EFFECTIVENESS OF MACHINABILITY ENHANCER IN RESPONDING THE MACHINING OF COMMON SINTERED FERROUS STEELS

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ABSTRACT

The Fe-Cu-C family of steels are the most common materials used in producing powder metal components. After conventional sintering, these materials feature a microstructure composed of ferrite and pearlite with the diffused carbon content determining the ratio. The structure is also strengthened by copper as substitutional alloying element. As more than 95% of the matrix is constructed by the base iron powder, the chemistry (purity) and manufacturing method of the base iron powder are considered to play important role in the machinability. This study evaluated the machining responses of sintered Fe-Cu-C steels manufactured from different base iron powder grades and graphite additions to understand the contribution of the base iron and the ratio of ferrite and pearlite to the overall machinability. A commercial machining enhancing additive was selected to evaluate its effectiveness in improving the machining of such sintered materials made with the different grades of base iron powder.

INTRODUCTION

As a near-net shape technology, powder metallurgy (PM) not only provides significant advantages in minimizing material and energy waste for mass production of components, but also benefits from flexibility in formulating material compositions for desired microstructures and properties. Despite the near-net shape of PM components, machining is often required to achieve desired dimensional tolerance, surface finish, or features that are unable to be made through the PM processes in an economic way or due to engineering difficulty.

Machining is a complex process. Many variables can influence the machinability of PM components. Table 1 summarizes the factors which are considered to affect the machining of PM materials [1]. For a given PM component, selecting a suitable tool based on the machining operation is important. The machining parameters also require optimization, i.e. find the ‘sweet spot’ in order to achieve maximum tool life and productivity. The machinability of a PM component is also determined by its material composition and the manufacturing route. The most common PM material, for example, the iron-copper-carbon (Fe-Cu-C) family of steels is composed of ferrite and pearlite microstructures after conventional sintering. The amount of diffused carbon determines the ratio of ferrite and pearlite and thus the hardness of matrix. The copper is alloyed into iron to form a stronger and harder matrix. Since the majority of matrix is constructed by a based iron powder, the chemistry (purity) and manufacturing method of a base iron powder are considered to play important role in the machinability.

Table 1: Factors affecting the machining of PM components

PM component	Manufacturing route	Machining
base iron	sintering temperature	type of cutting
alloying elements	sintering atmosphere	type of tool
carbon content	cooling rate	cutting speed
additives	sinter-hardening	cutting depth
microstructures	induction hardening	feed rate
hardness	heat-treatment	dry/wet machining
porosity	steam treatment	

Despite its high purity, a base iron powder used for manufacturing PM components still contains undesirable contaminants, i.e. impurities due to economic and technique limitations of the water atomization process. Such impurities are considered to deteriorate not only the properties of a sintered material but also its machinability. Therefore, it is interesting to investigate the machining responses of a sintered component made with different based iron powder grades.

On the other hand, commercial machining additives are very effective in improving the machinability of PM components, especially with the Fe-Cu-C materials [2~5]. To enhance machining, the machining additives are used to impart benefits such as lubrication, chip breaking and tool protection.
However, not every additive can provide all of these benefits to enhance the machining. Some of them may only work for certain types of materials and/or machining operations. Others may work better in certain ranges of cutting conditions, etc. [6]. As machining is a material removal process, productivity is often a key measurement directly linked to overall machining cost. An effective machining additive can have two approaches to enhance the machining: 1) extending the tool life with the same productivity; 2) increasing productivity with reasonable tool life. Ideally, machining additives are preferred to achieve longer tool life and increased productivity. When a sintered component is made with different base iron powder and contains different carbon content, therefore, it is necessary to investigate the effectiveness of a machinability enhancer in responding the machining of sintered ferrous steels under different machining conditions.

In this study, the machining responses of sintered Fe-Cu-C steels manufactured from different base iron powder grades and graphite additions were evaluated in order to understand the contribution of the base iron and the ratio of ferrite and pearlite to the overall machinability. A commercial machining enhancing additive was selected to evaluate its effectiveness in improving the machining of such sintered materials.

EXPERIMENTAL PROCEDURE

Materials

A common Fe-Cu-C material system (MPIF material code: FC-02xx) with and without machining additive was chosen for evaluations [7]. Commercial machinability enhancer (SM4, North American Höganäs) was added into the mixes to compare with a mix containing no machining additive. For the base iron powder, three commercial water-atomized iron powder grades were selected. Table 2 presents an analysis on the physical properties of these base iron powder grades.

Table 2: Physical properties of the base iron powder grades used in this study

	Base iron	Grade A1	Grade A2	Grade A3
Physical	AD	2.97	3.04	2.96
	flow	24.5	24.5	24.7
	SSA*, m^2/kg	42	35	43
	Particle size**, μm			
	D10	34.0	41.9	30.8
	D50	83.1	95.4	75.0
	D90	170.0	180.2	161.1

*SSA – BET specific surface area; ** measured by laser diffraction method

The base iron powder was mixed with the machining enhancer, copper (Cu-165, AcuPowder International), natural graphite (SW-1651, Asbury Graphite) and lubricant (Acrawax-C, Lonza). The composition of each mix is shown in Table 3. In addition, three levels of the graphite were mixed with one of the commercial base iron powder grades, the machining enhancer, the copper and the lubricant. The composition of each mix is shown in Table 4.

