Clayton Family Scholarship
Final Report

The effect of machining additives on the microstructure and hardness of PM alloy FC-0208

Elizabeth M. Drummond

Institute for Metal Forming
Lehigh University
Bethlehem, PA USA

July 2013
The effect of machining additives on the microstructure and hardness of PM alloy FC-0208

Elizabeth M. Drummond
Institute for Metal Forming, Lehigh University, Bethlehem, PA USA

Abstract

Machining additives have been used in powder metallurgy (PM) technology to increase the machinability of steels. Improving the machinability of PM steels is very important because it decreases tool wear and lowers the overall cost of PM components that require machining. Many factors affect the strength and machinability of PM steels including porosity, compaction ratio, and sintering, and one way to improve these factors is by machining additives. The machinability of PM steel parts can be improved by increasing the density of the part through a better compaction ratio of the green body and resulting in higher green strength, increasing the density through sintering, and adding additives to the PM steel. These machining additives have a great effect on the machinability and many companies have looked into ways to continue improving the additives. This project is a continuation of previous work of the effect of nine different machining additives on the machinability of the PM alloy FC-0208 steel measured by flank wear in the turning process. The results from the previous work show that all nine of the mixes included in this study increased machinability by approximately the same amount. The current part of the project focuses on material microstructure characterization and hardness values as functions of additives to fully understand the influence they have on the machinability of this PM alloy. The results show that the material characterization was inconclusive compared to the company’s results and the hardness values showed only one mix having lower hardness.
compared to the mix with no additives. However, this result may be detrimental to the mechanical properties of the PM steel because the previous experiment showed all nine mixes having improved machinability, not just one mix. Other experiments and more in depth material characterization will tell the complete effect of the additives. PM is a flexible metallurgical process that can be further enhanced by additives to increase the machinability of the PM parts. This work provides evolving insight into the effect of additives on machinability which can eventually make PM components more advantageous compared to traditional manufacturing techniques.
Table of Contents

Abstract

1. Introduction

2. Experimental Procedure
   2.1 PM alloy and additives
   2.2 Metallographic characterization parameters
   2.3 Hardness parameters and measurements

3. Results and Discussion
   3.1 Metallographic characterization
   3.2 Hardness

4. Conclusion

5. Future Work

Acknowledgements

References
1. Introduction

Additives are important to improve the machinability of PM steels, especially to reduce cost and increase production by decreasing tool wear. PM steel is difficult to machine primarily due to porosity. Machining can be very expensive, especially when the number machining operations increases or the harder the material is. It can cost $0.10 per cm$^3$ of removed material for a small component machining process [1]. Machining also becomes expensive based on the life of the tooling. Harder parts and higher amounts of porosity increase tool wear, two factors found extensively in PM parts. These factors lead to the use of additives to improve machinability and decrease cost.

There are many machining additives that improve PM parts in different ways. Manganese (Mn) is one of the most common additives. In its elemental form, it increases machinability when used in small amounts. Other machining additives are sulfur (S), manganese sulfide (MnS), and molybdenum disulfide (MoS$_2$) which are also very common. Additives such as boron nitride, tellurium, lead, tin, and polymers can also be used. According to the company Hoeganaes Corporation, MnS is the most commonly used additive, but they have developed a new proprietary machining additive, MA, that has comparable performance to MnS. The MnS additives act as internal lubrication to a cutting tool [2]. The research Hoeganaes Corporation conducted on MnS and MA were compared to a part with no additives. The conditions tested were no additive, 0.25% MnS, 0.35% MnS, and 0.3% MA. Although both additives decreased tool wear and increased the machinability of the PM parts, 0.35% MnS increased the machinability the most [2]. The mechanical properties of the alloy were not affected by either of the additives. By controlling the cooling rate after sintering, it was determined that the amount of martensite and bainite present can be controlled. It is more beneficial, with regards to
machinability, for the microstructure to have less martensite because martensite is such a hard phase. The value of machinability is measured in many different ways because there is no precise definition of machinability. Therefore, there are many ways of assessing machinability. Machinability is, however, understood to be influenced by the level of porosity, the microstructure features, and hardness values.

Figure 1: Graph of flank wear measurements vs. number of cuts for all mixes. Graph shows results from the previous part of the project [3].

