Enhanced Processing Developments in Steel Powders

Bruce Lindsley, Fran Hanejko and Cecilia Borgonovo

Hoeganaes Corporation, Cinnaminson, NJ 08077

Abstract

Powder Metallurgy is a cost effective manufacturing route for many automotive and industrial components, and its use in India is expected to expand in the coming years. Engineered powders with enhanced attributes are an important tool being used to help drive this expansion. Hoeganaes Corporation continues to develop and expand its product line to empower parts makers to produce components more efficiently and drive density to higher levels to achieve improved performance. Warm die compaction with AncorMax 225 enables green and sintered densities in excess of 7.4 g/cm³ at compaction pressures of approximately 750 MPa. This new advanced premixing technology is currently being utilized in the production of high density automotive and non-automotive ferrous components and will be discussed. Additionally, improved PM steel machinability is an ongoing focus as part tolerances become tighter, thereby requiring machining for production of the final part. The machining enhancer AncorCut will be shown to improve both turning and drilling operations in PM components made with different alloy grades.

Introduction

PM components are widely used in the automotive and off highway industries. Often, PM is preferred for parts that are characterized by intricate shapes, attainable directly after press and sinter. Porous PM components pose some challenges, however, as machinability is often different than fully dense materials. Additionally, certain mechanical properties that are especially sensitive to density may limit the use of PM. Both powder and component manufacturers strive to improve the performance of PM, enabling greater market penetration and increased value.

While the PM process produces net or near-net shape components, many parts are machined to deliver high precision features, cross holes, transverse grooves, etc. It is estimated that 40-50% of PM steels require additional machining in applications where wrought steels are normally employed [1]. Components with poor machinability result in higher insert costs, reduced capital utilization and unpredicted downtime. It is known that the machinability of PM steels differs from that of wrought steel due to the presence of porosity and the often heterogeneous microstructure [2]. Additionally, PM alloys typically contain higher levels of carbon (>0.5%) to achieve similar strengths as fully dense wrought products. The resulting higher micro-indentation hardness in combination with the porosity is most responsible for the different machining response of PM compared with wrought steels.

One of the advantages of PM is that machinability enhancers can be incorporated into the powder prior to compaction. Free-machining additives improve machinability by assisting in chip formation, lubrication of the tool face and reduction of both flank and crater wear [2]. The most common additive used is MnS. Many studies have shown the benefits of MnS additions to the machinability of PM steels [2-13]. While manganese sulfide has many beneficial attributes, it has some limitations and potentially negative effects. High humidity environments can quickly oxidize the MnS and deteriorate the machinability enhancing properties [4-6, 10]. Component rusting is accelerated when MnS is present and staining due to lubricant burn out worsens [8]. Chemically inert additives are therefore desirable. A recently introduced machining additive, AncorCut, has proved to be a stable additive as well as provide improved machining performance in PM steels. Both drilling and turning improvement will be assessed.

The ability to produce higher density components increases the number of potential parts that can be made with PM. Achieving high densities (>7.2 g/cm³) in powder metallurgy parts can be achieved via double pressing, copper infiltration, die wall lubrication, high pressure compaction, and high velocity compaction [14]. Die wall compaction, high pressure compaction (>1000 MPa) and high velocity compaction are limited because of reduced press speeds, tool breakage issues and inability to produce multi-level components. The typical PM approach of using admixed lubricants has proven to be the most economical approach for the production of PM parts. However, the traditional amounts of lubricants required reduce the maximum attainable green density because lubricants have a density of approximately 1.1 g/cm³ compared to iron having a density of about 7.85 g/cm³ [15]. This difference in density of the lubricant vs. the iron implies that for every 0.1% lubricant added there is a loss in green density of approximately 0.05 g/cm³. Thus, for an FC-0208 type material with 0.75% admixed lubricant; the maximum attainable green density is 7.10 to 7.15 g/cm³.

Increasing compacted part densities can be achieved by reducing the amount of premixed lubricant; however, reducing the internal lubricant must be done with caution. Simply reducing the amount of the lube can result in excessively high ejection pressures with a corresponding unacceptable surface finishes. To facilitate reduced lubricants levels, the high density lubricants used must give the same performance at the reduced level as the traditional lubricants and amounts. A newer lubricant system, AncorMax 225, has been utilized to produce parts with as little as 0.25% internal lubricant. This system requires warm-die compaction, where the die is heated into a range that optimizes the performance of the lubricant. In addition to promoting higher green densities; this new system demonstrates good lubrication, higher apparent densities in premixed powders and higher part green strengths. Additionally, because there is no need for die wall lubrication; compaction rates are equivalent to lower density PM parts. Component production experience with this advanced lubricant system is discussed.

