Improving Machinability of PM Components; Examining the stability of additives and machinability best practices

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ABSTRACT

The machinability of PM products is a key consideration for many applications. Most of the parts produced in industry require some level of secondary operations to ensure tolerances and to meet drawing specifications. The effectiveness and stability of the most widely used machinability additive (MnS) is reviewed and compared with an alternative additive - AncorCut. While MnS has great properties for tool wear reduction and increasing tool life, its limitations must properly be understood. The impact of moisture exposure across a range of production scenarios is investigated.

Key words:

Machinability, Ferrous PM, MnS, Stability

1. INTRODUCTION

Powder metallurgy (PM) processing and components are used widely in both the automotive and lawn-and-garden industry. Although PM is considered a near net shape technology, many parts are required to go through some level of secondary machine processing to finish the part and produce an in-tolerance product.

While not every PM component requires machining, an estimated 40-50% of all ferrous PM components require machining processing [1]. Although not a primary operation in the production of PM parts, it is still vital that the machining process is understood. As such, the machinability of PM components has been an area of research for many years. This area of work is expansive because it is the culmination of all previous processing utilized in the production of the part. The machinability or machining response of PM parts is very different to that of wrought steels and, as such, it has often been labeled as worse and /or difficult [2]. Four major theories and explanations have been used to explain the differences in PM machinability in comparison to wrought; namely that of the:

- Hard inclusion theory
- Plastic deformation theory
- Micro – interrupted cut theory
- Thermal conductivity theory

Each of these theories has been further evaluated and discussed by a number of authors [2, 3, 4].

During the development and evolution of the industry, one machining additive in particular has become the backbone and baseline for all other works. Manganese sulfide (MnS) is the single most widely used machining additive in the industry. Its background came from the production of free machining steels which was transferred over into PM. Other additives used in wrought alloys for machining purposes were not options as they were volatile and would not survive the sintering process in a porous PM component. While MnS is an effective machining additive, it is known to accelerate rusting in sintered parts [5]. Only recently has the impact of MnS exposed to atmosphere, and the resultant impact on machinability, been explored [6, 7]. Other additives that are conducive to ferrous powder metallurgy have therefore been introduced into the marketplace that avoid this reaction with the environment. One such additive that was introduced in 2014 is AncorCut. Previous work has shown that rusting of compacts is unaffected with AncorCut and is greatly reduced in comparison with MnS-containing compacts (Figure 1-1) [7].

Additionally, drilling response was not affected with AncorCut by exposure to humidity, whereas MnS-containing material exhibited a dramatic decrease in machinability (Figure 1-2) [7]. Alternative machining additives have thus gained traction for select applications where rust avoidance is important and exposure to hot, humid conditions are present. Manganese sulfide, however, remains the most widely used additive. As such, this work focuses on understanding how MnS reacts under different conditions and the subsequent effect on machinability. Best practices for the use of MnS-containing premixes can then be established.

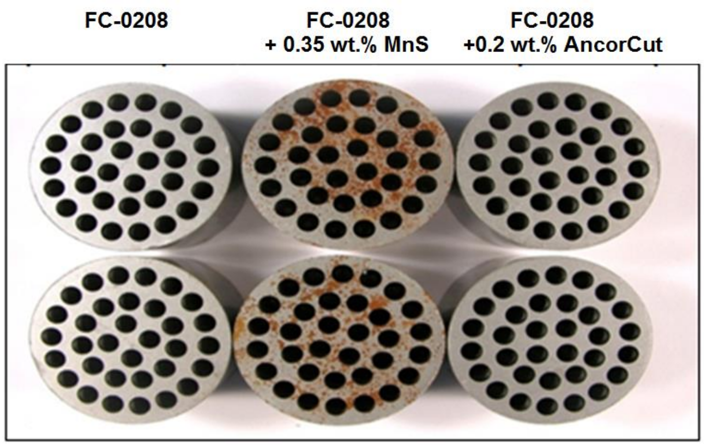

Figure 1-1: Rusting after 2 weeks of drilling with coolant [7].

