THE EFFECT OF POROSITY ON MACHINABILITY OF PM MATERIALS

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ABSTRACT

One of the distinct features of powder metallurgy (PM) material is porosity. Depending on the application, this can be advantageous or a disadvantage. While density levels may be kept low in bearing applications, structural parts requiring high strength will maximize density in order to meet mechanical properties. The geometry of the component being compacted will influence not only the overall density level, but also the consistency of the density throughout the component. PM materials are considered more difficult to machine due to the porosity. While it is generally accepted that porosity negatively impacts machinability of PM steels, detailed works generally lack on the relationship between porosity and machinability, especially when a machinability enhancer is utilized. In this study, machinability of the popular iron-copper-carbon steel was evaluated at different density levels. Commercial machining enhancing additives were examined in the study to determine the effect of density (or porosity) level on their overall effectiveness.

INTRODUCTION

As a near-net shape technology, powder metallurgy (PM) provides significant advantages in minimizing material and energy waste for mass production of structural parts. Porosity is one of the inherent features present in PM components. For bearing applications, the porosity can provide opportunity for improved performance such as self-lubrication. However, it adversely affects the mechanical properties such as strength and hardness of materials used as structural parts. Therefore, components that require high strength aim to maximize density by minimizing the porosity. In addition, density distribution commonly exists in PM components and is largely influenced by the geometry being compacted. Such inherent feature of PM materials extend to its secondary operations such as machining.

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. PM materials are considered more difficult to machine compared to wrought steels due to the presence of porosity which is considered to cause constant interrupted cutting on a micro scale [1]. Based on the aspect on porosity, resin-impregnation and copper infiltration are two techniques developed to improve the machinability of PM materials by filling the porosity. However, the application of these techniques is limited due to the significant cost increase for the additional manufacturing process. Therefore, the majority of PM components are still machined with the presence of porosity.

Machining is a complex process with many factors that can influence the machinability of PM components. Table 1 summarizes the factors which are considered to affect the machining of PM materials. The machinability of a PM component is determined by its material composition and the manufacturing route. Depending on the material composition and manufacturing route, different microstructures and hardness can be achieved. 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.

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	

Typical machining operations on PM components include turning, drilling, tapping, milling, grinding, reaming and grooving, etc. in which turning and drilling are the most common machining operations involved in cutting PM materials. To enhance machining, machining additives are used to impart benefits such as lubrication, chip breaking and tool protection. In spite of the presence of porosity, commercial machining additives are very effective in improving the machinability of PM components, especially with iron-copper-carbon (Fe-Cu-C) materials [2~5]. In many practices, however, poor machining with early tool failure is often simply linked to the porosity as the dominant factor regardless the machining additive was added or not. This could easily lead to a wrong direction for exploring solutions. In fact, systematic studies are lacking details on how porosity or density influences the machining response of PM components in different machining conditions. Studies on the effectiveness of machining additives are also lacking under different density levels with the same PM materials.

In this study, Fe-Cu-C materials, the most common materials used to manufacture PM components, were selected for evaluating the effect of porosity on the machinability of PM materials. At the same time, commercial machining enhancers are also examined in the study to determine the effect of density level on their overall effectiveness.

EXPERIMENTAL PROCEDURE

Materials

A common Fe-Cu-C material system (MPIF material code: FC-0208) with and without machining additive was selected for evaluations [6]. Commercial machinability enhancers (MnS-E, SM3 and SM4, North American Höganäs) were added with their typical amount and compared to a mix with no machining additive. The base iron powder (ASC100.29, North American Höganäs) 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 2.

Table 2: Chemical compositions of premixes

Premix	ID	Base iron	Chemical Composition, wt%			
			Cu	Graphite	Lubricant	Additive
FC-0208	A	ASC100.29	2.0	0.85	0.75	None
	B	ASC100.29	2.0	0.85	0.75	0.5%MnS
	C	ASC100.29	2.0	0.85	0.75	0.15%SM3
	D	ASC100.29	2.0	0.85	0.75	0.3%SM4

Compaction and Sintering

The premixes were compacted into ring specimens with dimensions ϕ55 x ϕ35 x H20 mm at three green density levels: 6.6, 6.8, 7.0 g/cm^3. These density levels cover the range of density that is used to produce most of components made from the FC-0208 material. The rings 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 at different density levels was evaluated with the sintered ring specimens in two machining operations: drilling and turning. The effectiveness of MnS was evaluated in both drilling and turning while the SM3 and SM4 were evaluated in turning and drilling respectively. SM3 and SM4 are two recently developed machining additives to replace MnS and eliminate corrosion and stain concerns [4, 5]. SM3 exhibits superior performance to MnS in turning operation while SM4 provides similar performance as MnS in drilling operation. Therefore, this study evaluated the capability of SM3 and SM4 in replacing MnS respectively in drilling and turning operations.

