitated by more complex engine design and electrification of vehicles requiring smaller, intricate parts capable of improved strength and function. In turn, parts makers look to powder producers to provide more dimensionally stable powder or technically enhanced powders as one component of the multitude of variables which influence dimensional behavior. Understanding which variables ultimately dictate dimensional behavior is quite complex, as no one single element of the whole process overrides all others [1], and has been addressed by numerous authors over the years. Much of the research has focused on the influence of alloying ingredients, part geometry, sintering temperature, and even the role a sintering tray plays [2-9]. With regards to material choice and the impact alloying has on dimensional change, a common approach many parts makers now employ is using bonded systems to prevent excessive Cu segregation in Fe-Cu-C systems. There are two primary, effective ways to bond fine particulate to the base iron; one is through a chemical diffusion bonding process and the other through utilizing a glue to mechanically bond the particles. Even though an improvement in dimensional accuracy has been realized in connection with using diffusion alloy products such as FD10Cu or FD20Cu, where the Cu particulate was diffusion bonded to iron particulate, there remains a desire to further improve accuracy. In this respect, the current work builds upon prior research [10] to explore using Cu-free material systems based on prealloyed molybdenum steel. The capability to achieve even greater consistency and accuracy is more likely when starting with a homogeneous material system, with an added benefit to possibly eliminate secondary processing steps such as sizing.

Experimental Procedure

An initial study was completed by preparing laboratory premixes using commercially available Ancorsteel® 1000B and Ancorsteel 30 HP base iron powders from Hoeganaes Corporation. An FC-0205 (Sint-D11) type composition was made using Ancorsteel 1000B combined with 10 wt% FD-20Cu and 0.65 wt% Timcal UF4 graphite; an FL-3905 composition was prepared using Ancorsteel 30 HP with 0.60, 0.65, or 0.70 wt% UF4 graphite. All premixes were prepared with 0.6 wt% lubricant. All laboratory procedures were carried out in accordance with MPIF standards [11]. Dimensional and mechanical properties were evaluated using transverse rupture (TR) and dogbone tensile bars compacted to green densities of 6.90, 7.00, 7.10 g/cm^3 at a compaction temperature of 60 °C. All test pieces were sintered at 1120 °C for 25 minutes in a mixed atmosphere of 90 v/o nitrogen and 10 v/o hydrogen. Half of the test samples were subjected to a heat treatment by austenitizing at 900 °C for 45 minutes followed by quenching in a circulating oil bath at a temperature of 65 °C. All heat treated samples were tempered at 205 °C for 1 hour prior to testing. The mechanical properties were evaluated on sets of five bars for each premix and density combination. Sintered carbon values were also measured using a Leco 200 carbon-sulfur combustion gas analyzer with reference standards run before and after test samples. Serial production of an automotive sprocket was performed at GKN Sinter Metals using a production quantity of FC-0205, where weight stability and critical dimensions were monitored on 50 samples once a stable compaction process was established in forming 1,000 parts for the purpose of this study. Additionally, production quantity premix samples of FL-3905 and FL-4405 (using base iron Ancorsteel 85 HP) were evaluated on the same part and compaction conditions in order to compare weight and dimensional stability with the established FC-0205 serial production results. An image of the sprocket is shown in Figure 1A and cross-sectional schematic in 1B with nominal dimensions for ID and height shown. Evaluation of the parts were done in the green state, as-sintered, and heat treated. Sintering was performed in a commercial sized production belt furnace at a temperature of 1120 °C in a 95/5 atmosphere; no accelerated cooling was utilized. Heat treating of all sprockets was done at a temperature of 880 °C for 50 min followed with quenching in a circulating oil bath at 60 °C. The heat treated sprockets were subsequently tempered at 205 °C for 1 hour prior to evaluation.

