Additives for Improved Machining of Copper PM Steels

Bruce Lindsley\(^1\) and Craig Stringer\(^2\)

\(^1\)Hoeganaes Corporation Cinnaminson, NJ 08077

\(^2\)Pennsylvania State University, DuBois PA 15801

*Presented at PowderMet 2012
Nashville, TN June 10-13*

**ABSTRACT**

Copper-containing PM alloys are the most widely used PM steels on the market. As such, there are many applications that utilize these alloys and require secondary machining, such as connecting rods and VVT components. Machinability additives can be easily admixed into the powder to improve cutting performance of the final part. The expectation of a machinability additive is to improve machining, be non-reactive and have no negative effect on the mechanical properties of the component. This paper discusses the effect of several additives on both the drilling and turning performance of iron-copper-carbon PM steels.

**INTRODUCTION**

Machinability is an important consideration in the production of many ferrous PM components. While PM structural part manufacturing is generally considered a net or near net shape process, machining to achieve high precision features has become necessary in certain applications, such as VVT components. Additionally, certain features, such as transverse holes and undercuts, can not be compacted using conventional press technology. The machinability of PM steels differs from that of wrought steel due to the presence of porosity and the often heterogeneous microstructure [1]. To achieve similar strengths as wrought products, PM alloys typically contain higher levels of carbon ranging from 0.5 to 0.8% sintered carbon. 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. Additions of up to 2% copper in steels greatly strengthen the ferrite phase and further reduce machinability. Higher additions of copper in conventionally sintered parts will leave some free copper in the part and will result in an improvement in machinability. Copper-infiltration is an extreme example of free copper in parts and is generally accepted as a highly machinable production route. FC-0208, with nominally 0.8% sintered carbon and 2% copper, falls within the group of higher carbon, little to no free-copper, difficult to machine alloys.

PM, however, has the advantage of being able to admix materials into ferrous alloys, and both powder producers and part makers have taken advantage of this ability by incorporating machinability additives
such as MnS into the steel. These free-machining additives improve machinability by assisting in chip formation, lubrication of the tool face and reduction of both flank and crater wear [1]. MnS is used extensively in wrought free-machining grade steels. During the cutting process, MnS deforms along the shear plane, reduces tool contact time, and forms a lubricating layer on the tool [2]. Many studies have shown the benefits of MnS additions to the machinability of PM steels [1,3-8]. While manganese sulfide has many beneficial attributes, it has some limitations and potentially negative effects. The use of MnS may damage the sintering furnace through the production of a sulfur containing gas [3]. High humidity environments can quickly oxidize the MnS and deteriorate the machinability enhancing properties [5,6]. In addition, MnS becomes less effective as alloy content increases [7,8].

An additive (designated MA) was introduced by Hoeganaes Corporation prior to 2006 to improve the machinability of PM steels. The additive is chemically inert and therefore reduces the tendency for rusting compared with MnS [8]. This additive was found to be particularly effective in sinter-hardened steels, especially when advanced tool materials, such as multi layered coated carbide and boron nitride, are used [8]. More recent data has shown that this additive is also effective in Fe-Cu-C alloys [9]. In this study, the machining behavior of FC-0208 was investigated with no machining additive and the addition of MnS, MA, or hexagonal boron nitride (hBN). The benefits of each additive are discussed under several different processing conditions.

EXPERIMENTAL PROCEDURE

The FC-0208 alloy studied was made using a commercially available base iron (Ancorsteel® 1000B) to which 2% atomized copper (AcuPowder 8081), 0.85% graphite (Asbury 3203) and 0.75% EBS wax (Lanza AcrawaxC) was added. Within each set of experiments, a large master mix of FC-0208 was produced from which sublots containing machining additives were produced. This was done to minimize variables that could affect machinability outside of the machining additives. The additives studied were MnS, MA and hBN. Two particle sizes of MnS are available from ARC Metals (MnS with a d50 of 5 μm and MnS 75A with a d50 of 8 μm) and both were tested. Rings measuring nominally 45 mm (1.75 inch) outer diameter, 25 mm (1 inch) inner diameter and 32 mm (1.25 inch) tall were compacted to 6.9 g/cm³ density on a 140 ton Dorst press and sintered in an Abbott belt furnace at 1120 °C (2050 °F) in 90% N₂ – 10% H₂ atmosphere. Time in the hot zone was 45 minutes. Pucks measuring 45 mm (1.75 inch) diameter and 32 mm (1.25 inch) tall were also compacted to 6.9 g/cm³ density from the same premixes and sintered with the rings. The sintered density of the compacts was nominally 6.8 g/cm³.