Table 3: Chemical compositions of premixes made with different based iron powder grades

Group	ID	Base iron	Chemical Composition, wt%			
			Cu	Graphite	Lubricant	Additive
FC-0208	**11**	Grade A1	2	0.8	0.75	None
	12	Grade A2	2	0.8	0.75	None
	13	Grade A3	2	0.8	0.75	None
	21	Grade A1	2	0.8	0.75	0.3%SM4
	22	Grade A2	2	0.8	0.75	0.3%SM4
	23	Grade A3	2	0.8	0.75	0.3%SM4

Table 4: Chemical compositions of premixes made with different carbon levels

Group	ID	Base iron	Chemical Composition, wt%			
			Cu	Graphite	Lubricant	Additive
FC-02xx	**11**	Grade A1	2	0.8	0.75	None
	14	Grade A1	2	0.5	0.75	None
	15	Grade A1	2	0.2	0.75	None
	21	Grade A1	2	0.8	0.75	0.3%SM4
	24	Grade A1	2	0.5	0.75	0.3%SM4
	25	Grade A1	2	0.2	0.75	0.3%SM4

Compaction and Sintering

The premixes were compacted into ring specimens with dimensions ϕ55 x ϕ35 x H20 mm at a green density of 6.9 g/cm^3. The specimens were then sintered in a mesh belt furnace at a temperature of 1120 °C (2050 °F) for 20 minutes in an atmosphere of 90% nitrogen and 10% hydrogen with a normal cooling rate of 0.5 °C/s (1°F/s).

Machining Tests

The machining response of the Fe-Cu-C materials was evaluated with the sintered ring specimens in a turning operation. A CNC lathe (Mazak Quick Turn Nexus 200II) was used with a TiAlN coated tungsten carbide insert to cut the inner diameter (ID) of the ring specimen at a cutting speed ranging from 183 to 548 smm (600~1800 sfm). The depth of each cut was 0.5 mm (0.02 in). All tests were performed in dry and wet conditions, i.e. with and without coolant respectively. Machining responses were evaluated by measuring the tool wear after a number of cuts were made using a scanning electron microscope (SEM).

RESULTS

Machining responses of the FC-0208 materials made from different base iron powder grades

The sintered ring specimens were cut in dry and wet conditions respectively. A tool failure in this study was determined when the flank wear of a cutting edge exceeded 200 μm after certain number of cuts were made. Figure 1 presents the number of cuts made at three different cutting speeds when the tool wear reached or exceeded the tool wear limit in dry machining. Different machining responses were observed between the Fe-Cu-C materials made with the three grades of base iron powder. The base iron powder grade A1 (Mix 11) showed the best machinability while the performance of grade A2 (Mix 12) was close to the grade A1. The based iron powder grade A3 (Mix 13) performed the worst. The effect of machining these materials with coolant is shown in Figure 2. Similar tool wear was formed after cutting the same amount of material, i.e. no difference in machinability was observed at the tested cutting speeds. Figure 3 presents the status of tool wear in dry and wet machining.

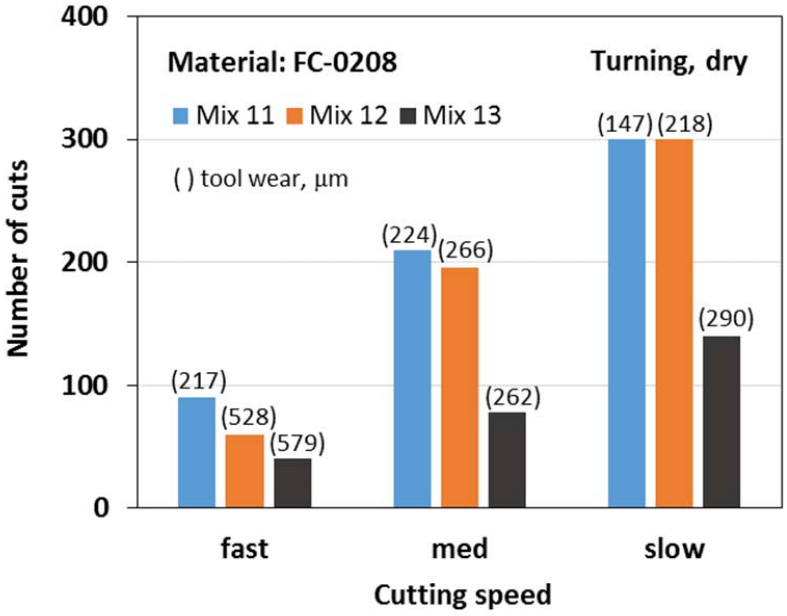


Figure 1. Number of cuts made at different cutting speeds in dry machining. Base iron powder used in the FC-0208 mixes: grade A1 (Mix 11), grade A2 (Mix 12) and grade A3 (Mix 13)