For drilling, a CNC mill was used with a plain and TiN coated high speed steel (HSS) drill bit to drill ϕ3mm blind holes in a depth of 10 mm with a feed rate ranged from 0.05 to 0.15 mm/rev. Machining responses were evaluated based on the number of holes drilled before the tool failure. Unless specified, the test was terminated when 72 holes were drilled for a given drilling condition. Tool wear for selected tests was also examined under a scanning electron microscope (SEM). All tests were performed in dry and wet conditions, i.e. with and without coolant respectively.

For turning, a CNC lathe was used with a TiAlN coated tungsten carbide insert to cut the inner diameter (ID) of the ring specimen at a cutting speed ranged from 600 to 1800 sfm (183-548 smm). The depth of each cut was 0.5 mm. Machining responses at different density levels were evaluated by measuring the tool wear after a number of cuts were made using a scanning electron microscope (SEM). All tests were performed in dry and wet conditions, i.e. with and without coolant respectively.

RESULTS

Sintered properties of the FC-0208 materials

The sintered properties of the FC-0208 materials (sintered ring specimen) were examined and the results are shown in Table 3. For each density group, the materials with and without machining enhancers have identical sintered density, diffused carbon level and apparent hardness. The porosity for each density group was calculated as 17, 14, and 12% respectively. Sulfide compound was detected in material B containing MnS. No sulfide compound was found in material C and D containing SM3 and SM4, where

the sulfur content in these two materials was identical to the level found in material A with no machining additive.

The microstructure of sintered ring samples was also examined and all of the FC-0208 materials were fully pearlitic. As an example, Figure 1 shows the microstructures obtained from material A with no machining additive. They have identical microstructures and present different porosity ranged from 12.0% to 17.0%. The microhardness ($MHV_{0.1kg}$) of the material matrix was measured and the average was 263 with a range of 236 to 297 which was within the typical range for a FC-0208 material.

Table 3: Sintered properties of Fe-Cu-C materials used for machining tests

FC-0208 at 6.6 g/cm^3 (green density)

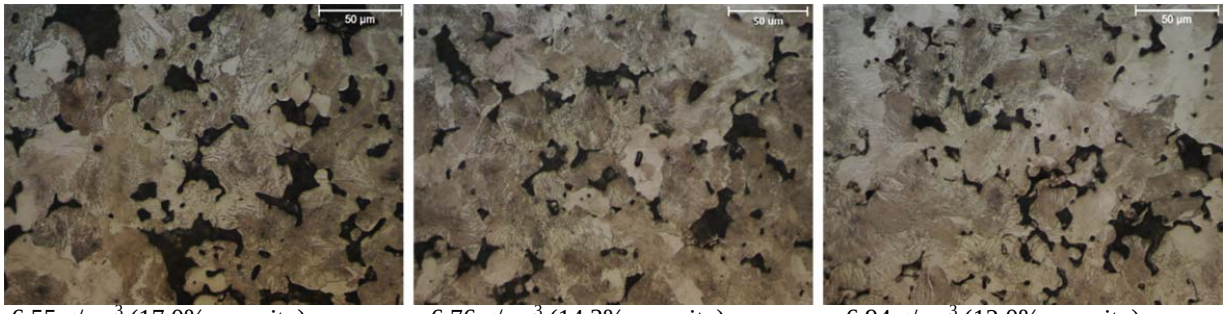
Material ID	A	B	C	D
additive	none	0.5% MnS	0.15%SM3	0.3%SM4
sintered density (g/cm^3)	6.55	6.56	6.56	6.54
porosity (%)	**17.0**	**16.9**	**16.9**	**17.1**
%C	0.78	0.81	0.76	0.77
%S	0.004	0.168	0.006	0.005
hardness, HRB	64 (59-68)	65 (62-68)	64 (62-67)	64 (60-67)

FC-0208 at 6.8 g/cm^3 (green density)