Experimental Procedure

Machining trials were performed in the Machining Laboratory within the Innovation Center at Hoeganaes Corporation. Premixes with no machining additive, 0.35% MnS and 0.2% AncorCut were investigated with several alloy systems, shown below in Table I. Standard transverse rupture bars and machining rings measuring nominally 45 mm outer diameter, 25 mm inner diameter and 32 mm tall were compacted to 6.9 g/cm^3 density and sintered in an Abbott belt furnace at 1120 °C in 90% N_2 – 10% H_2 atmosphere. Time in the hot zone was 45 minutes. The sintered density of the compacts was nominally 6.8 g/cm^3.

Table I. Alloys studied in the machinability study

Alloy	Mo	Ni	Mn	Cu	Gr
FC-0208	-	-	0.1**	2.0	0.9
FD-0405	0.5*	4.0*	0.1**	1.5*	0.6
FLC2-4808	1.2**	1.4**	0.4**	2.0	0.9

*** diffusion alloyed, ** prealloyed**

Turning studies were run using a 0.25 mm depth of cut and 0.25 mm feed at cutting speeds of 150 smm (FLC-4808) and 230 smm (FC-0208 and FD-0405). The abbreviation smm is surface meters/min. Twenty five cuts were made on each ring so that final diameter of a machined ring was nominally 32 mm. The target number of rings per test was 60, for a total of 1500 cuts per test. For FLC-4808, extended tests were run as tool life exceeded 1500 cuts. The turning tests were run using a Haas ST-10 CNC lathe with no coolant. Machinability was measured as the change in diameter of the machined ring after the first pass using an automated probe within the lathe. This data was then normalized to zero at the start of the test so that the change in part diameter could be observed. An increase in machined part diameter over several parts is an indicator of tool wear. The tools used in this experiment were an alumina-TiCN coated carbide insert (Kennametal KCP25) in a CNMG 432 FN geometry and a polycrystalline boron nitride (cBN) tipped insert in a CNGA 432 geometry, with a light hone edge preparation, from Shape-Master Tool.

Drilling studies were conducted on a HAAS VF-1 vertical milling center. Maximum torque at 2000 rpm is 12.5 kg-m. A 2 mm tungsten carbide ball stylus 50 mm long from Renishaw was employed to measure variation in diameter. The setup (Fig.2a) involves three specimens (pucks) clamped by an aluminum fixture. The solid pucks had the same dimensions and density as the cylindrical turning samples with the exception of no inner diameter. Every puck can contain 33 holes which leads to a total of 99 holes drilled per cycle. Infinite life has been set at 990 holes (10 cycles).

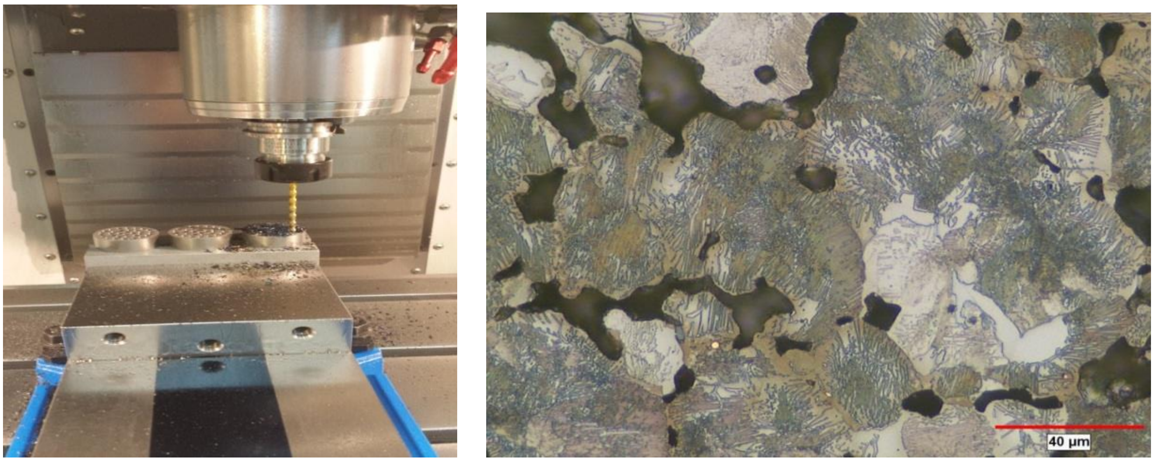


Figure 1: a) Drilling set up with aluminum fixture; b) Nital etched microstructure. FC-0208.

Drill bit diameter was 4.75 mm and depth of drilling about 25 mm. Screw machine length drill bits have been chosen over jobbers to minimize bending and wobbling of the bit. Diameter was probed every 5 – 10 holes depending on tool material. Table 1 also reports speeds, feeds, and coolant conditions (LUBRICUT 4265 diluted with water in a 5:100 ratio has been selected for coolant) used for the investigation.

High density compaction tests and production components were pressed with alloy FLN2-4400, made with a highly compressible base iron Ancorsteel 85 HP (0.85% Mo) and mixed with 2% Ni powder and 0.35% graphite. The AncorMax 225 lubricant system also utilizes binder-treatment, so Ni dusting is reduced. Powder flow and apparent density was determined using MPIF standard test methods 3 and 4. Compressibility was determined using standard green strength bars at compaction pressures of 550, 690, and 830 MPa with a die preheat temperature of 107 °C. Laboratory sintering was also done at 1120 °C in a 90% nitrogen – 10% hydrogen atmosphere with conventional cooling. TRS and tensile properties were determined using MPIF test standard methods 41 and 10.