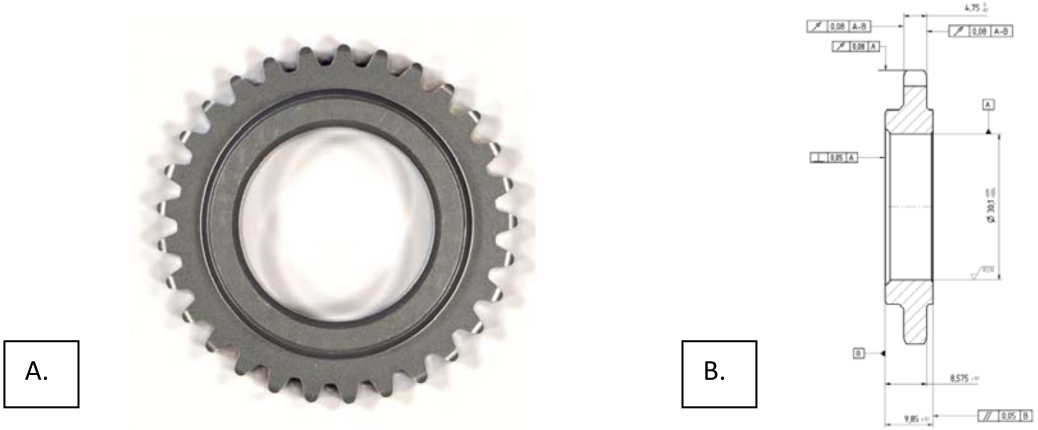

Figure 1: (A) Image of serial production sprocket having a nominal ID of 30.1 mm and overall OD of 56.64 mm; (B) cross-sectional schematic.

Results & Discussion

Laboratory evaluation of material systems

The as-sintered and heat-treated dimensional change (DC) was evaluated using TRS bars over a range of density for FC-0205 and FL-3905, Figure 2. In the as-sintered condition, the FC-0205 material has a DC range of +0.04% (0.56% to 0.60%) with an increase in density from 6.77 g/cm^3 to 6.97 g/cm^3. Conversely, FL-3905 exhibits a DC range of +0.02% (0.25% to 0.27%) over a density increase from 6.86 g/cm^3 to 7.08 g/cm^3. Further, small adjustments in carbon content have very little influence on dimensional behavior of FL-3905. In the heat-treated state, Cu-containing steels appear to be even less stable, with an observed DC increase of +0.05% (0.49% to 0.54%) over a comparable density change. Likewise, the FL-3905 material system shows less DC stability when heat-treated; though still as stable as as-sintered FC-0205 with an increase of +0.04.

The as-sintered and heat-treated tensile properties were evaluated at a density of 7.0 g/cm^3 for FC-0205 and FL-3905, Figure 3. Referring to MPIF Standard 35 [12], data was interpolated for material system FL-4405 (0.85 wt% prealloyed molybdenum steel) and included in the chart for comparison as well. In the as-sintered condition, the FC-0205 material has superior 0.2% offset yield strength (YS) at 310 MPa and ultimate strength (UTS) at 430 MPa over FL-3905 with an average YS = 260 MPa and UTS = 325 MPa. By comparison, the FL-4405 is equivalent to the Cu steel, if not slightly better at an estimated YS = 340 MPa and UTS = 430 MPa. In the heat-treated condition, the FC-0205HT material exhibits a UTS of 760

MPa versus an average of 660 MPa for FL-3905HT. The UTS for FL-4405HT was estimated at 1020 MPa. Yield strength is not reported herein for these materials in the heat-treated state as it is generally accepted that YS and UTS are approximately the same for heat-treated materials [12].

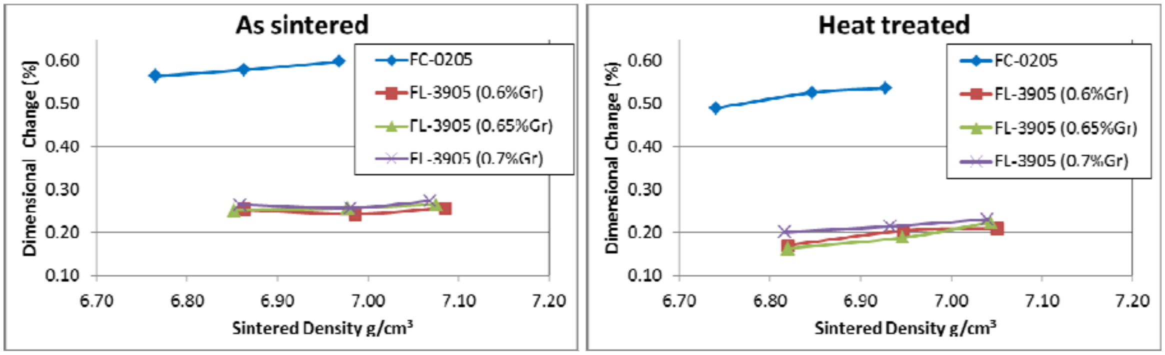

Figure 2: Dimensional change of FC-0205 and FL-3905 (at 3 levels of admixed graphite) in the as-sintered and heat-treated conditions over a range of densities.