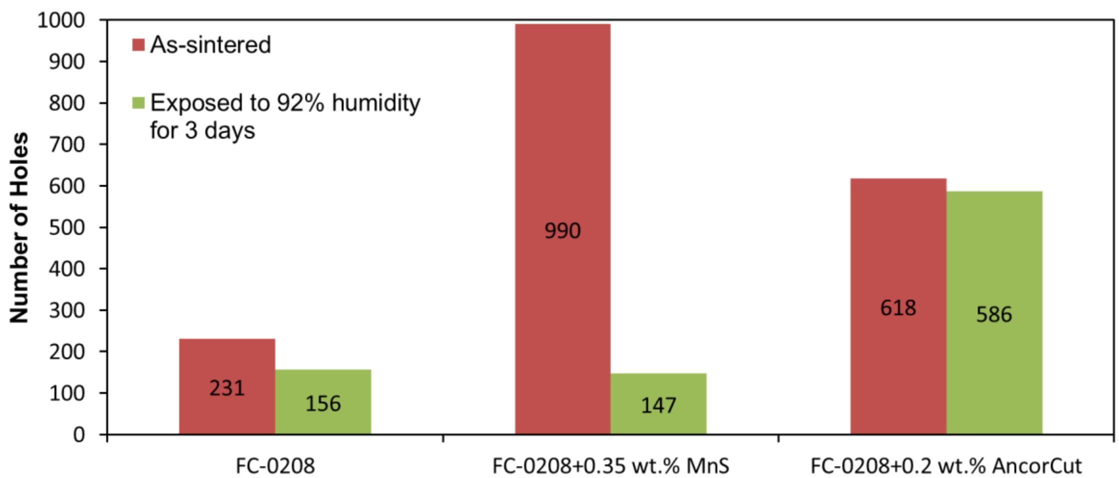

Figure 1-2: Effect of humidity exposure on drill bit life [7].

2. MATERIALS

In order to test the machining response of the selected additive under various conditions, MnS powder was first mixed into a common ferrous alloy system. The alloy composition utilized in this study was that of FC-0208 / F-08C2 (Fe-2Cu-0.8C) in accordance to MPIF standard 35 or ISO 5755, respectively. All mixes were made using the composition and additives noted in Table 2-1. Two separate mix compositions (0% MnS and 0.35% MnS) were produced in order to isolate the effect of MnS under multiple variables.

Table 2-1: Material Specifications

Material	Iron Base	Copper	Carbon	Manganese Sulfide	Lubricant
FC-0208 Spec.	Bal.	1.5 – 3.9	0.6 – 0.9	-	-
Amount (wt. %)	Bal.	2.0	0.85	0 or 0.35	0.75

3. EXPERIMENTAL TECHNIQUES

Machinability response was studied utilizing a HAAS VF-1 vertical mill machine under standard cutting conditions with standardized samples. All samples were pressed to a green density of 6.9 g/cm^3.

In the case of drilling, 31.75 mm (1.25") OAL cylindrical samples with a nominal OD of 44.45 mm (1.75") samples were produced. Each test constituted the drilling of a maximum of 990, 25.4 mm (1.0") deep holes. In total, 30 separate cylinders were utilized with 33 holes being drilled in each. Cutting conditions were kept constant with a bit RPM of 2000, feed rate of 158.75 mm/min (6.25 IPM) and coolant either on or off. In all situations, a standard 4.763 mm (3/16'') HSS screw length drill bit was utilized. The VF-1 is capable of a maximum 30 HP and 8100 RPM with a resolution of 2.5 um. Part and hole measurements were determined using a Renishaw measurement contact probe.

Samples were sintered in an Abbott continuous-belt sintering furnace with conditions selected to represent nominal industrial processing. Samples were sintered at a temperature of 1120 °C under a flowing 90% N_2 / 10% H_2 atmosphere and had nominally 20 minutes above 1100 °C.