The results from the previous experiment on this alloy are shown in Figure 1. Figure 1 shows that all nine mixes improved machinability by approximately the same amount. The work presented in this report will attempt to elaborate on the previous results and understand how the additives alter the material structure to achieve this increase in machinability.
2. Experimental procedure

2.1 PM alloy and additives

Hoeganaes Corporation supplied the powder metal alloy components used in the experiment. The steel alloy is FC-0208 and the nominal composition is shown in Table 1. The components given by Hoeganaes are cylindrical pucks that have a height of 1.25 inches (31.75 mm), an outer diameter of 1.75 inches (44.45 mm), and an inner diameter of 1 inch (25.44 mm). Since the experiment is a continuation of a previous experiment, the outer diameter is 1.25 inches (31.75 mm) after a reduction in the outer diameter through turning [1].

Table 1: The nominal composition of the PM alloy FC-0208

<table>
<thead>
<tr>
<th>Element</th>
<th>Mn</th>
<th>Cu</th>
<th>C</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight Percent</td>
<td>0.1%</td>
<td>0.2%</td>
<td>0.8%</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Ten different mixes were provided for analysis. Mix 1 does not have any additives and will serve as a comparison in results and discussion. The rest of the mixes, 2-9, vary in chemical composition of the additives as well as the amount of each additive. There are 50 samples of each mix. Each went through the turning process in the previous experiment. The same tool was used to machine each mix, gradually wearing throughout cutting, until the final puck 50.

2.2 Metallographic characterization parameters

Metallographic analysis of sample 1 and sample 50 from the mixes were examined under Light Optical Microscopy (LOM) to determine whether or not the microstructure changed from being machined with a new cutting tool compared to a worn cutting tool, at the edge of the sample. Samples were sectioned and mounted in epoxy to be ground, polished, and etched.
Each sample was ground to 600 grit paper, polished with 1 micron diamond, and etched in 4% picral (4g picric acid and 100 mL ethanol). Extra care was taken in preparing these samples because of their porosity, so the samples were put in an ultrasonic bath in between grinding and polishing and each polishing step. The samples were then viewed under LOM to obtain micrographs of the locations near the edges.

2.3 **Hardness parameters and measurements**

Rockwell A with a load of 60 kg and a Brale (diamond) indenter was used to determine hardness values of two samples from each mix, using ASTM E18-12. The machine was calibrated first using calibration bars from the National Institute for Standards and Technology. For each sample, 10 hardness values were recorded. The samples were ground to 600 grit paper on each side to obtain a smooth and flat surface. Average values were taken for each sample and then calculated using the equation from the calibration curve, to obtain the actual hardness values.

3. **Results and Discussion**

3.1 **Metallographic characterization**

The conclusions for the microstructure of this alloy are limited because the micrographs are showing a much lower level of porosity than exists in comparable samples. This conclusion was formulated after extensive discussion with research staff from Hoeganaes Corporation, which is very familiar with the studied alloys. The sample preparation has led to false images because sample preparation of ductile metals and alloys can smear sample preparation metal over
pores. Porosity is a very important factor to the machinability of the material and the amount and distribution of the porosity within the PM sample is crucial to the understanding of how the microstructure affects the machinability.

Micrographs of Mixes 1-02, 1-50, 2-01, 2-50, 3-01, and 3-50 were examined. Figures 2-7 show the micrographs of each of these mixes. The micrographs do not seem to show much difference from one to the next. The micrographs were also sent to Hoeganaes, to check on the microstructure and porosity level. Hoeganaes determined that the micrographs did not show representative level of porosity. This could have been a result of the sample preparation in which the pores could have been smeared. Nevertheless, after hearing back from Hoeganaes, it was determined to look at the hardness values of these samples as more independent material characteristic from sample preparation.

![Figure 2: Micrograph of Mix 1-02 Edge](image-url)
Figure 3: Micrograph of Mix 1-50 Edge

Figure 4: Micrograph of Mix 2-01 Edge
Figure 5: Micrograph of Mix 2-50 Edge

Figure 6: Micrograph of Mix 3-01 Edge
Figure 7: Micrograph of Mix 3-50 Edge
3.2 Hardness

A calibration hardness curve was determined first, as shown in Figure 8. The calibration curve was determined by using calibration bars (HRA) of 48.9±1.0, 72.9±1.0, and 84.1±0.5. Once the calibration was plotted, Equation (1) was determined as the linear fit line and used to calculate the actual hardness values for all of the mixes.

\[ y = 0.9831x + 1.8878 \]  \hspace{1cm} (1)