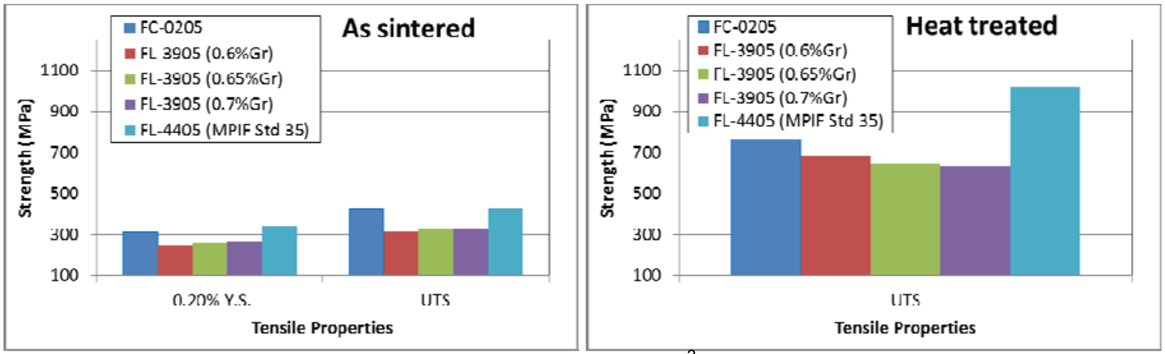

Figure 3: Tensile properties at a green density of 7.0 g/cm^3 for FC-0205, FL-3905 (at 3 levels of admixed graphite), and FL-4405 (as interpolated from [12]) in the as-sintered and heat-treated conditions.

Manufacturing compaction trials

Compaction trials using three separate premixes of FC-0205, FL-3905, and FL-4405 were performed under manufacturing settings, all with the same type and amount of lubricant and graphite. Information on weight and dimensions were captured on the first 50 parts of each run once a stable process was deemed achieved. Figure 4 illustrates the weight scatter for as-compacted parts from each respective premix. It is clear that FC-0205 (Figure 4A) exhibits an increased range in weight (0.46g) over the 50 parts. By comparison, FL3905 (Figure 4B) and FL-4405 (Figure 4C) display a much tighter range in weight at 0.23g and 0.25g, respectively.

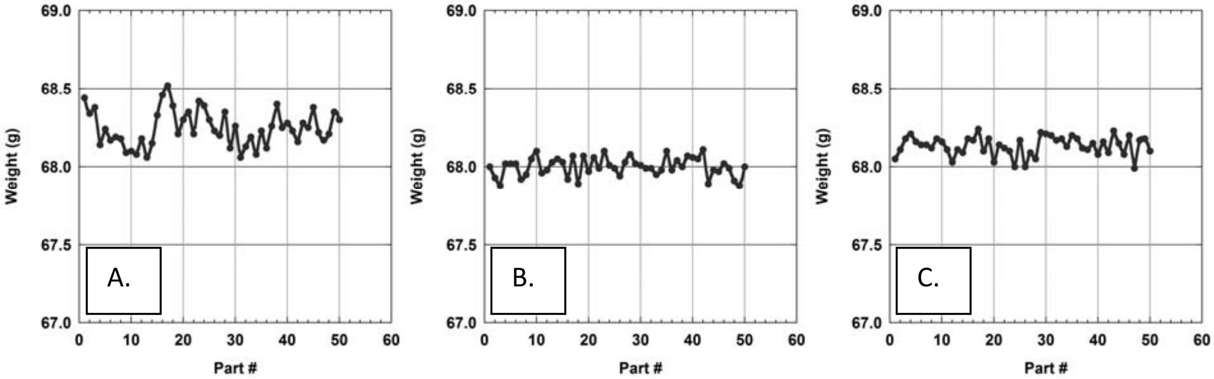

Figure 4: Weight scatter on the first 50 sprockets, as compacted to 6.9 g/cm^3, using material A) FC-0205, B) FL-3905, and C) FL-4405.