Joint development was performed with Cloyes Gear [16], and during production, the gears shown in Figure 3 were evaluated for the following key characteristics:

- **weight variability**
- **press tonnage**

Both parts were compacted on standard mechanical PM compaction equipment. The tools were modified to incorporate cartridge heating elements into the stress ring of the die. No powder heating was done prior to introducing the powder into the die cavity. To measure the repeatability of the binder-treated premix, multiple set-ups and production runs were completed to insure product and press performance consistency.

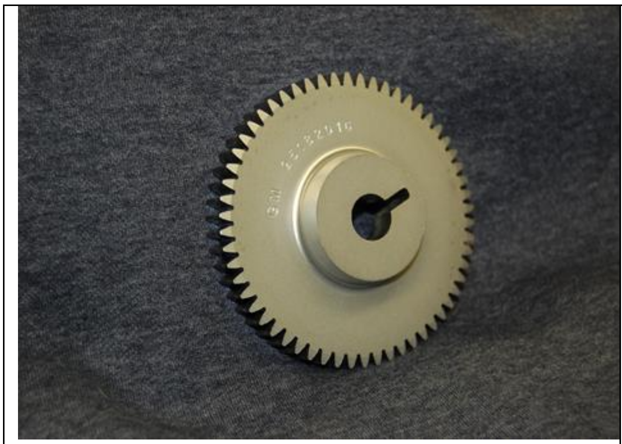
	
3 a. Main running gear, weight ~450 grams	**3 b. Sprocket, weight ~1100 grams**

Figure 3. Automotive valve train components produced by Cloyes Gear (material: pre-alloyed 0.85% molybdenum steel with 2% nickel, 0.35% graphite (FLN2-4400) [16]

Results and Discussion

Turning of FC-0208

The turning comparison of no additive, MnS and AncorCut in FC-0208 are shown in Figure 4. The AncorCut (blue) results in a clear improvement to the no additive (red) condition. As will be shown later, the time between sintering and machining can play a role in machinability. Tests were run within one day of sinter and after several weeks. Neither the AncorCut nor the no additive material exhibited any significant change in behavior. The orange curves represent 0.35%MnS material, where two distinct behaviors were observed. The machinability of MnS after 1 day was excellent and found to be slightly better than AncorCut, however, after storage of 3 weeks in closed containers, the MnS performed worse than AncorCut. It is known that MnS has poor shelf life in the powder form, but this is also true of MnS within PM parts. MnS degrades over time causing reduced machinability. This will be explored further in latter parts of the paper. All subsequent machining tests run with MnS were performed within one day of sintering unless otherwise noted.

Figure 4. Turning comparison of no additive, AncorCut with MnS after 1 day (run 2) and after 3 weeks (run 1)

Turning of FD-0405

The 4% Ni diffusion alloy is a popular alloy system for higher performance applications, where compressibility, toughness and robust processing are important. It is also known as an alloy that is difficult to machine given the mixed microstructures of ferrite, pearlite, martensite and Ni-rich austenite present after sintering. Figure 5 illustrates the difficulty turning this material with no additive (red). The test did not even reach 200 cuts before tool failure. The addition of machining additive is greatly beneficial for this alloy, as both MnS and AncorCut result in the tests reaching the 1500 cut goal. Less tool wear was observed with AncorCut, indicating that this additive is the better choice for this more highly alloyed material.

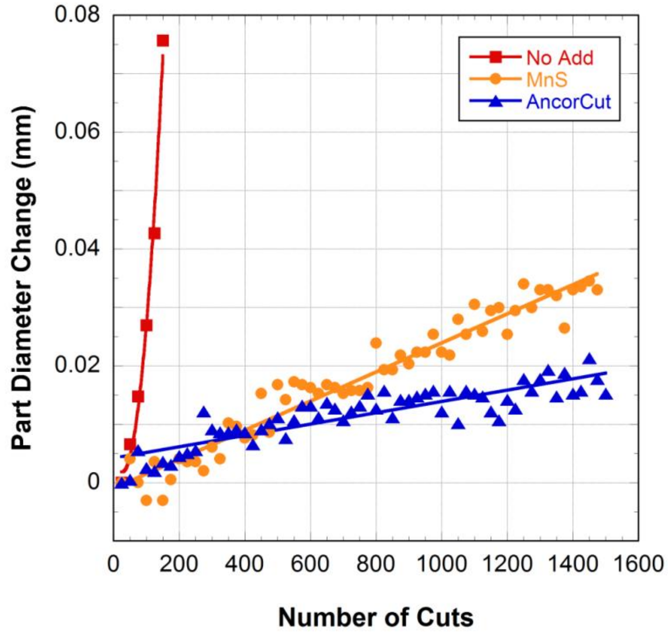


Figure 5. FD-0405 turning comparison of no additive, AncorCut with MnS

Turning of FLC2-4808

The final material turned was FLC2-4808, a sinter-hardening grade with poor machinability. It was determined that the carbide insert could not be used to machine this fully martensitic material, so tests were run with a cBN insert. Even with the cBN insert, a slower cutting speed of 150 smm had to be used. The test results in Figure 6 show extreme tool wear in the no additive condition, whereas the AncorCut tests ran for 2000 cuts with almost no tool wear. The combination of the cBN insert and the AncorCut machining additive was found to be extremely beneficial.