Table 2 shows the average hardness values for the two samples of each mix. Table 2 also shows the actual hardness values calculated using Equation (1). Table 3 shows the average of the two samples of each mix from Table 2. The data in Table 3 was then plotted, as shown in Figure 9.
Table 2: Average hardness value of the samples tested and the actual hardness values calculated using Equation (1).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average Values</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-11</td>
<td>49.16</td>
<td>50.22</td>
</tr>
<tr>
<td>1-42</td>
<td>49.50</td>
<td>50.55</td>
</tr>
<tr>
<td>2-05</td>
<td>50.58</td>
<td>51.61</td>
</tr>
<tr>
<td>2-45</td>
<td>50.91</td>
<td>51.94</td>
</tr>
<tr>
<td>3-02</td>
<td>50.96</td>
<td>51.99</td>
</tr>
<tr>
<td>3-39</td>
<td>51.04</td>
<td>52.07</td>
</tr>
<tr>
<td>4-04</td>
<td>50.70</td>
<td>51.73</td>
</tr>
<tr>
<td>4-42</td>
<td>51.25</td>
<td>52.27</td>
</tr>
<tr>
<td>5-03</td>
<td>42.75</td>
<td>43.92</td>
</tr>
<tr>
<td>5-45</td>
<td>42.66</td>
<td>43.83</td>
</tr>
<tr>
<td>6-01</td>
<td>51.85</td>
<td>52.86</td>
</tr>
<tr>
<td>6-50</td>
<td>48.72</td>
<td>49.78</td>
</tr>
<tr>
<td>7-06</td>
<td>51.07</td>
<td>52.09</td>
</tr>
<tr>
<td>7-37</td>
<td>51.05</td>
<td>52.08</td>
</tr>
<tr>
<td>8-05</td>
<td>50.79</td>
<td>51.82</td>
</tr>
<tr>
<td>8-50</td>
<td>50.92</td>
<td>51.95</td>
</tr>
<tr>
<td>9-03</td>
<td>50.41</td>
<td>50.45</td>
</tr>
<tr>
<td>9-44</td>
<td>51.29</td>
<td>52.31</td>
</tr>
<tr>
<td>10-04</td>
<td>49.64</td>
<td>50.69</td>
</tr>
<tr>
<td>10-45</td>
<td>50.43</td>
<td>51.47</td>
</tr>
</tbody>
</table>

Table 3: Average actual hardness values for each of the 10 mixes.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix 1</td>
<td>50.385</td>
</tr>
<tr>
<td>Mix 2</td>
<td>51.775</td>
</tr>
<tr>
<td>Mix 3</td>
<td>52.030</td>
</tr>
<tr>
<td>Mix 4</td>
<td>52.000</td>
</tr>
<tr>
<td>Mix 5</td>
<td>43.875</td>
</tr>
<tr>
<td>Mix 6</td>
<td>51.320</td>
</tr>
<tr>
<td>Mix 7</td>
<td>52.085</td>
</tr>
<tr>
<td>Mix 8</td>
<td>51.885</td>
</tr>
<tr>
<td>Mix 9</td>
<td>51.380</td>
</tr>
<tr>
<td>Mix 10</td>
<td>51.080</td>
</tr>
</tbody>
</table>
Figure 9: Plot of the actual hardness value of each mix. Solid line shows the hardness value of Mix 1 for comparison to the other mixes.

Figure 9 shows the comparison of the hardness value of each mix compared to Mix 1, which has no additives. The horizontal line going through Mix 1’s hardness value is for a visual representation of the comparison of the ten mixes. These hardness values were used to determine a change in machinability based on the hardness value of Mix 1. A greater hardness value generally leads to a decrease in machinability. As shown in Figure 9, all of the mixes except Mix 5 have higher hardness values than Mix 1. This means that every mix, except Mix 5, does not have a combination of additives that increased the machinability, using hardness as a metric. Mix 5, as shown by this data, is the only mix that increases the machinability of the part because the composition and additives resulted in a lower hardness value than Mix 1.

These results oppose the results found in the previous experiment involving turning in which all of the mixes improved machinability by approximately the same amount. This opposition shows more clearly how difficult it is to determine and analyze machinability of PM
steel. Although Mix 5 lowered hardness, it may actually be an unfavorable mix because it lowered a desirable mechanical property, hardness.

4. Conclusions

Nine mixes of unknown varying compositions and additives were examined and compared to a mix with no additives to determine the effect of machining additives on the microstructure, hardness, and machinability of the PM steel alloy FC-0208:

1. The microstructure analysis was inconclusive based on confirmation from Hoeganaes Corporation about the porosity level presented in micrographs being significantly lower than their expectation in samples, which could be due to specific sample preparation.

2. Mix 5 was the only mix to show a decrease in hardness value compared to Mix 1 referring to an increase in machinability. However, comparing the results of the previous experiment, Mix 5 may actually be a poor machining additive due to its detrimental effect on the mechanical properties of the component; this is especially of note because all of the other mixes showed an increase in machinability from the turning experiment without decreasing hardness.