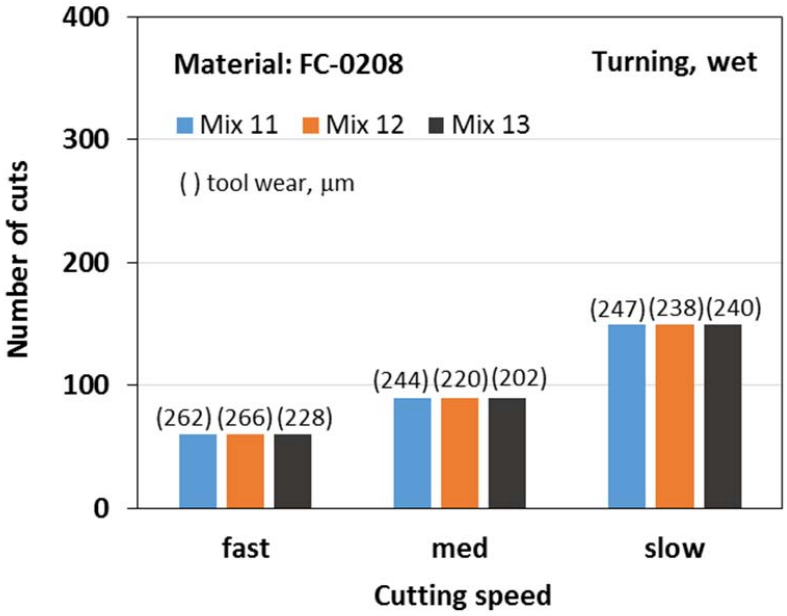
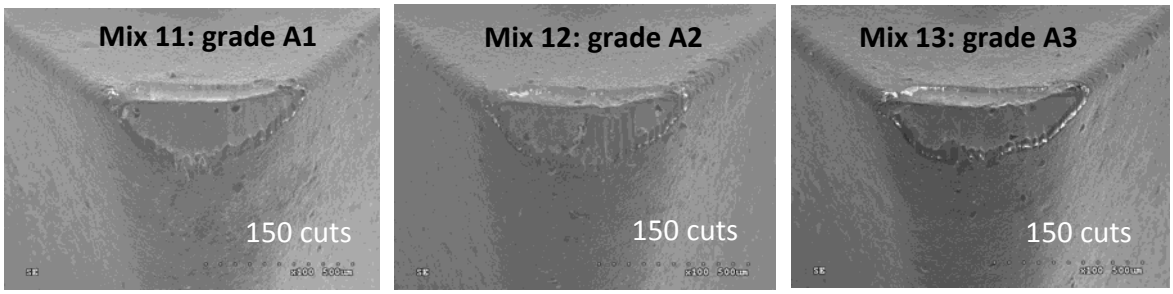


Figure 2. Number of cuts made at different cutting speeds in wet machining. Base iron powder used in the FC-0208 mixes: grade A1 (Mix 11), grade A2 (Mix 12) and grade A3 (Mix 13)



a) Dry machining at slow cutting speed



b) Wet machining at slow cutting speed

Figure 3. Status of tool wear after cutting the FC-0208 materials in dry and wet conditions

Effectiveness of machinability enhancer used in the FC-0208 materials made from different base iron powder grades

Figure 4 presents the machining responses of the FC-0208 materials containing the machinability enhancer SM4 in dry machining. Compared to the machining on the materials without the enhancer (Figure 1), the machinability enhancer significantly improved the machining at all tested cutting speeds with minimal tool wear (53~87 µm). The improvement was effective and consistent for all materials made with the three grades of based iron powder. When the materials were cut in wet condition, as shown in Figure 5, the machinability enhancer also worked effectively and the tool wear was far below the tool failure limit despite more material cutting compared to the materials without the enhancer. With the addition of machinability enhancer, the tool life could be extended 2 times or more at all tested cutting speeds. Figure 6 presents the status of tool wear when cut the materials containing the machinability enhancer in dry and wet machining.

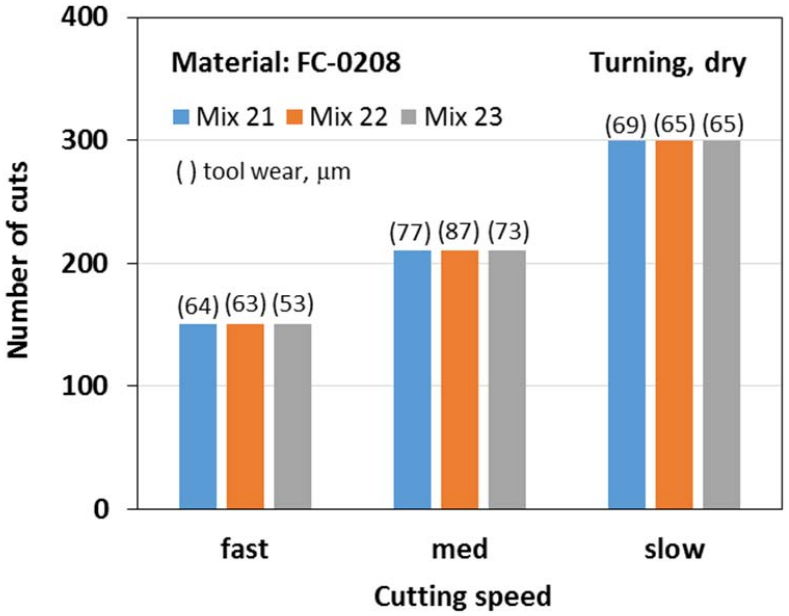


Figure 4. Number of cuts made with machinability enhancer SM4 at different cutting speeds in dry machining. Base iron powder used in the FC-0208 mixes: grade A1 (Mix 21), grade A2 (Mix 22) and grade A3 (Mix 23)