The height of the parts were also monitored and captured during each stage of additional processing, Figure 5. For each graph, the target height of 9.85 mm is highlighted in the middle in addition to the upper limit (UL) and lower limit (LL) per the specification for manufacturing the sprocket. The height for FC-0205 based parts increases when going from the green to the sintered state, as is expected with a Cu-containing system, and is well known to the PM industry. In contrast, the prealloyed Mo steels exhibit shrinkage when sintered, though upon heat treating (Q&T) growth is observed, likely due to the formation of martensite.

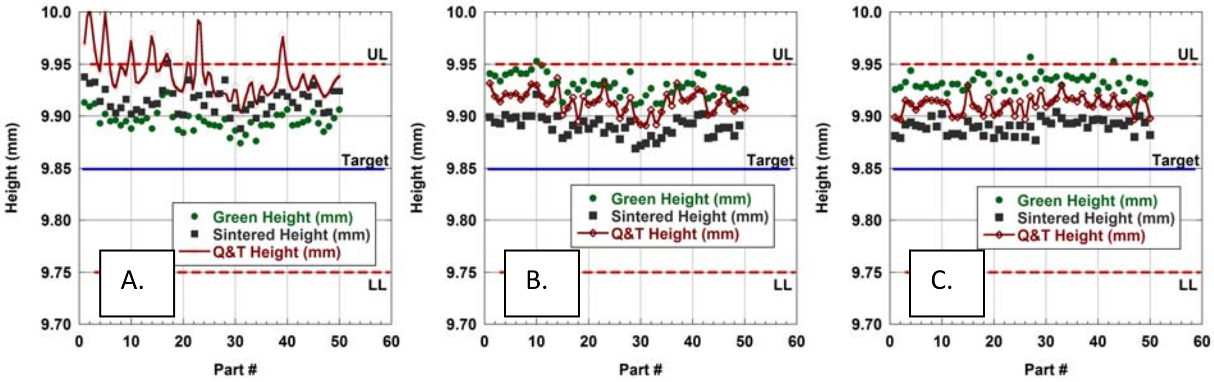

Figure 5: Height scatter on the first 50 sprockets, as compacted to 6.9 g/cm3, using material A) FC-0205, B) FL-3905, and C) FL-4405 in the green, sintered, and heat-treated state (Q&T).

The statistical analysis, based on measurements of 50 sprockets for each composition, on weight, height, and inner and outer diameters are listed in Table 1 (as-compacted green state), Table 2 (as-sintered), and Table 3 (heat treated). The information provided indicates the prealloyed steels provide a more consistent result in manufacturing sprockets, having reduced ranges and lower standard deviations for most measurements over the FC-0205 based sprockets.

Table 1: Statistical analysis of green parts compacted to 6.9 g/cm^3

50 parts	Green Weight (g)	ID min (mm)	ID max (mm)	OD min (mm)	OD max (mm)	Green Height (mm)
FC-0205						
Average	68.247	29.953	29.957	56.338	56.341	9.895
Range	0.460	0.003	0.004	0.004	0.003	0.049
σ	0.113	0.001	0.001	0.001	0.001	0.010
FL-3905						
Average	68.001	29.961	29.963	56.335	56.339	9.930
Range	0.230	0.003	0.003	0.008	0.009	0.042
σ	0.060	0.001	0.001	0.003	0.003	0.010
FL-4405						
Average	68.133	29.963	29.967	56.338	56.344	9.933
Range	0.250	0.004	0.003	0.003	0.003	0.042
σ	0.062	0.001	0.001	0.001	0.001	0.008