Material ID	A	B	C	D
additive	none	0.5% MnS	0.15%SM3	0.3%SM4
sintered density (g/cm^3)	6.76	6.80	6.74	6.75
porosity (%)	**14.3**	**13.8**	**14.6**	**14.4**
%C	0.76	0.79	0.77	0.76
%S	0.004	0.165	0.005	0.004
hardness, HRB	72 (71-74)	73 (71-75)	70 (69-74)	70 (70-73)

FC-0208 at 7.0 g/cm^3 (green density)

Material ID	A	B	C	D
additive	none	0.5% MnS	0.15%SM3	0.3%SM4
sintered density (g/cm^3)	6.94	6.97	6.92	6.95
porosity (%)	**12.0**	**11.7**	**12.3**	**11.9**
%C	0.76	0.81	0.78	0.77
%S	0.003	0.163	0.005	0.005
hardness, HRB	79 (73-80)	77 (75-80)	77 (73-79)	78 (74-80)



6.55 g/cm^3 (17.0% porosity) 6.76 g/cm^3 (14.3% porosity) 6.94 g/cm^3 (12.0% porosity)

Figure 1. Microstructures of the FC-0208 material in different sintered densities (porosity)

Machining responses of the FC-0208 materials in drilling operation

Drilling tests with the FC-0208 materials without machining enhancer

The sintered ring specimens were drilled with plain and TiN coated HSS drill bits in both dry and wet conditions. Table 4 presents the number of holes drilled on the FC-0208 materials without machining enhancer. Three different feed rates were used to evaluate the machining responses. In the dry drilling, more holes were made with the samples having higher density (less porosity). There was no significant difference in drilling performance between the plain and TiN coated drill bits. In the wet drilling, however, the effect of porosity was minimized and the number of holes drilled was dependent on the feed rate and the type of tools. In fact, more holes were made with the sample having lower density (more porosity) when a plain HSS was used. Faster drilling with more holes could be achieved with the TiN coated drill bit compared to the use of plain drill bit. Figure 2 summarized the machining responses of the FC-0208 materials without machining enhancer in dry and wet drilling operation. The porosity had a large effect in dry drilling but no effect in wet drilling.

Table 4: Number of holes drilled on the FC-0208 material without machining enhancer

Material A: plain HSS, dry

feed, mm/rev	Density 6.6	Density 6.8	Density 7.0
0.05	12	16	52
0.075	1	2	62
0.1	3	3	4
total	**16**	**21**	**118**

Material A: TiN coated HSS, dry

feed, mm/rev	Density 6.6	Density 6.8	Density 7.0
0.05	13	29	70
0.075	2	10	28
0.1	2	3	5
total	**17**	**42**	**103**

Material A: plain HSS, wet

feed, mm/rev	Density 6.6	Density 6.8	Density 7.0
0.1	72	72	72
0.125	33	29	27
0.15	10	2	5
total	**115**	**103**	**104**

Material A: TiN coated HSS, wet

feed, mm/rev	Density 6.6	Density 6.8	Density 7.0
0.1	72	72	72
0.125	72	72	72
0.15	72	54	72
total	**216**	**198**	**216**

Note: a) test was terminated after 72 holes drilled; b) dry: drilling without coolant; wet: drilling with coolant

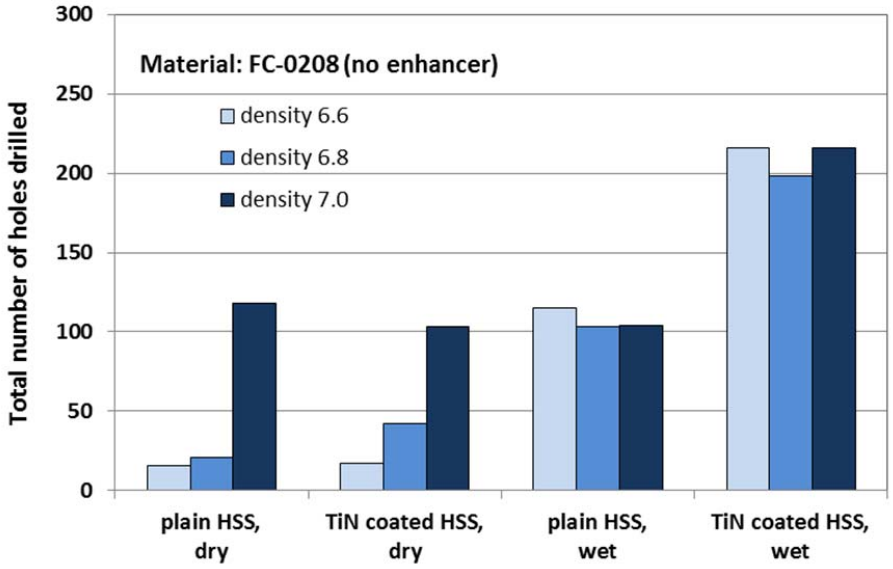


Figure 2. Total number of holes drilled on the FC-0208 material without machining enhancer at three different feed rates (dry drilling: 0.05~0.1 mm/rev; wet drilling: 0.1~0.15 mm/rev)