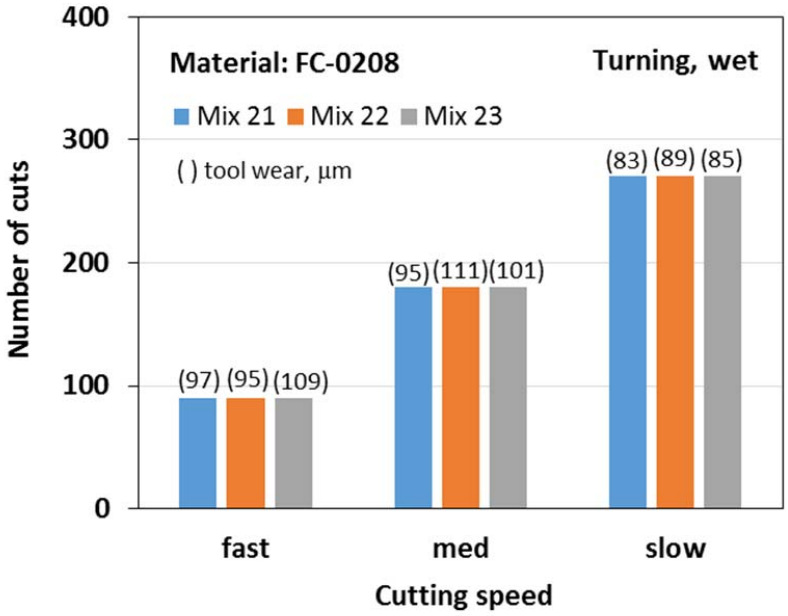
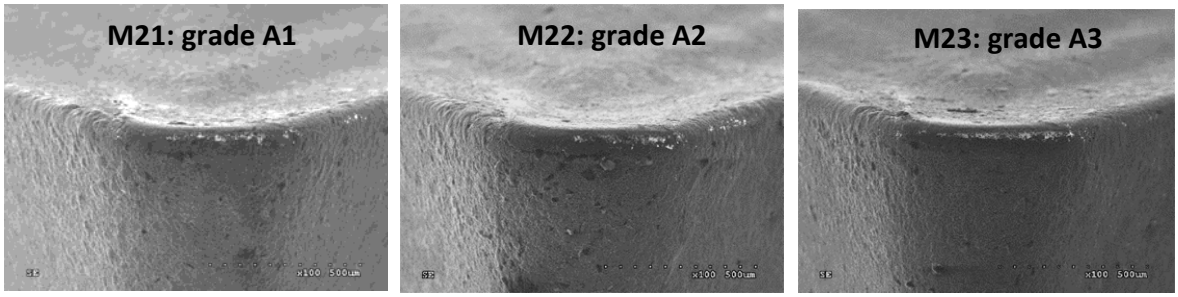
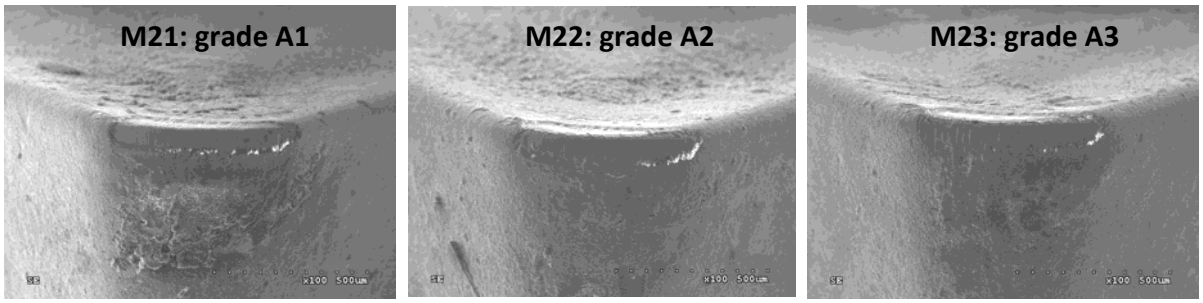


Figure 5. Number of cuts made with machinability enhancer SM4 at different cutting speeds in wet machining. Base iron powder used in the FC-0208 mixes: grade A1 (Mix 21), grade A2 (Mix 22) and grade A3 (Mix 23)



a) Dry machining at fast cutting speed (150 cuts)



b) Wet machining at medium cutting speed (180 cuts)

Figure 6. Status of tool wear after cutting the FC-0208 materials containing machinability enhancer SM4 at fast and medium cutting speeds in dry and wet conditions respectively

Machining responses of the FC-02xx materials made with different carbon levels

According to MPIF Standard 35 [7], the FC-02xx materials with 0.2, 0.5, and 0.8% carbon content can be defined by the following material codes: FC-0200, FC-0205 and FC-0208 respectively. The machinability of the Fe-Cu-C materials with these three levels of carbon content was evaluated at two cutting speeds in dry and wet conditions. The results are presented in Figure 7 and Figure 8. As expected, better machining was achieved with the materials having lower carbon levels (FC-0200 and FC-0205) than with the material having higher carbon level (FC-0208) either in dry machining or in wet machining. However, the machinability was very similar between the FC-0200 and FC-0205 materials. Figure 9 presents the status of tool wear in dry and wet machining.