Table 2: Statistical analysis of as-sintered parts compacted to 6.9 g/cm^3

50 parts	ID min (mm)	ID max (mm)	OD min (mm)	OD max (mm)	Sintered Height (mm)
FC-0205					
Average	30.027	30.033	56.463	56.471	9.915
Range	0.010	0.008	0.020	0.019	0.063
σ	0.002	0.002	0.004	0.005	0.012
FL-3905					
Average	29.931	29.936	56.286	56.292	9.891
Range	0.009	0.008	0.011	0.011	0.054
σ	0.002	0.003	0.003	0.003	0.011
FL-4405					
Average	29.935	29.937	56.291	56.296	9.890
Range	0.008	0.011	0.012	0.012	0.027
σ	0.002	0.002	0.003	0.003	0.007

Table 3: Statistical analysis on heat-treated parts compacted to 6.9 g/cm^3

50 parts	ID min (mm)	ID max (mm)	OD min (mm)	OD max (mm)	Q&T Height (mm)
	FC-0205				
Average	30.038	30.055	56.532	56.539	9.940
Range	0.033	0.017	0.026	0.028	0.103
σ	0.007	0.004	0.005	0.006	0.023
FL-3905					
Average	29.948	29.959	56.358	56.370	9.914
Range	0.021	0.027	0.020	0.025	0.046
σ	0.006	0.007	0.004	0.006	0.011
FL-4405					
Average	29.961	29.970	56.369	56.379	9.911
Range	0.025	0.028	0.029	0.023	0.033
σ	0.005	0.007	0.006	0.006	0.008

Table 4 provides the apparent hardness and sintered carbon content of the sprockets in the as-sintered and heat-treated condition. The presence of Cu in the as-sintered state is known to be effective at boosting hardness due to solid solution strengthening effects and as a result is an attractive alloying ingredient, though its impact is less influential when compared to small amounts of prealloyed Mo when heat treated. Prealloyed Mo steels are very responsive to cooling rate and small amounts of Mo improve the hardenability of the material, allowing for larger parts to achieve and retain higher hardness over Cu steels at elevated cooling rates.

Table 4: Apparent hardness and sintered carbon of sprockets

Material	As-sintered Hardness	Heat-treated Hardness	SC (wt %)
FC-0205	74 HRB	46 HRC	0.59
FL-3905	65 HRB	49 HRC	0.61
FL-4405	72 HRB	48 HRC	0.61

To better understand the dimensional behavior and mechanical response of the different materials, sections from as-sintered and heat-treated sprockets were taken for metallographic inspection. The as-sintered microstructures shown in Figure 6 illustrate a large contrast between FC-0205 and the prealloyed steels. The FC-0205 material is composed of lamellar pearlite, ferrite, copper diffusion and copper precipitates. Due to the admixed method of Cu addition, the microstructure is heterogeneous with some areas not containing any Cu alloying. The FL-3905 material, having a fully prealloyed Mo addition, the structure is divorced pearlite with a small portion of lamellar pearlite and ferrite. Lastly, FL-4405 has a more uniform and finer distribution of divorced pearlite and ferrite. In the heat-treated condition, Figure 7, the microstructures of the different material systems are more similar, being primarily martensite. They would be difficult to differentiate without knowing the chemistry in advance. One differentiator between the FC-0205HT material and the prealloyed Mo steels, is the presence of Cu precipitates at prior particle and/or grain boundaries. Cu precipitates are commonly found in Cu-containing PM steels [10].