Turning studies were run using a 0.25 mm (0.01 inch) depth of cut and 0.25 mm (0.01 inch) feed at different cutting speeds: 76 surface meters per minute (250 surface feet per minute), 152 smpm (500 sfm), 229 smpm (750 sfm), 308 smpm (1000 sfm) and 381 smpm (1250 sfm). 25 cuts were made on each puck so that final diameter of a machined puck was nominally 32 mm (1.25 inch). The turning tests were run using a Haas ST-10 CNC lathe with no coolant. Machinability was measured in several ways. Flank wear on the tool was measured and documented at select intervals. Additionally, the diameter of the machined ring was measured after the first and last pass using an automated probe within the lathe. An increase in machined part diameter over several parts is an indicator of tool wear. Finally, the temperature of the machined ring was measured using a contact thermocouple after every 25 cuts to assess if worn tools result in more frictional / adiabatic heating. The tool used in this experiment was an alumina-TiCN coated carbide insert (Kennametal KCP25) with an insert geometry of CNMG 432 FN.

The machinability of the mixes was also evaluated by drilling on a HAAS VF-20 Vertical CNC Mill. Thirty three holes 25 mm deep were drilled into each puck in a pattern such that the hole being drilled was not next to the previous hole drilled. The drill was a bright polished high speed steel with a 28.6 mm
(1.125 inch) flute length regular spiral and a 118° tip angle. The diameter was 4.8 mm (3/16”) and a speed of 1250 rpm and feed of 0.15 mm/revolution (0.006”/rev) was used. Drills were run to failure or until all of the samples were used. An average of three tests was used for the samples that exhibited drill failure. Again, no coolant was used during the test.

RESULTS AND DISCUSSION

Turning
The initial turning tests were run at a cutting speed of 229 surface meters per minute (750 sfm) and it was found that FC-0208 with no additive caused failure of the tool after 500 cuts. Figure 1 shows the change in final part diameter with increasing number of cuts and the no additive sample (in red) exhibited a rapid change in diameter as the tool began to fail beyond 400 cuts. Both of the MnS-containing samples and the MA-containing sample resulted in improved tool wear, as 1500 cuts were successfully made and the change in diameter of the part was quite small. It can be seen in Table I that the slope of part diameter vs number of cuts is greatly reduced with the addition of these three additives. The slope of the no additive sample was measured prior to the rapid change in part diameter at 425 cuts. Finally, the sample containing 0.08% hBN showed very rapid wear, with tool failure occurring with less than 300 cuts made. It should be noted that some of the data sets in Figure 1 were vertically shifted so that the data points did not overlap. The use of different additives in FC-0208 test rings did not result in a difference in the diameter of the first machined part.

![Figure 1. Change in part diameter at 229 smpm (750 sfm). Diameter measured every 25 cuts. Curves have been vertically offset for improved observation.](image)