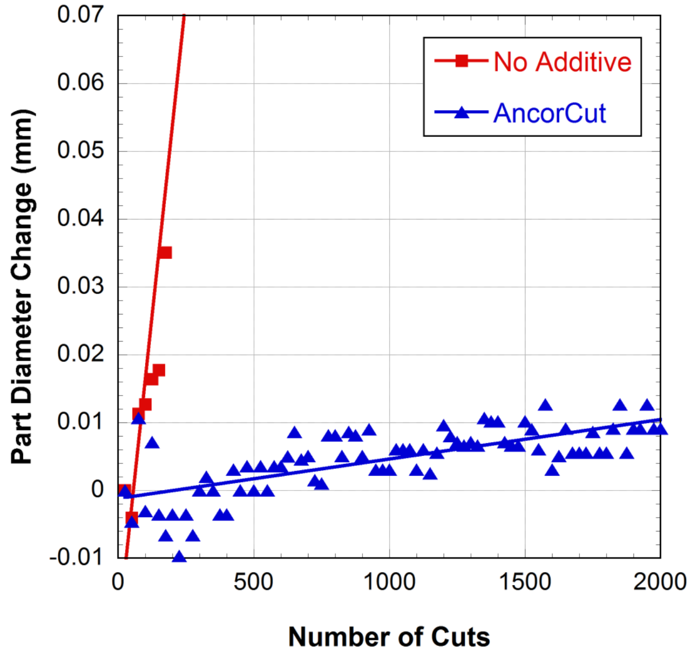


Figure 6. Turning behavior of FLC2-4808 at 150 smm using a cBN insert

Drilling of FC-0208

Table 2 displays number of holes drilled for each test condition. MnS showed the best performance for high speed steel bits at low feeds and no coolant. MnS also provided the longest tool life in drilling with carbide bits for both feeds. AncorCut exhibited excellent behavior for high speed steel with coolant at high feeds and also provided 2 to 3 times the tool life vs no additive for carbide. The results shown here demonstrate that tool life is highly dependent on the cutting conditions and drill bit materials, and that test results from one test can not necessarily be used as a guide to predict the response under different test conditions.

Given that MnS resulted in the longest tool life for carbide drill bits, it was initial assumed that it was the best machining additive for carbide. The precision of each hole, however, suggests otherwise. Figure 7 shows the variation in hole diameter for the three conditions. A much greater variation is found with MnS than either the no additive or the AncorCut condition. If hole precision and reasonable tool life are paramount, the best premix contained AncorCut.

Table 2. Drill life for FC-0208 under different machining conditions

Test Code	Coolant	Additive		
		No add	MnS	AncorCut
HSS (159 mm/min)	NO	98	921	357
HSS (159 mm/min)	YES	313	334	445
HSS (318 mm/min)	NO	2	186	3
HSS (318 mm/min)	YES	366	183	403
Carbide (318 mm/min)	YES	254	990	598
Carbide (508 mm/min)	YES	103	425	348

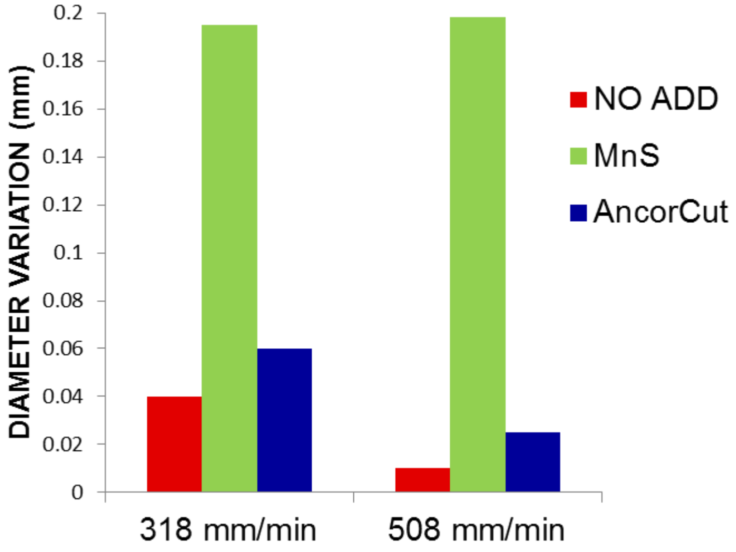


Figure 7. Drilled hole diameter variation in FC-0208 with no additive, MnS and AncorCut