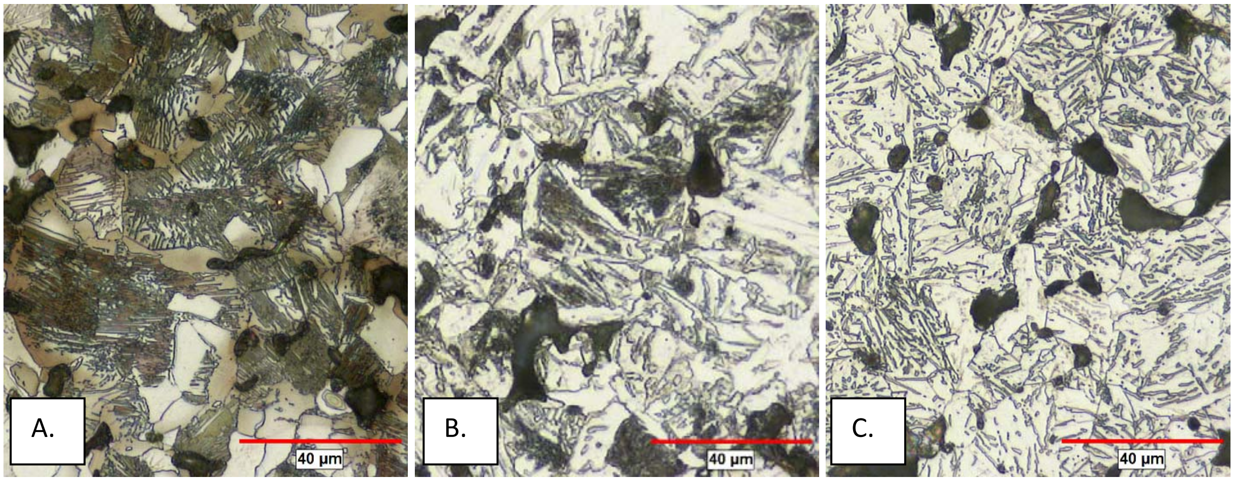

Figure 6: As-sintered microstructure of A) FC-0205, B) FL-3905, and C) FL-4405; etched with 2vol%Nital+4wt%Picral.

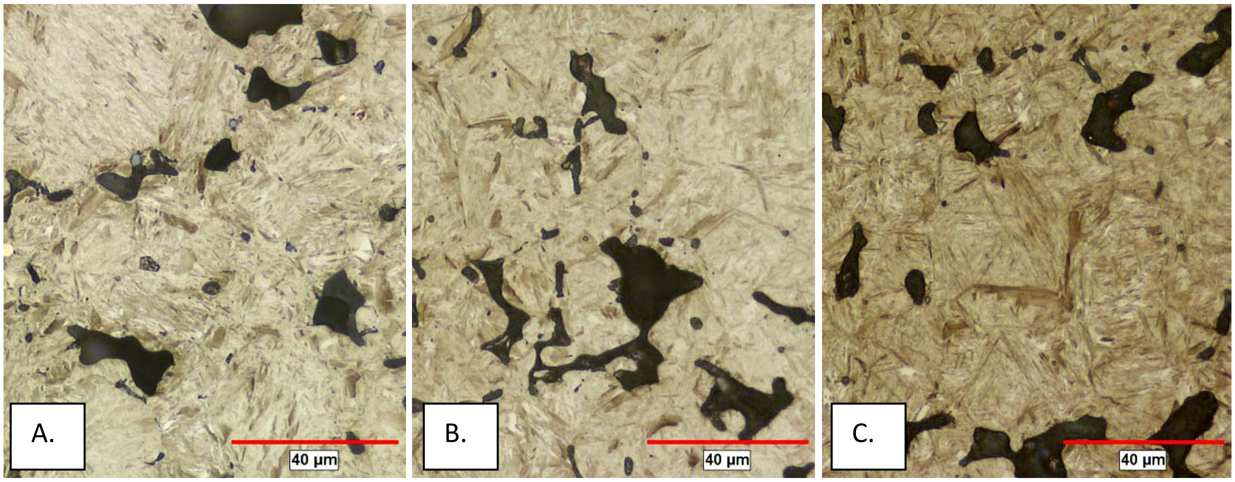

Figure 7: Heat-treated microstructure of A) FC-0205HT, B) FL-3905HT, and C) FL-4405HT; etched with 2vol%Nital+4wt%Picral.

Conclusions

- Prealloyed Mo steel, FL-3905, was shown to be more dimensionally stable than FC-0205 over a range of density and carbon content in lab testing.
- As-sintered strength of FC-0205 is superior to FL-3905, though FL-4405 is equivalent.
- FL-4405 has superior strength over FC-0205 when heat treated.
- Prealloyed Mo steels, FL-3905 and FL-4405 premixes, demonstrated better weight and dimensional consistency in comparison with FC-0205 premix.
- Heat treating prealloyed Mo steels promotes increased hardness and mechanical properties over FC-0205HT.

Acknowledgements

The authors are grateful for the significant work that went into collecting data at GKN Sinter Metals Radevormwald, Germany. Additionally, to Eric Alesczyk at Hoeganaes for the metallographic analysis.

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