Drilling tests with the FC-0208 materials containing machining enhancer

The sintered ring specimens containing machining enhancers were also drilled with plain and TiN coated HSS drill bits in both dry and wet conditions. The same feed rates were used as described in Table 4. Figure 3 summarized the machining responses of the FC-0208 materials containing 0.5% MnS and 0.3% SM4 respectively in dry and wet drilling operations compared to the material without enhancer. As shown in Figure 3, no effect of porosity was observed either in dry or wet drilling when the machining enhancer was used. Both MnS and SM4 greatly improved the machinability of the FC-0208 materials and assisted to drill 72 holes with either plain or TiN coated drill bits at the three different feed rates without tool failures. To further define the capability of the machining enhancers in machinability improvement, additional tests were performed to drill the sintered ring specimens up to 180 holes with a single plain HSS drill bit in dry and wet conditions and the results are shown in Figure 4. Compared to the material without enhancer, MnS improves the drilling significantly either in dry or wet machining without the effect of porosity. For SM4, it also improves the drilling significantly and performs very similar to the MnS even though certain porosity effect was observed in dry drilling. In addition, the wet drilling could be run at twice faster feed rate than the dry drilling in the presence of machining enhancer, i.e. the productivity could be doubled in wet machining compared to the dry machining. As a comparison, the status of tool wear after cutting the FC-0208 materials with and without machining enhancer in wet machining are shown in Figure 5. Excessive tool wear was found after drilled 5 holes in the material without machining additive while normal tool wear was presented after drilled 180 holes in the materials with MnS and SM4 machining enhancer.