Drilling of FD-0405

FD-0405 exhibited very short tool life with high speed steel drill bits, so only the carbide bit results were pursued and included in the paper. Figure 8 shows the drilling results using coolant and a cutting speed of 508 mm/min at 3500 rpm. In a similar fashion to the turning results, attempting to machine FD-0405 without the addition of a machining enhancer leads to poor results. Far fewer than 100 holes were machined without an addition. A nine time improvement in tool life was found with MnS and a 17 time improvement was found with AncorCut. From the machining results presented in the paper, it is clear that higher alloy materials greatly benefit from machining enhancers. Fe-Cu-C steels also show an improvement with enhancers, but it is less dramatic.

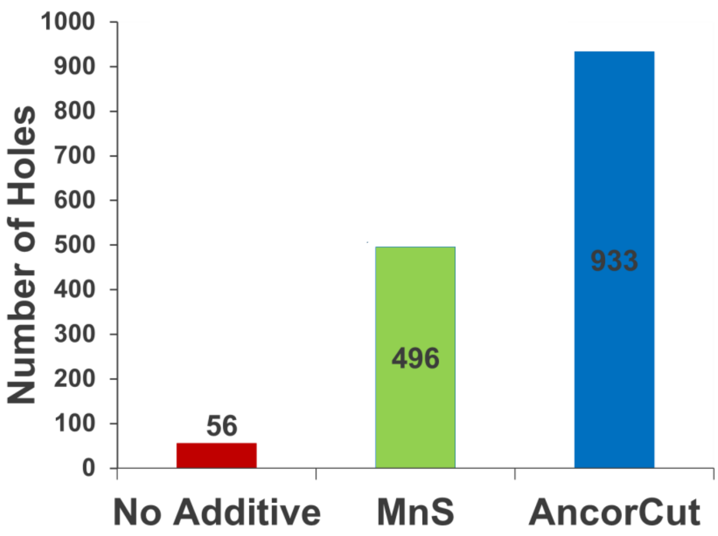
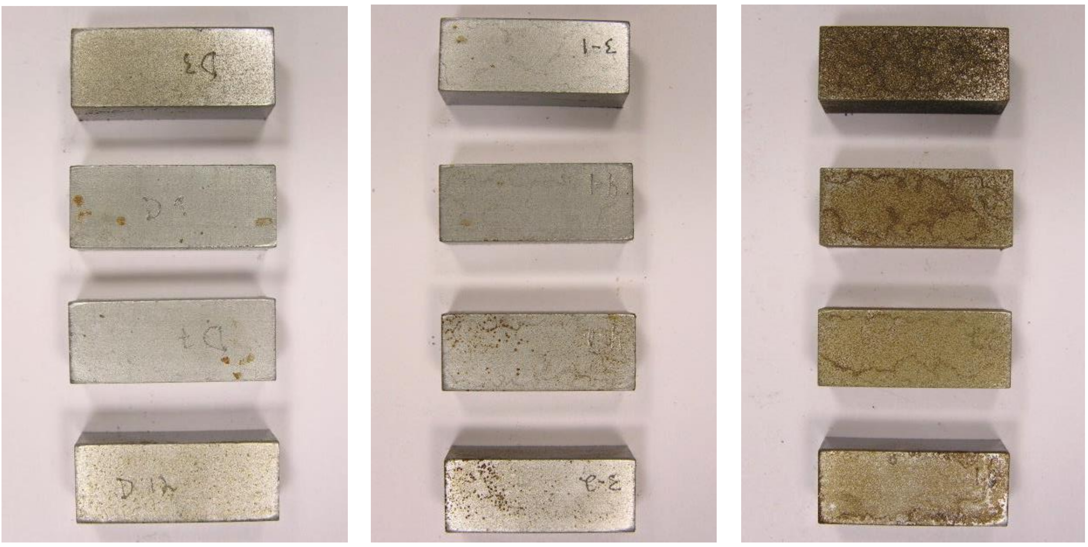


Figure 8. Carbide drill life in FD-0405 with no additive, MnS and AncorCut at 3500 rpm and 508 mm/min feed

Rusting Tests

One of the primary benefits of MnS-alternative machining enhancers is the reduction in rusting and staining on the surface of PM components. Figure 9 shows the accelerated rusting when MnS is present, whereas the no additive and the AncorCut samples had similar appearances, when exposed to higher humidity. MnS oxidizes to form manganese oxide or manganese sulfate type compounds and sulfuric acid may be evolved in the presence of water, thereby causing accelerated corrosion. Additionally, MnS can alter how lubricants are removed from PM parts during the de-lubrication process, leading to staining on the surface of parts. In many applications, MnS can not be used for these reasons. The earlier turning results illustrated how MnS machinability can degrade under typical lab environments. For drilling, samples were exposed to humidity levels of 92% for three days and then machined. These were compared with the results of samples drilled within one day of sintering. It was found that the no additive machinability decreased 30%, MnS decreased 85% and AncorCut decreased 5%, Fig. 10. AncorCut provided the best stability in machinability with respect to humidity expose.