Moisture exposure of the samples was conducted utilizing a model LH-6 humidity chamber produced by Associated Environmental Systems and performed under standard conditions marked as; 60% relative humidity (RH) and 40 °C for three days. These exposure settings were selected based on data collected from transport trailers and warehouse data loggers. While these values may be high for some plant locations, they were chosen to represent one point in a spectrum of time, temperature and humidity exposure levels. Figure 3-1 shows the visual shift occurring with exposure of MnS powder to moisture with increasing time. The left most image is fresh, unaffected MnS while the right most picture represents MnS after extreme exposure to moisture. The image in the middle of the spectrum shows that of MnS powder exposed to the standard conditions utilized in the study; namely 60% RH and 40 °C for three days.

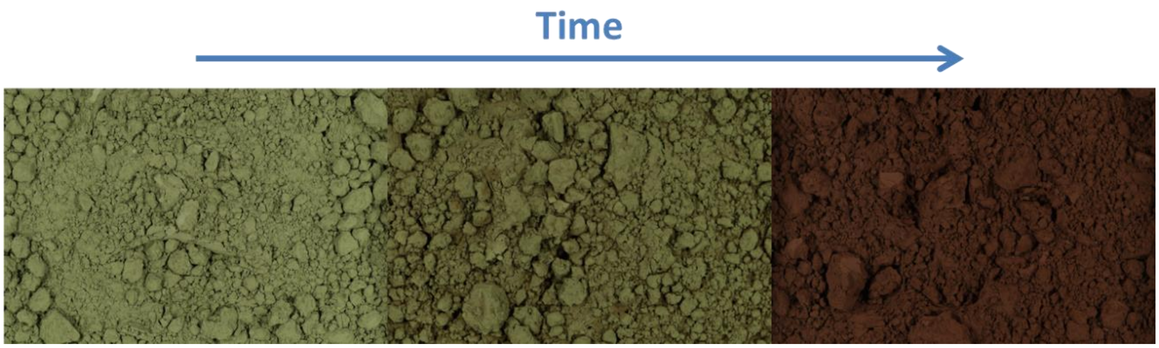

Figure 3-1: Effect of moisture exposure over on MnS powder over time

In order to assess the effect of moisture exposure on PM components, samples were tested in one of three distinctive conditions. These processing conditions were selected to represent possible plant or production lifecycles and represent manufacturing timeline possibilities, namely:

- FIFO of parts where there was no delays during production through to machining
- A delay after production of green parts prior to sintering and machining where parts were exposed to moisture in the green state
- A delay after production of sintered parts prior to machining where parts were exposed to moisture

These three production scenarios are hereafter denoted by; "Nominal", "Exposed Green", and "Exposed Sintered" respectively.

Material characterization and property testing was tested in accordance with applicable MPIF, ASTM and ASM standards.

4. RESULTS AND DISCUSSION

In order to assess the effect of moisture exposure on PM components, the effect of said exposure was investigated across three different parameters. This section will address the impact that exposure has on part physical properties and machinability with a focus on the latter.

Sections 4.1 and 4.2 will first show representative data for the two mixes when produced under ideal (Nominal) conditions and then show the impact that exposing PM components to moisture during various stages of production can have (Exposed Green and Exposed Sintered).

4.1. Effect of Moisture Exposure on Component Properties

In order to test the effect of moisture exposure on the physical properties of the PM component, standard material testing was performed on the mixes. Hereafter, the mixes will be denoted as "No Add" and "MnS"; both mixes were made in accordance with the composition in Table 2-1 with 0 and 0.35 wt.% MnS, respectively.

As expected when adding an extra additive to the mix (MnS), green density of the attained part at a given density was reduced. Over the range of compaction pressures investigated, a maximum of 0.03 g/cm^3 difference was observed and occurred at the highest pressure tested (@ ~ 700 Mpa).

Subsequent samples were produced from both mixes at a constant green density in order to determine mechanical and material property data. Table 4-1 and Table 4-2 show that regardless of the addition of MnS, the sintered components largely behave in a similar fashion regardless of the presence of MnS. Overall only a small shift in properties was observed on the order of ~ 5% maximum reduction with MnS added.

Table 4-1: TRS Properties of mixes produced under Nominal production conditions.