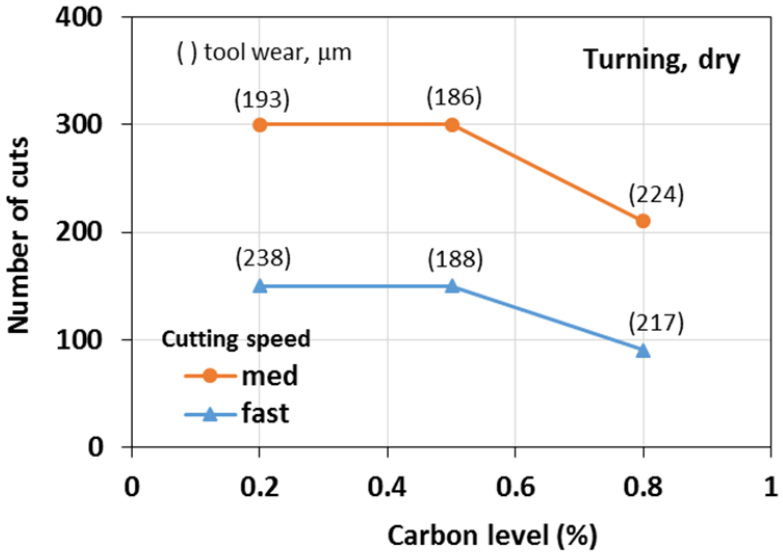


Figure 7. Number of cuts made at different cutting speeds in dry machining of FC-02xx materials

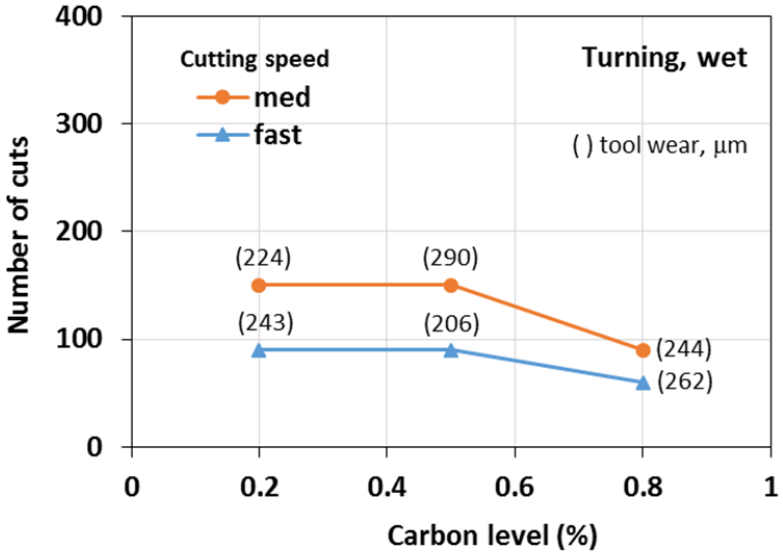
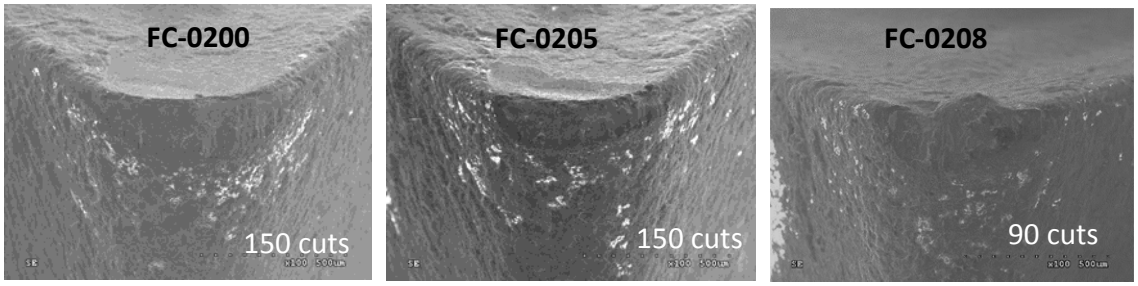
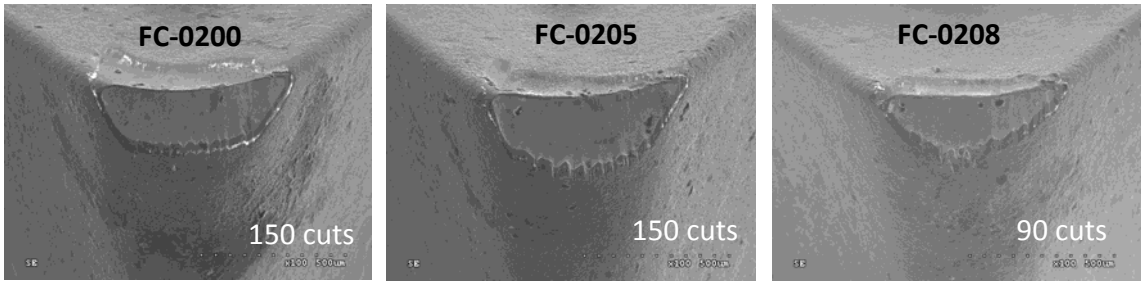


Figure 8. Number of cuts made at different cutting speeds in wet machining of FC-02xx materials



a) Dry machining at fast cutting speed



b) Wet machining at medium cutting speed

Figure 9. Status of tool wear after cutting the FC-02xx materials in dry and wet conditions

Effectiveness of machinability enhancer used in the FC-02xx materials with different carbon levels

Figure 10 presents the machining responses of the FC-0208 materials containing the machinability enhancer SM4 in dry and wet machining. Compared to the machining on the materials without the enhancer (Figure 7 and Figure 8), the machinability enhancer significantly improved the machining by extending the tool life by more than 2 times in both dry and wet machining. It demonstrated that the machinability enhancer can work effectively regardless the carbon levels in the FC-02xx materials. Despite more material cutting compared to the materials without the enhancer, the tool wear was still far below the tool failure limit. Figure 11 presents the status of tool wear when cut the materials containing the machinability enhancer in dry and wet machining.