(a) (b) (c)

Figure 9. Surface rusting of FC-0205 test bars with (a) no additive, (b) AncorCut and (c) MnS exposed for 10 days at nominally 80% humidity.

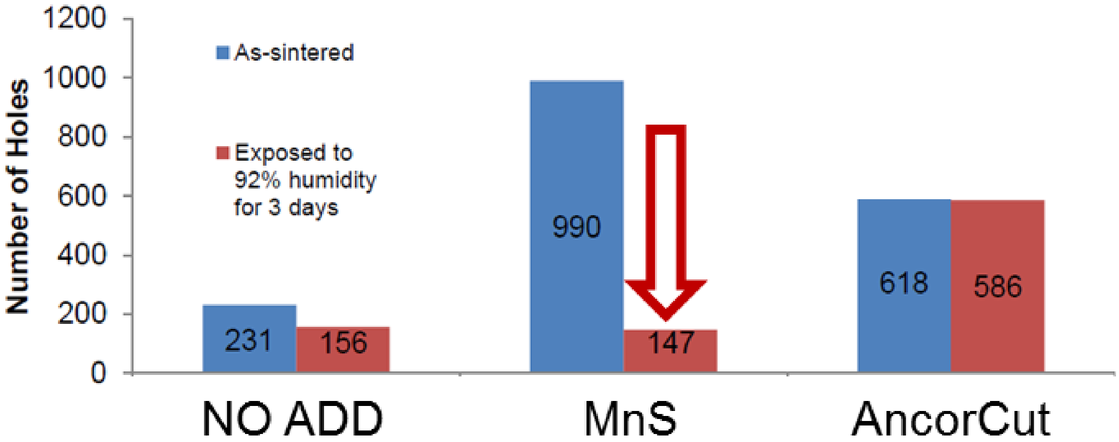


Figure 10. Drilling response before and after humidity exposure (92% for 3 days)

High Density Processing

The AncorMax 225 system was successfully utilized in the production of the automotive components shown in Figure 3. These parts have a pressed weight of approximately 500 grams and 1100 grams with a minimum green density of 7.25 g/cm³ and 7.2 g/cm³, respectively. The AncorMax system replaced a warm compaction system, where the powder had to be heated in addition to the die. The eliminated complication of powder heating was cited as a benefit of this system.

A summary of the flow and apparent density (AD) of the material produced to date is given in Table 3. The AD of this material averaged 3.35 g/cm³ with a powder flow of <26 seconds per 50 grams through a Hall flow cup. The first production lot was sampled and evaluated for standard MPIF testing of compressibility, green strength, as-sintered TRS and tensile, and heat treated TRS and tensile. For the heat treated properties, the samples were first austenitized at 870 °C for one hour at temperature followed by oil quenching into heated oil (70 °C) and then tempering at 200 °C for one hour. Results from this laboratory testing are shown in Table 4 and Table 5.

Table 3. Powder Properties of the FLN2-4400 Premix Prepared via AncorMax 225 Processing. Compact produced at 755 MPa and a die temperature of 107 °C.

Characteristic	Average
AD (g/cm³)	3.36
Flow (per 50 g)	25
Compressibility (g/cm³)	7.40
Green strength (MPa)	32
As sintered Density (g/cm³)	7.44

Table 4. Laboratory Compressibility, Green Strength, As-Sintered and Heat Treated TRS values

Compact-ion Pressure (MPa)	Green density (g/cm³)	Green Strength (MPa)	As sintered			Heat Treated		
			Density (g/cm³)	TRS (MPa)	HRA	Density (g/cm³)	TRS (MPa)	HRA
550	7.20	29	7.20	1175	45	7.21	1535	57
690	7.37	34	7.37	1325	48	7.38	1875	57
830	7.49	35	7.47	1455	49	7.48	2105	59

Table 5. Laboratory Sintered Tensile Data

Compaction Pressure	As sintered					Heat Treated			
	YS MPa	UTS MPa	Elong. %	HRA		YS MPa	TS MPa	Elong %	HRA
550	390	545	2.1	49		850	920	1.0	61
690	410	600	2.8	51		905	1025	1.1	64
830	415	605	3.0	52		955	1050	1.1	64

The production experience of the main running gear and sprocket shows good consistency in pressing tonnage and weight control. Shown in Figures 11 and 12 are graphs representing the total compaction tonnage applied and the part-to-part weight variability. In each plot two evaluations are presented. These evaluations represent two distinct production sequences run approximately 4 weeks apart using two distinct lots of premixed powder. The results show a maximum deviation of less than 1% over the two distinct production trials, with improvements evident in the second production run. In addition to the good compaction performance, ejection and surface finish are key attributes. It was determined in both the lab and in production of these components that the surface finish was equivalent or better than the warm compaction method being used previously.