Table I. Slope of the change in diameter per 25 cuts

<table>
<thead>
<tr>
<th>Additive</th>
<th>Slope (mm/25 cuts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Add</td>
<td>14.1 x 10^{-4}</td>
</tr>
<tr>
<td>0.3% MA</td>
<td>4.45 x 10^{-4}</td>
</tr>
<tr>
<td>0.35% MnS</td>
<td>4.40 x 10^{-4}</td>
</tr>
<tr>
<td>0.35% MnS 75A</td>
<td>5.53 x 10^{-4}</td>
</tr>
<tr>
<td>0.08% hBN</td>
<td></td>
</tr>
</tbody>
</table>
The temperature of the machined rings was measured immediately after cutting and is shown in Figure 2 for the 5 additive conditions. As the cutting tools wore, the surface temperature of the rings increased due to increased friction. For the no additive sample, the temperature steadily increased to 425 cuts and then suddenly increased to much higher temperatures. This corresponds with the abrupt change in part diameter in Figure 1 and suggests failure of the tool. The sample containing hBN also exhibits a rapid increase in part temperature and again alignment can be seen between the part diameter change and the temperature. The sample containing MA shows a slow, steady increase in the part temperature and is approximately 25 °C hotter than either of the MnS-containing samples. The lower part temperature of the MnS samples suggests that MnS has improved lubricity, resulting in less frictional heating. Although no effort was made to measure the temperature of the tool itself, it is likely that a hotter part is an indicator of a hotter temperature at the tip of the insert. Tooling with poor resistance to thermal changes may not work as well with MA additive relative to MnS. Heating of the ring came from two sources: the cutting operation and the mandrel holding the ring. The temperature of this mandrel increased during the tests from the warm ring being machined and then transferred some of this heat to the next part being tested. The periodic drop in sample temperature is related to the machine sitting idle while the wear on the tool was being measured.

Flank wear on the tool was measured using a Leica stereoscope and Clemex imaging software after every 50, 100, 300, 600, 900, 1200 and 1500 cuts. Additional measurements were made when rapid wear of the tool was observed. Figure 3 illustrates the tool wear at 750 sfm for all five materials. The length of the wear scar increased rapidly with both the no additive and the hBN sample, while both MnS samples and the MA sample showed a lower, predictable wear rate. The resultant wear scar with the MnS samples was slightly shorter than that of the MA sample, so abrasive wear is marginally lower with MnS.

Figure 2. Final part temperature measured after every 25 cuts.
Upon examination of the tool, it is clear why the no additive and the hBN samples exhibited a dramatic increase in part diameter and temperature. Figures 4 A and D show failure of the tool tip where both the coating and pieces of the underlying carbide have been removed. The maximum flank wear is quite large in these samples and it was determined that tool failure typically occurred when the flank wear reached a length of approximately \(300 \, \mu m\). Although not shown here, crater wear was also observed in both the no additive and hBN samples as well. The sample containing MA additive (B) exhibits a uniform wear scar of 170 \(\mu m\), indicating consistent tool wear during the test. No cratering was observed on the adjacent face. Finally, the sample containing MnS (C) has a similar wear scar length to the MA sample but developed grooves in the cutting tool throughout the test. Similar grooves were found with the coarser MnS grade and also during a repeat test. It is unclear how or why these grooves occur, but their presence was found to have a significant effect on the surface roughness of the parts. Table II shows the surface roughness of machined ring 1 (25 cuts) and ring 60 (1500 cuts). The no additive, MA and MnS samples had an Ra value near 1.9 \(\mu m\) after 25 cuts, while the hBN sample was lower at 1.65 \(\mu m\). This lower value may be due to the significant tool wear that occurred after 25 cuts with this sample. After 1500 cuts, a large difference in the MnS and MA samples was measured. The roughness of the MA sample decreased to 1.4 \(\mu m\) while the MnS sample significantly increased to 2.8 \(\mu m\). As surface finish is often used as a measure of tool life, the MnS did not perform as well as the MA using this criterion.
Table II. Surface roughness Ra (in $\mu$m) of the first and last ring for the four materials tested.

<table>
<thead>
<tr>
<th>Sample</th>
<th>No Additive</th>
<th>0.3% MA</th>
<th>0.35% MnS</th>
<th>0.08% hBN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring 1 (25 cuts)</td>
<td>1.94</td>
<td>1.96</td>
<td>1.88</td>
<td>1.65</td>
</tr>
<tr>
<td>Final Ring (1500 cuts)</td>
<td>Failure at 500 cuts</td>
<td>1.40</td>
<td>2.82</td>
<td>Failure at 250 cuts</td>
</tr>
</tbody>
</table>

Effect of Cutting Speed

The influence of machining additives with changing cutting speed was investigated for the no additive, MA and MnS compositions. Five speeds were investigated with the no additive material and it was found that tool failure occurred at all but the slowest speed (see Figure 5). Rapid tool wear was observed at cutting speeds from 500 sfm to 1250 sfm and only at the lowest speed of 250 sfm did the tool survive 1500 cuts.