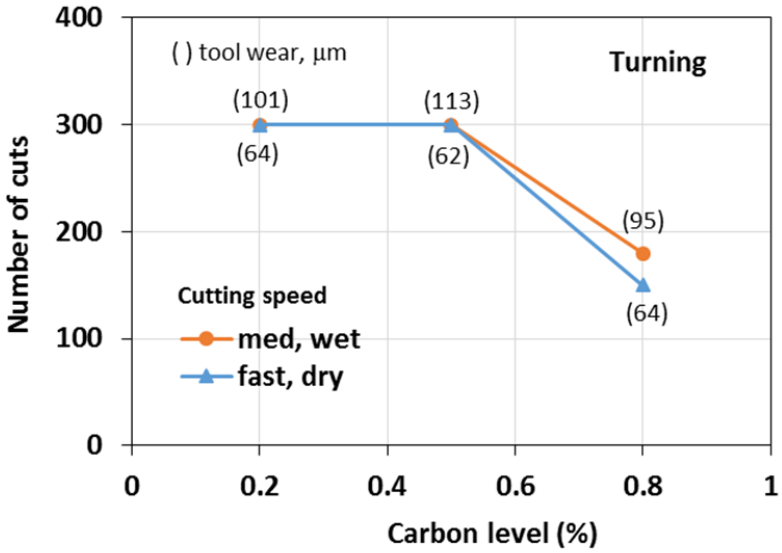
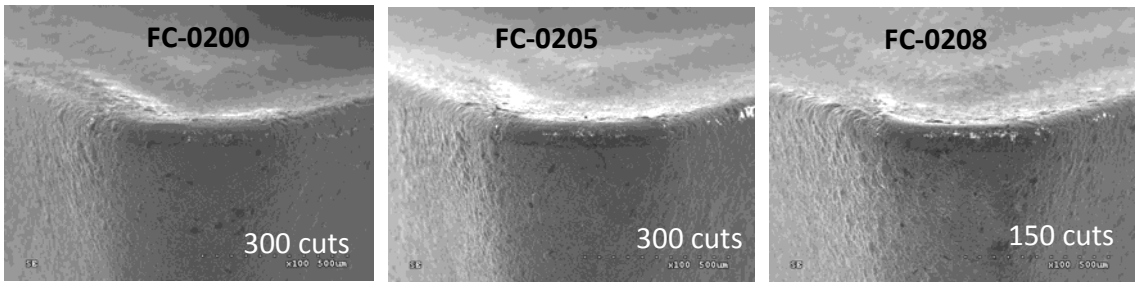
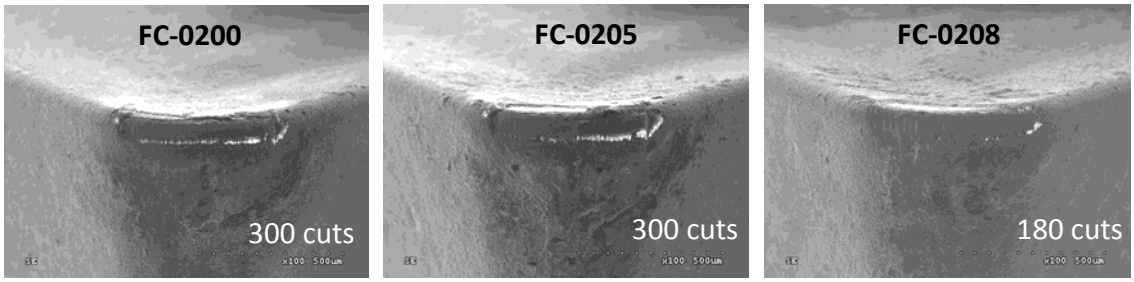


Figure 10. Number of cuts made with machinability enhancer SM4 at different cutting speeds in dry and wet machining of the FC-02xx materials



a) Dry machining at fast cutting speed



b) Wet machining at medium cutting speed

Figure 11. Status of tool wear after cutting the FC-02xx materials containing machinability enhancer SM4 at fast and medium cutting speeds in dry and wet conditions respectively

DISCUSSION

Commercial iron powder is generally manufactured using either mechanical or chemical methods. Water atomization of molten iron is a primary manufacturing method today. It is the least expensive large-scale process to produce a solid and irregular particle structure with high apparent density and good flowability, so it is widely used to produce high density PM structural components.

The base iron powder grades used in this study were high purity (99.5%Fe or higher) water-atomized iron powder with low oxygen and carbon content. Table 5 presents an analysis on the chemical compositions of the base iron powder grades used in this study. The impurities include bulk dissolved elements (such as Cr, Mo, Ni, Cu, Si, Mn, etc.) and oxide inclusions. They are undesirable contaminants which can vary dependent on raw material and manufacturing processes. As can been in Table 5, the base iron powder grade A3 contains much higher impurities compared to the grade A1 and the grade A2, which have identical impurity content.

Table 5. Chemical compositions of the base iron powder grades

	Base iron	Grade A1	Grade A2	Grade A3
Chemistry	%Fe	99.6	99.7	99.5
	%O	0.07	0.05	0.09
	%C	0.003	0.003	0.002
	%Impurity	0.28	0.26	0.44

After the machining tests, the machined FC-0208 materials made with these three grades of base iron powder were used for microstructural analysis. As shown in Figure 12, all of the FC-0208 materials presented a full pearlitic microstructure and had identical hardness in either macro (HRB) or micro (MHV) scale.