Mix	Green Density (g/cm^3)	Sintered Density (g/cm^3)	DC D/S %	DC G/S %	HRA	TRS (MPa)
No Add	6.90	6.79	0.42	0.23	47	980
MnS	6.90	6.78	0.44	0.24	48	975

Table 4-2: Tensile Properties of mixes produced under Nominal production conditions.

Mix	Green Density (g/cm^3)	YS (MPa)	UTS (MPa)	Elongation (%)
No Add	6.9	405	485	1.3
MnS	6.9	400	460	1.2

Furthermore, Figure 4-1 shows that there was no observable trend when looking at the mechanical properties of sintered products regardless of production scenario. Exposed Green parts did show small levels of rusting, but these areas of Fe_2O_3 were then reduced and eliminated during sintering leaving a largely unaffected sintered product. Alternatively, while the MnS samples produced in the Exposed Sintered state did show an increased propensity for part rusting, mechanical properties were unaffected.

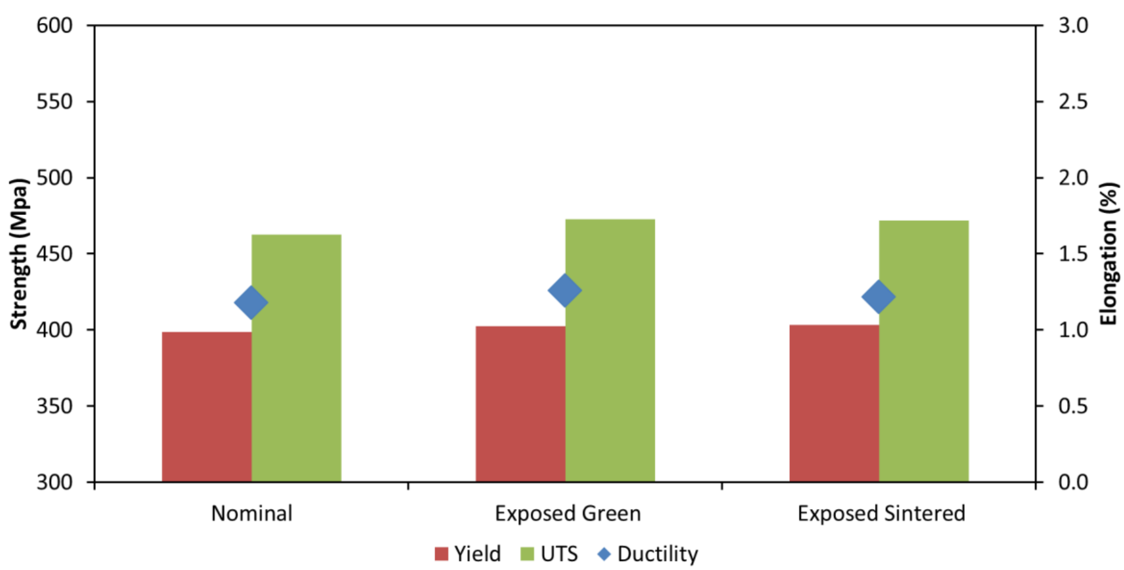

Figure 4-1: Effect of production scenario on MnS containing components.

4.2. Effect of Moisture Exposure on Machinability

In order to assess the impact that moisture exposure has on different production scenarios and thus exposure timing, it is first important that a baseline set of data be produced. No Add and MnS powders were used to produce parts for machining. In order to prevent any uncontrolled moisture exposure, samples were stored in closed containers with desiccant in both the green and sintered state until machined.

As expected for the Nominal scenario, and seen in Figure 4-2, when no coolant was used during the drilling operation, the components produced with No Add failed after a very limited number of holes. Contrarily, the samples produced with MnS showed limited drill bit wear (low slope of reduction in hole diameter) and met the run out condition of 990 holes drilled.