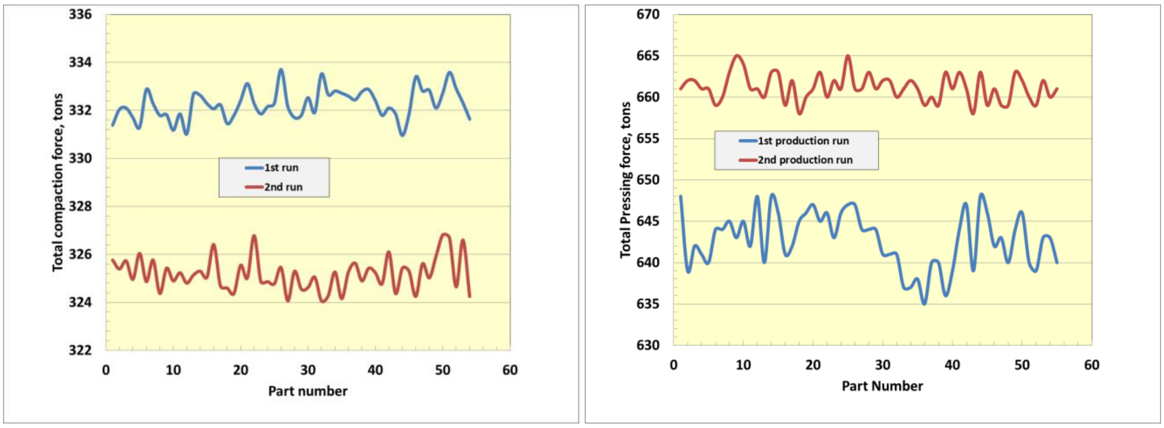


Figure 11. Compaction force required for the main running gear and sprocket for two distinct set ups approximately 1 month apart.

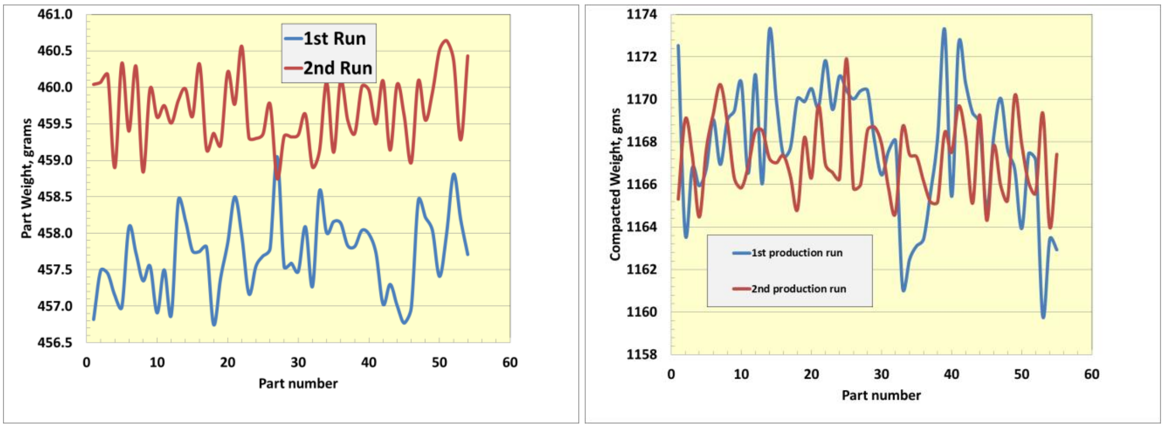


Figure 12. Weight control for the main running gear and sprocket for the two initial production runs.

A further benefit observed with this new premix alternative is the enhanced uniformity of green density throughout the compacted part. Figure 4 is an unetched photomicrograph of the cross section of a non-automotive gear at the 'neutral' zone. It demonstrates the uniformity of density in the body of the gear plus at the gear tips. This gear was compacted to an overall density of ~7.45 g/cm³ utilizing FLN2-4405 material and a lube content of 0.25 wt%. Details of the gear are a major diameter of 18.5 mm with a height of 5 mm and module of ~0.8 mm. Larger components up to 45 mm tall have been successfully produced to densities approaching 7.4 g/cm³ with 0.40 wt% lubricant.

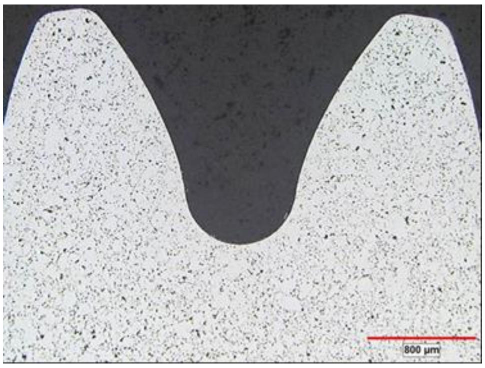


Figure 13. As-polished microstructure showing uniform density in gear teeth.