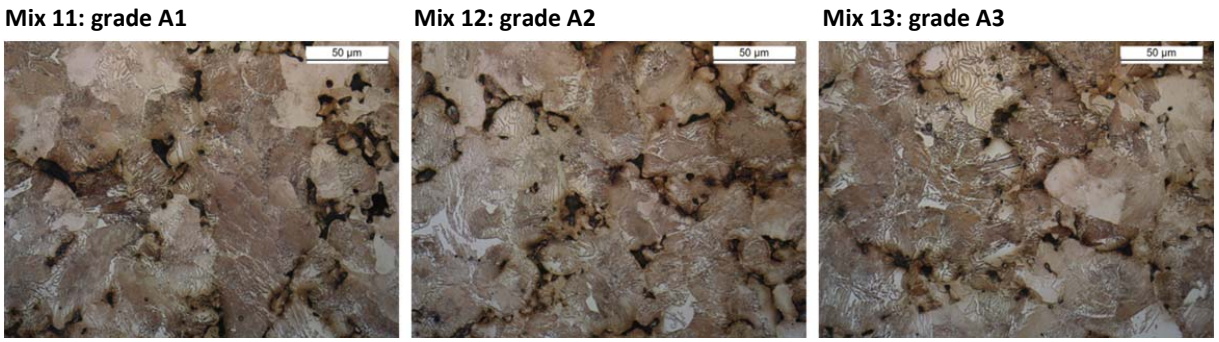


Figure 12. Microstructures of the FC-0208 materials made with different base iron powder grades

Since these materials were prepared in the same manner of compaction and sintering, the differences in machining responses found in dry machining (Figure 1) are considered to be contributed by the base iron powder. The base iron powder grade A3 consistently showed difficult machining at three different cutting speeds compared to grade A1 and grade A2. The high impurities in grade A3 is considered to the dominant factor that impacted the machinability of the sintered material. Even though it was not remarkable, grade A2 was also found to be less machinable than grade A1. As both iron powders contain very similar amount of impurities, the difference in machining responses may be contributed by the distribution variation of dissolved elements and variables in manufacturing processes.

Machining is a complex tribological process that involves the performance of surfaces related to lubrication, friction and wear described in multiple mechanisms [8-9]. The friction between the cutting tool and workpiece material generates heat and the resulted thermal effects play important roles in tool wear. In this study, quicker tool wear (or short tool life) occurred when machining the FC-0208 material made with grade A3 base iron powder, indicating the thermal effects with this base iron were greater than with the grade A1 and A2 base iron powders. In wet machining (Figure 2), however, identical tool life, i.e. similar tool wear after cutting the same amount of work pieces was found between the sintered materials made with these base iron powder grades. This means the extra thermal effects created by the grade A3 base iron powder were minimized by the coolant so no differences in machining response could be observed between the materials made with the different base iron powder grades.

With the addition of a machinability enhancer such as SM4, this study demonstrated its effectiveness in improving the machining of FC-0208 materials by providing lubrication to reduce the heat generation and protecting the tool from the thermal effects. When the machining enhancer was used, the thermal effects caused by the base iron powder grades in dry machining were eliminated (Figure 4). Furthermore, exceptional improvement in the machining of the PM materials was achieved in both dry and wet machining with the SM4 additive. Figure 13 shows an example of the chip formation after cutting the FC-0208 materials with and without machinability enhancer. Despite being machined in wet condition, the material without enhancer formed long discolored chips starting from the beginning of machining (30 cuts), indicating the thermal effects were significant. The tool failed after 90 cuts. With the addition of the machinability enhancer SM4, the material formed short chips from 30 cuts to 180 cuts without discoloration. The shape and color of cutting chips indicated SM4 worked as a good chip breaker and largely reduced the thermal effects during machining resulting in an extended tool life.



a) FC-0208 (30 cuts) b) FC-0208 +0.3%SM4 (30 cuts) c) FC-0208 +0.3%SM4 (180 cuts)

Figure 13. Appearance of machined chips formed at medium cutting speed in wet machining. Base iron powder used in the FC-0208 mixes: grade A1

When the carbon level was altered in the Fe-Cu-C materials, the machinability of the sintered material changes depending on the ratio of ferrite (soft) and pearlite (hard) phases formed in the matrix. As the carbon level increases, the amount of pearlite increases so the material becomes difficult to machine. However, a ferritic matrix is generally considered to be hard to machine as the material is gummy and it is easy to cause adhesive wear on the cutting tool. Therefore, a material with a microstructure in a ratio of 50/50 ferrite and pearlite is generally easy to machine. In this study, the microstructures of the FC-02xx materials made with the same base iron powder grade but containing three levels of carbon content are presented in Figure 14. Compared to the FC-0200 material which had a ferritic matrix with a small amount of pearlitic phase and the FC-0208 material which has a full pearlitic matrix, the FC-0205 material contained similar amount of ferrite and pearlite phases distributed in the matrix. The material hardness varied depended on the carbon content: the FC-0200 material was the softest while the FC-0208 was the hardest.