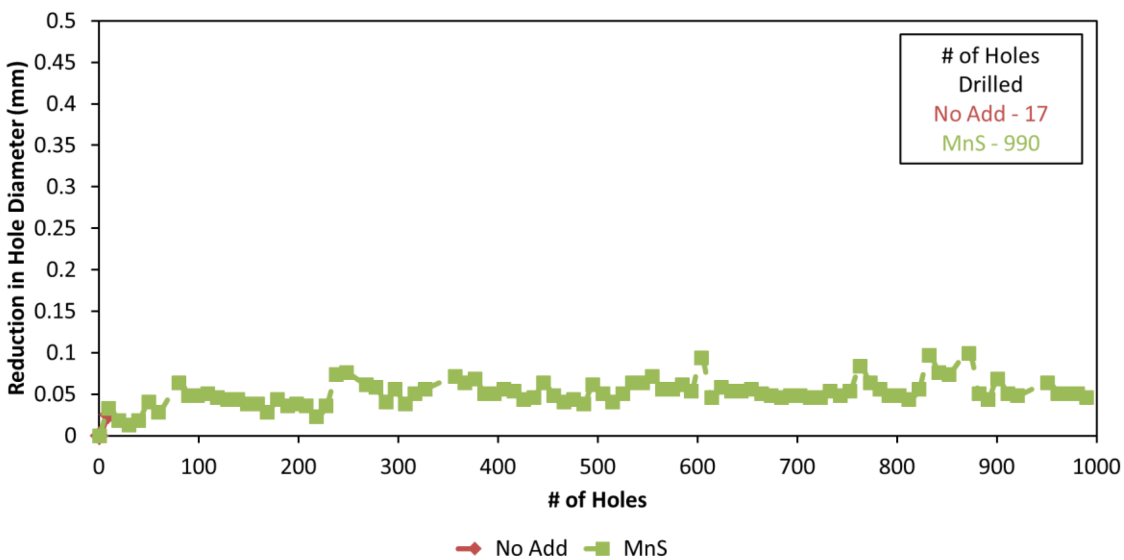

Figure 4-2: Drilling response of nominally sintered components under dry cutting conditions

Alternatively and again as expected and in line with previous work, when samples were drilled with coolant, the No Add components showed increased tool life while MnS containing components reacted negatively. Beyond the change in tool life, there was also a clear change in the wear dynamics of the drill bit as seen by a change in the slope of the graph (Figure 4-3). In this scenario, it can be seen that although the MnS mix still outperformed the No Add components in terms of tool life, depending on the end part specification, tolerances may become an issue.

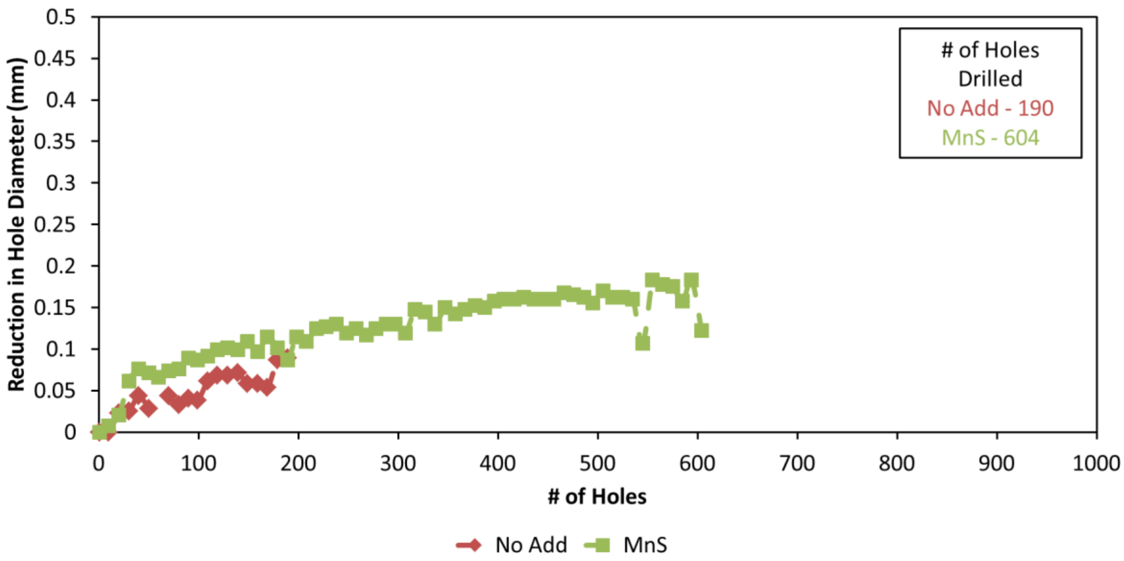

Figure 4-3: Drilling response of nominally sintered components under coolant cutting conditions

Now that a baseline machinability response was established under the Nominal production scenario, the effect of part exposure was investigated. Table 4-3 shows the number of holes drilled after exposure was conducted in accordance to both production scenarios when drilling was conducted dry.