Greater tool life and productivity was found with the mixes containing either MA or MnS. Good tool life was attained between 500 and 1000 sfm for the MA-containing mix, indicating that upwards of four times productivity can be obtained under the conditions tested (Figure 6). It is interesting to note that the 750
and 1000 sfm conditions resulted in lower tool wear than the 500 sfm condition, pointing to a machining ‘sweet spot’ for this composition at these speeds. More rapid wear was discovered at 1250 sfm and grooves were observed on the tool cutting surface. Tool life at 1250 sfm was still better than the no additive sample at 500 sfm and above. The 250 sfm condition was not tested due to the good results at higher speeds. Little difference in sample temperature was noted at the different speeds with the exception of 1250 sfm at 700+ cuts as the tool approached failure. Sample temperature appears to be a strong function of additive composition rather than cutting speed.

Samples containing MnS 75A were tested at 500, 750 and 1250 sfm and low tool wear was obtained at all three speeds (Figure 7). Virtually no difference in tool wear or sample temperature was observed at the different speeds, and under the conditions tested, samples containing MnS could be machined over a wider range of speeds as compared with the MA additive. Slightly lower tool wear was observed with MnS as compared with MA, although the change in part diameter for both additives over the 1500 cuts was similar. For MnS, the average change in part diameter over 1500 cuts for all three speeds was 43.5 μm (0.0017 inch), and for MA, the average change in diameter for speeds 500, 750 and 1000 sfm was 44.0 μm (0.0017 inch). Surface finish was not measured at speeds other than 750 sfm, so it is unknown if the surface finish remains an issue with MnS at alternate speeds. Grooves in the cutting tool were observed at 500 sfm, so it is likely surface finish remains an issue at this speed, whereas no grooves were noted at 1250 sfm and the surface finish most likely improved.

![Figure 5. Tool wear at various cutting speeds after machining FC-0208 with no machining additive](image)
Figure 6. Tool wear at various cutting speeds after machining FC-0208 with 0.3% MA additive

Figure 7. Tool wear at various cutting speeds after machining FC-0208 with 0.35% MnS additive
Drilling
Blind holes were drilled into the sintered pucks until either drill failure or when consumption of all of the samples occurred. Drill failure was characterized as a drill fracture. Figure 8 reveals that samples with no machining additive addition failed within 25 holes cut. The sample with MA additive was only slightly better, with an average of 40 holes drilled prior to failure. Given the turning results above, it was somewhat surprising to find that the boron nitride containing sample performed significantly better than the no additive sample, with an average of over 300 holes cut per drill bit. This sample exhibited a large variation in number of holes cut, ranging from 196 to 462. Finally, the manganese sulfide containing samples demonstrated superior drillability, with both particle sizes resulting in no tool failure after 1000+ holes at 1250 rpm and 495+ holes at 1500 rpm.

Figure 8. Drilling test results showing holes to failure at 1250 rpm. Both MnS particle sizes were tested and yielded similar results. The MnS** samples were tested at 1500 rpm.

To better understand the different behaviors displayed in the Figure 8, drilled holes were cross-sectioned and imaged on the SEM. The depth of cut per revolution is apparent at the top end of the first hole drilled before any tool wear occurred, Figure 9. This is present in all materials tested. However, this feature quickly disappears for most of the materials. Figure 10 presents the surface of the hole at 75% of the test life (75% hole) for the no additive sample, hBN and the MnS sample. The MA sample was not included as it had similar performance and appearance as the no additive condition. The surface appears smeared in the no additive and hBN samples, suggesting that tool wear has occurred and the material along the surface of the hole is deforming instead of being cleanly cut. The MnS sample continues to show the depth of cut lines along the surface, indicating little wear of the tool. The sides of the hole are also straighter, forming a truer hole. The presence of MnS facilitates drilling to a great degree for the conditions tested.
Figure 9. Inner surface of the first hole drilled in the hBN additive sample. The depth of cut striations are apparent.