3. Machinability is difficult to define as well as complex to analyze due to the sheer number of influential factors.
5. Future Work

Future work may have to be done on the material characterization to obtain a better understanding of the microstructure at the edges. Although much progress was made in this work on the preparation of PM components, the procedure used for this work is still not ideal to examined PM microstructures. A better understanding of the porosity and microstructure will come from this and therefore the machinability. A better or new method of sample preparation for the PM steel will have to be used or developed to avoid false micrographs and results.

Acknowledgements

The author would like to thank the Center for Powder Metallurgy Technology for funding this research project and sparking an interest in powder metallurgy. The author is grateful for the help and guidance of Professor Wojciech Z. Misiolek, Loewy Professor in the Institute for Metal Forming at Lehigh University and thankful in his work to organize this research project. The author would also like to thank Anthony P. Ventura for the continual help throughout the research project when questions arose. The collaboration with Dr. Bruce Lindsley from Hoeganaes Corporation, his time spent on discussion of research results and providing samples is also greatly appreciated by the author.
References


July 31, 2013

James P. Adams
CPMT Headquarters
Director, Technical Services
Metal Powder Industries Federation
105 College Road East
Princeton, NJ 08540-6692

Dear Jim:

I would like to thanks again for a letter of May 13, 2013 from Thomas G. Gasbarre informing me about the continuation of The Clayton Family Scholarship for Studies in Powder Metallurgy for a Lehigh undergraduate student. Elizabeth Drummond is continuing her PM experience this summer working on the additive manufacturing project at TE Connectivity and she will be CPMT student in next academic year. We are making necessary arrangements for her to continue it during an academic year here at Lehigh. There is a good support from TE Connectivity so we are positive that she will be working on additive manufacturing for another year. We do plan to continue working with our industrial partners, which would give our students an excellent exposure to powder metallurgy industry and its challenges.

I would like to express my thanks to you, to Thomas G. Gasbarre and to the Center for P/M Technology for supporting powder metallurgy education among engineering students. I want to personally thank you and Jim Dale for your great guest lecture in my Powder Metallurgy course at Lehigh in the spring semester of 2013. I would like to ask you to join me again in spring 2014 and to talk again about PM to the Metal Processing and Properties class in materials science and to graduate mechanical engineering course called Advanced Manufacturing Science. I hope I can as always count on Jim and Jim.

Sincerely,

Dr. Wojciech Z. Misiolek, FASM
Loewy Professor of Materials Forming and Processing
1. A letter or statement from the student that includes opinions or information based on their studies in powder metallurgy.

My study in Powder Metallurgy has been very well rounded thus far. The research I completed throughout the academic year and the Powder Metallurgy (PM) course I took this past spring semester, I believe, helped me obtain a summer internship at TE Connectivity working on a Direct Metal Laser Sintering (DMLS) project. I was the only student in my year to take the Powder Metallurgy elective course and it was very worthwhile. The course expanded my understanding of PM. The elective course and the research opportunity have sparked an interest in PM. The research was a great opportunity to do lab work on my own and collaborate with the Institute of Metal Forming group at Lehigh University. I learned a great deal from the research and I believe it helped me manage my time better through the semesters. Specifically from my research, I learned that it is very difficult to define and analyze the machinability of the PM steel FC-0208 due to the many factors that can affect machinability, from the material to the test method.

2. A letter or statement from the student’s professor that includes opinions or information based on the students studies in powder metallurgy.

(See attached)

3. Information or a report on co-op or internship programs with a PM related company, if completed.

I am currently interning at TE Connectivity in Harrisburg, PA working on a project involving Direct Metal Laser Sintering (DMLS). My project involves changing process parameters to determine the effect on physical and mechanical properties of the material. The machine has been running Aluminum, Stainless Steel, and Maraging Steel, a tool steel. The project focuses on the tool steel. Different parameters that can be changed are laser power, scanning speed, spot size, and focal distance. The varying experiments I am conducting are surface roughness measurement, tensile tests, metallographic analysis, bend tests, and density. I have learned so much from this internship not just from changing the parameters, but also setting up and running my own build jobs in the DMLS. I have also learned a lot about how to work in a company.

Arrangements are being made between TE Connectivity and Lehigh University to extend my internship experience and to continue my summer project during my senior year under CPMT scholarship at Lehigh.

4. Current GPA.

3.03

5. Future plans for the coming year or upon graduation.
For the coming year, I plan to continue my studies in material science and engineering as a senior. I will be applying to jobs for after graduation. I also hope to continue doing research so I can continue my study of Powder Metallurgy. From my experience so far, I hope I can obtain a job involving additive manufacturing and the study of metals.

6. Any other information relevant to the student’s studies in powder metallurgy.