Interestingly, when parts were produced in accordance with the Exposed Green scenario, no observable change in the machining response of the components was observed. Alternatively, in both sample sets produced in accordance with the Exposed Sintered condition, drastically different tool life was observed.

Here, the No Add components showed an increased machinability response in the Exposed Sintered state in comparison to the other exposure conditions. A similarly drastic, but opposite effect was observed for the MnS components; here the machining response was greatly decreased in the Exposed Sintered state in comparison to that of the other production scenarios.

Table 4-3: Number of holes drilled under dry conditions

	Production Scenario		
Mix	**Nominal**	**Exposed Green**	**Exposed Sintered**
No Add	17	14	174
MnS	990	990	244

A similar trend was also observed when the looking at the machining response of both mixes when processed under coolant conditions as seen in Table 4-4. No significant difference was again found between the Nominal and Exposed Green production scenarios. In the MnS samples, machinability again decreased in the Exposed Sintered condition.

Table 4-4: Number of holes drilled under coolant conditions

	Production Scenario		
Mix	**Nominal**	**Exposed Green**	**Exposed Sintered**
No Add	190	184	213
MnS	604	511	253

When looking at the trends observed in both Table 4-3 and Table 4-4, two additional observations are noted. The No Add, dry machined, sample in the Exposed Sintered condition (174 holes), had a similar tool life compared to the No Add, Nominal samples when machined with coolant (190 holes). The second observation is that the MnS samples in the Exposed Sintered condition had similar tool life regardless of coolant condition (244 holes and 253 holes).

The different machining behavior of the Exposed Sintered, no coolant samples can be explained by two opposing effects. Firstly, the No Add components pick up moisture throughout the open pore network structure when produced in this production scenario. This moisture pickup is likely keeping the component and tool cooler when processed and doubling as a lubricant similarly to that of coolant being added. The result of this internal lubrication is an increase in tool life. Limited internal oxidation may also have a beneficial effect, although none was visually apparent.

Alternatively, with the MnS components, the same moisture pickup has allowed for the MnS powder contained within to begin to degrade. This same degradation is observed when the nominally produced samples were machined under coolant conditions but in this circumstance, time did not allow for the same level of degradation to occur.

The very different response of both mixes to the varying exposure production scenarios can be explained by the state of the pore network in the parts. Since both sets of products were exposed to the same moisture levels during production, then the atmosphere itself can be ruled out. Instead, it is not the exposure to, but the interaction between the moisture containing atmosphere and the part that has changed.

This change in machinability performance and the lack of effect on the Exposed Green samples can be explained by the fact that the product contains wax (present as lubricant). Due to the presence of wax that has not been burned out yet, and thus a more closed pore network, the moisture was unable to interact with the MnS and iron internally in the part. It is theorized that if MnS containing sintered samples were produced with a closed pore network (ex. high density or surface impregnated with resin or oil) and subsequently exposed to moisture a different trend would be observed.

5. CONCLUSIONS

- No observable impact on the mechanical material properties was observed with different moisture exposure conditions in either the no additive or MnS containing samples.
- The machinability of the as-sintered samples (Nominal) and the green samples that were exposed to humidity (Green Exposed) were very similar. Exposure of green parts to moisture appears to have very little effect on the MnS within the compact.
- The machinability of the sintered samples that were exposed to humidity (Sinter Exposed) significantly changed compared with the other two production scenario conditions. Drillability of the samples containing MnS decreased while the drillability of the no additive samples improved.
- Timing of moisture exposure and thus production planning can have a great impact on the machinability performance of products.

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