Figure 10. Inner surface of the 75% hole for the no additive, hBN and the MnS sample.
DISCUSSION

FC-0208 is a difficult alloy to machine due to its fully pearlitic microstructure and the copper strengthening of the ferrite phase. From the limited testing performed within the scope of this paper and from the greater PM literature, not using a machinability enhancer will lead to short tool lives and poor productivity. Of the three additives tested, all showed an improvement in machinability for at least one test type (turning or drilling), but none excelled in all of the machining criteria.

The addition of MA additive to FC-0208 greatly improved the machinability in turning, providing low tool wear rates, good part diameter control and very good surface finish. Compared with the no additive condition, faster cutting speeds appear to be beneficial with this additive, resulting in both higher productivity and longer tool life. There is a cutting speed ‘sweet spot’ at 750 to 1000 sfm with MA and the cutting conditions selected for these experiments. Some testing and optimization of cutting conditions is therefore recommended with the adoption of an MA-containing premix in various applications. As was noted in earlier work, MA additive has the added benefit of no detrimental effect with respect to rusting, whereas MnS is known to accelerate rusting [8]. For turning at speeds of 750 to 1000 sfm, the FC-0208 containing MA had the best all-around performance. However, MA additive provided little benefit to HSS tool life in drilling, so therefore it is only recommended for turning-type applications.

MnS performed well in both turning and drilling, as low tool wear was observed in both operations. In turning, the addition of MnS resulted in good tool life at all cutting speeds, with little dependence on cutting speed on tool wear, part temperature and part diameter. Nevertheless, at the two lower speeds, grooves or channels formed on the cutting surface, resulting in poor surface finish. Higher speed eliminated the formation of these grooves, so MnS was the best performer at 1250 sfm. In drilling, MnS was clearly the best additive and provided far superior tool life and a consistent bore surface finish. For components that undergo multiple machining operations that include drilling, MnS is the best machining additive.

The addition of hBN produced an interesting result, in that it reduced tool life in turning but increased life in drilling. The improvement in drill life has been attributed to the lubricious, layered structure of hBN, which is the reason it is sometimes used as a lubricant. hBN extended tool life relative to no additive or MA, but could not match the performance of MnS. The regular cutting striations found in MnS sample holes quickly disappear in the hBN samples and the surface appears deformed. Nevertheless, hBN produced a tenfold increase in number of holes drilled relative to no additive. The turning results are somewhat puzzling, as earlier unpublished work showed an improvement in tool life with the addition of hBN under similar conditions. It is known that hBN can interfere with carbon adsorption from graphite to iron during sintering [5]. This interference can leave some free graphite that can act as a machining additive itself. The earlier work used a grade of hBN that increased the amount of free graphite, thereby increasing machinability and lowering mechanical properties in the steel. In the current work, a different grade of hBN was selected that did not inhibit carbon adsorption, resulting in a fully pearlitic microstructure with mechanical properties similar to the other samples tested. It is believed that this difference is responsible for the different machining behavior. Therefore, it may not be possible to achieve good turning performance and good mechanical properties with the addition of hBN.

CONCLUSIONS

FC-0208 is a widely used alloy system in PM steels due to its ease of processing, good mechanical properties and cost effectiveness. Machining this alloy, however, can be a challenge. Short tool life was realized in both turning and drilling without the addition of a machinability enhancer. The addition of MA or MnS greatly improved the turning performance of FC-0208. Both productivity and tool life can
be increased with either additive, although MA additive generated superior surface finish. In drilling, the addition of MnS resulted in the best performance, while hBN increased tool life compared with no additive. The addition of MA additive is not recommended for drilling.

ACKNOWLEDGMENTS

The authors would like to thank Jason Gotta of Hoeganaes Corporation for all of his efforts in machining the turning samples and documenting tool wear. The author would also like to thank Fritz Bopp of Sinter Metals Germantown for his surface roughness measurements.

REFERENCES