Conclusions

Engineered powders with enhanced attributes are an important tool for developing new parts and improving current applications. A newly introduced machining enhancer, AncorCut, was found to improve machinability of a variety of

alloy systems and microstructures. This benefit in machinability was observed with both turning and drilling of several different alloy systems. The new additive also avoids the accelerated corrosion (rusting) found in sintered PM parts containing MnS, and provides stable machining characteristics. Warm die compaction with AncorMax 225 enables green and sintered densities in excess of 7.4 g/cm³ at compaction pressures of approximately 750 MPa. This new advanced premixing technology is currently being utilized in the production of high density automotive and non-automotive ferrous components, thus providing parts producers another tool to improve the manufacturing and cost competitiveness of PM components.

References

1. Kalpakijan S., and Schmid S. R., *Manufacturing Processes for Engineering Materials*, 2008, Pearson Education Inc., Upper Saddle River, NJ

2. R. Causton and C. Schade, "Machinability: a material property or process response?", *Advances in Powder Metallurgy & Particulate Materials*, compiled by R. Lawcock and M. Wright, Metal Powder Industries Federation, Princeton, NJ, 2003, part 7, p. 154-169.

3. H. Sanderow, J. Spirko and R. Corrente, "The machinability of P/M materials as determined by drilling tests", *Advances in Powder Metallurgy & Particulate Materials*, compiled by R. A. McKotch and R. Webb, Metal Powder Industries Federation, Princeton, NJ, 1997, part 15, p. 125-143.

4. A. Salak, M. Selecka and H. Danninger, *Machinability of powder metallurgy steels*, 2nd edition, Cambridge International Science Publishing, Cambridge, 2006.

5. S. Cleays and K. Chopra, "Enhanced machinability and oxidation resistance with MnS containing additions to iron", *Advances in Powder Metallurgy & Particulate Materials*, compiled by R. A. McKotch and R. Webb, Metal Powder Industries Federation, Princeton, NJ, 1997, part 15, p. 111-123.

6. C. Stringer, D. Merritt and B. Lindsley, "Influence of Post Sinter Conditions on the Machinability of PM Copper Steel", *Advances in Powder Metallurgy & Particulate Materials*, compiled by I. Donaldson and N. Mares, Metal Powder Industries Federation, Princeton, NJ, 2012, part 6, p. 16-23.

7. B. Hu and S. Berg, "Optimizing the use of manganese sulfide in P/M applications", *Advances in Powder Metallurgy & Particulate Materials*, compiled by H. Ferguson and D. Wychell, Metal Powder Industries Federation, Princeton, NJ, 2000, part 5, p. 191-197.

8. B. Lindsley and C. Schade, "Machinability additives for improved hard turning of PM steel alloys", *Advances in Powder Metallurgy & Particulate Materials*, compiled by W. Gasbarre and J. von Arx, Metal Powder Industries Federation, Princeton, NJ, 2006, part 6, p. 16-26.

9. J. Engquist and R. Hennen, "Improving value in machined PM parts by material selection", *Advances in Powder Metallurgy & Particulate Materials*, compiled by T. Jesberger and S. Mashl, Metal Powder Industries Federation, Princeton, NJ, 2009, part 13, p. 1.

10. B. Lindsley and C. Stringer, "Additives for Improved Machining of Copper PM Steels", *Advances in Powder Metallurgy & Particulate Materials*, compiled by I. Donaldson and N. Mares, Metal Powder Industries Federation, Princeton, NJ, 2012, part 6, p. 50-61.

11. M'Saoubi R., Czotscher T., Andersson O., Mayer D., "Machinability of Powder Metallurgy Steels Using PcBN Inserts", *Procedia CIRP*, 2014, Vol.14, pp. 83-88.

12. Blais C., L'Esperance G., and Bourgeois I., "Characterization of Machinability of Sintered Steels During Drilling Operations", *Powder Metallurgy*, 2001, Vol.44 (1), pp. 67-76.

13. Jandeska W., "Effect of Drilling and Tooling Parameters on the Machinability of Select Powder Metallurgy Materials", 2010, The Center for Powder Metallurgy Technology, Princeton, NJ.

14. W. James, K. Narasimhan, "Warm Compaction and Warm-Die Compaction of Ferrous PM Materials", Presented at PM-13 International Conference and Exhibition on Powder Metallurgy for Automotive and Engineering Industries, Precision and Additive Manufacturing in Pune, India, 2013

15. H. G. Rutz, F. G. Hanejko, "High Density Processing of High Performance Ferrous Materials", Advances in Powder Metallurgy and Particulate Materials – 1994, Vol. 5, Metal Powders Industries Federation, 1994, pp 117-133.

16. S. Shah, Gregory Falleur, F. Hanejko and S. Patel, "Production of High Density PM Automotive Components Utilizing Advanced Warm Die Compaction Technology" Advances in Powder Metallurgy and Particulate Materials – 2014, Metal Powders Industries Federation, 2014, pp. 3-117 to 3-129.