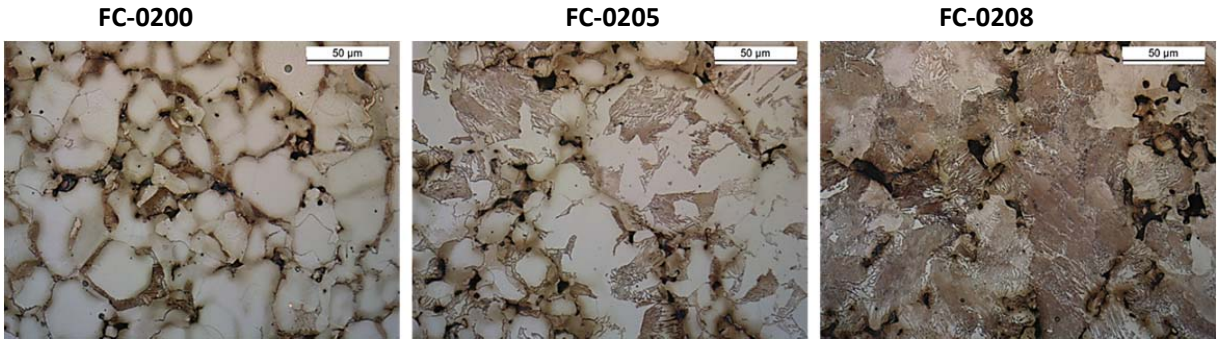


Figure 14. Microstructures of the FC-02xx materials made with different carbon levels

The machining tests showed the FC-0208 material was more difficult to machine in either dry machining or wet machining compared to the FC-0205 and FC-0200 materials. However, the machinability of FC-0200 material was identical to that of the FC-0205 material even with the ferrite phase as the majority matrix constituent. The improved machinability found in this material was benefited from contributions of the copper addition and the small amount of carbon. Typically a ferritic matrix has a microindentation hardness around 100, the average hardness of the FC-0200 material used in this study was measured as 153 when the copper (2%) was added together with a small amount of carbon (<0.2%). Therefore, the addition of copper and carbon strengthened the ferritic matrix to make it more brittle and thus reduced gumminess. Consequently, the tool wear was reduced and the machinability was improved. Figure 15 compared the machinability of F-0000 (full ferritic matrix, no copper and carbon addition) with the FC-02xx materials used in this study when they were cut in the same machining conditions. It shows that the F-0000 material had very poor machinability because of its soft and gummy matrix.

When assessing the effectiveness of the machinability enhancer in improving the machining of FC-02xx materials made with different carbon levels, this study demonstrated the SM4 additive works well for all tested carbon levels added into the FC-02xx materials by providing more than 2 times longer tool life regardless the types of material matrix, i.e. the ratio of ferrite and pearlite in the matrix. Based on this study, therefore, the machinability enhancer SM4 can provide potential capability not only for longer tool life but also for higher productivity to result an overall cost saving in machining.

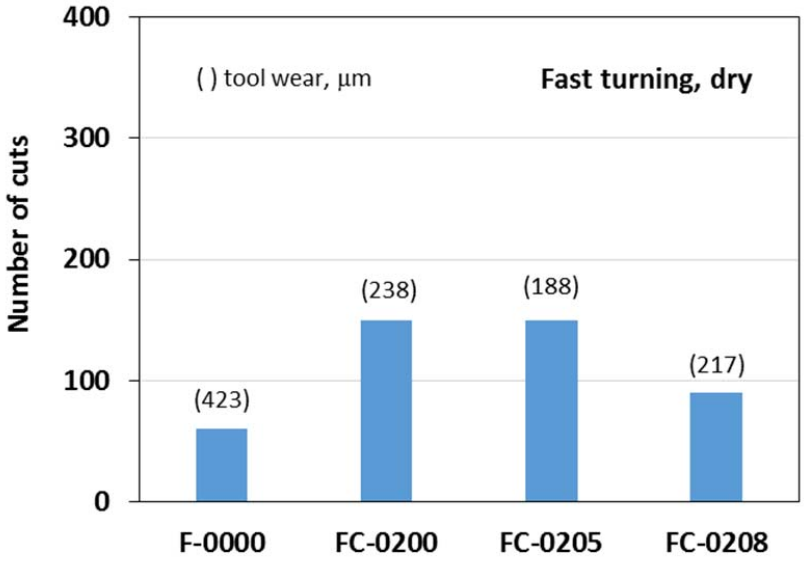


Figure 15. Comparison of machinability between Fe-C and Fe-Cu-C materials

CONCLUSION

The effect of base iron powder grade and carbon levels on machinability of a common Fe-Cu-C material has been evaluated under various machining conditions including dry and wet machining. Comparing the materials with and without machining enhancing additive, the following conclusions can be made from this study:

1. The machining responses of FC-0208 materials made with different base iron powder grades were different in dry machining. The extra thermal effects contributed by the impurities in the base iron powder played the dominant role on tool wear and failure. No differences between the iron powder grades were observed in wet machining due to the thermal effects being eliminated by coolant.

2. The effect of carbon levels on the machinability of FC-02xx materials was significant and it became difficult to machine when a full pearlitic microstructure was created. Due to the matrix strengthening effect of copper, the FC-0200 material had similar machinability to the FC-0205 material even as the ferrite phase was the majority in its matrix.

3. The effectiveness of a commercial machining enhancer SM4 was proven to be able to improve the machining of Fe-Cu-C materials in terms of longer tool life and higher productivity regardless the carbon levels and the type of atomized base iron powder grades.

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