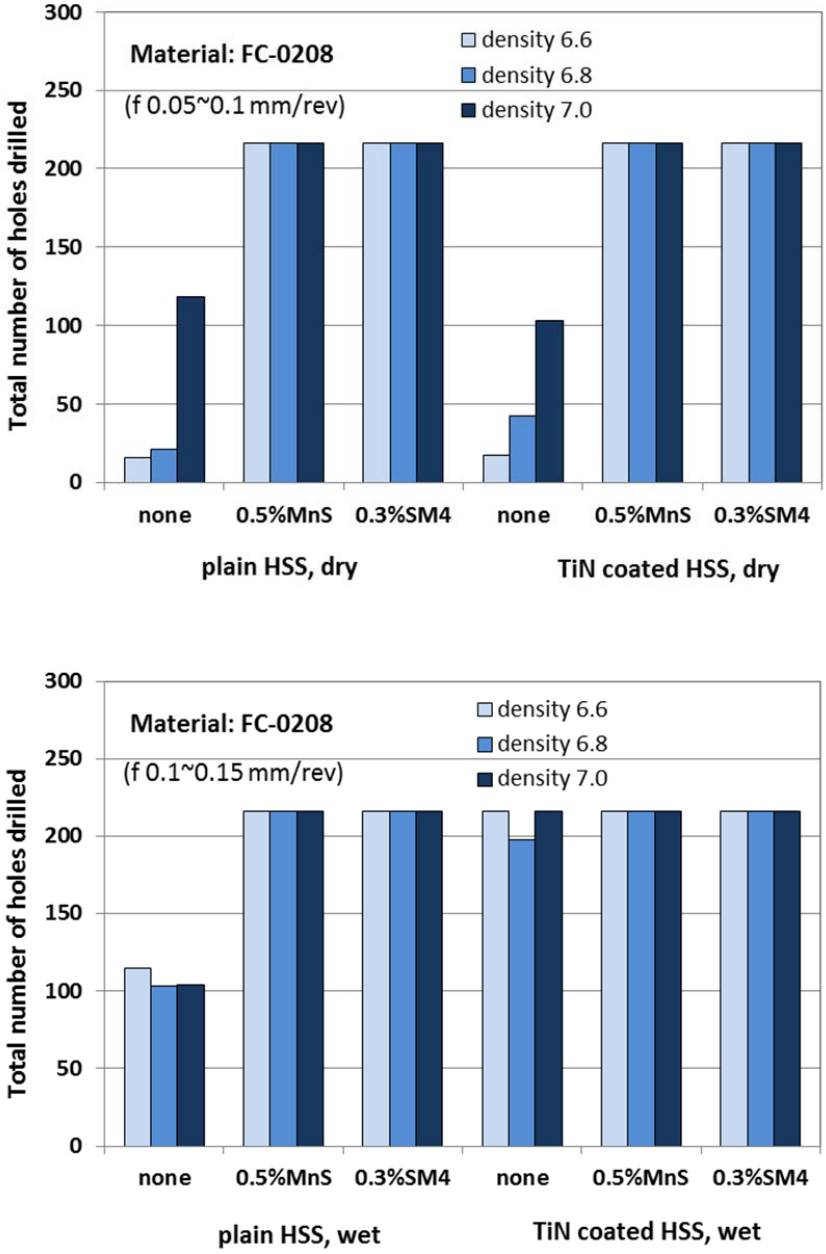


Figure 3. Comparison of machining responses between the FC-0208 materials with and without machining enhancer drilled at three different feed rates (top: dry drilling; bottom: wet drilling)

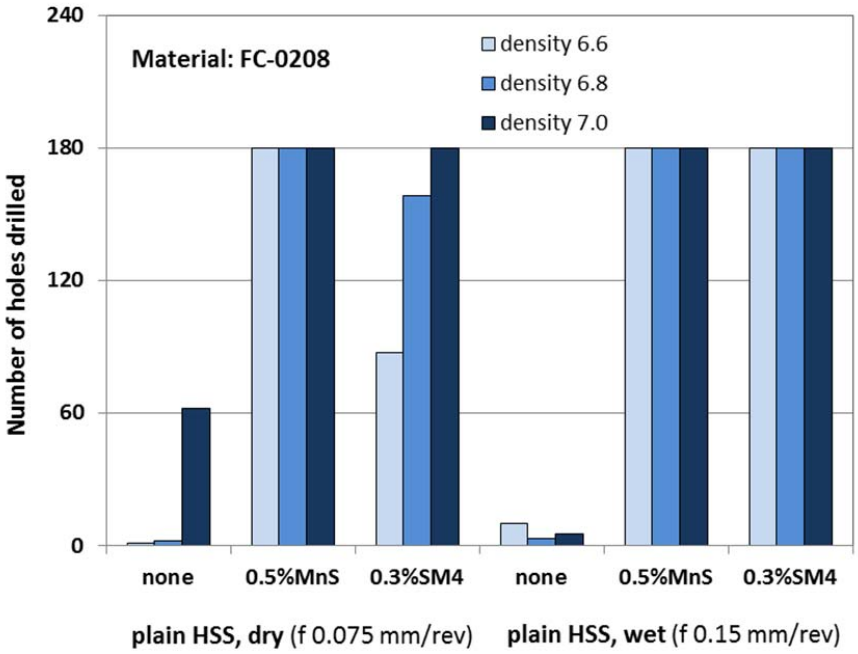
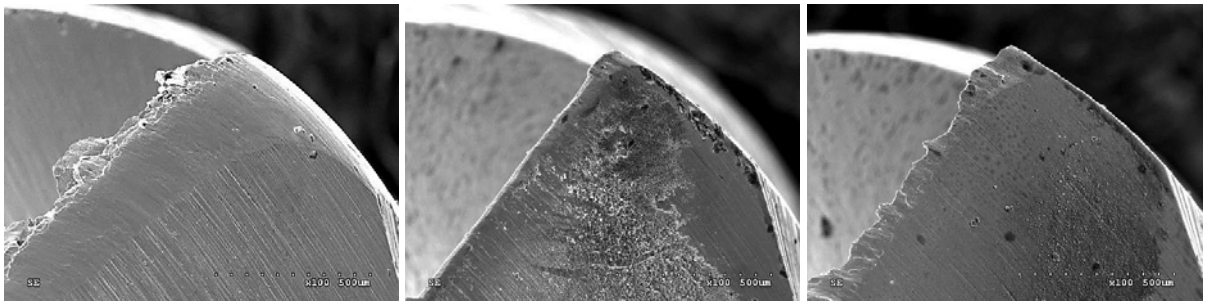


Figure 4. Machining responses of the FC-0208 materials containing machining enhancer in dry and wet drilling compared to the material without enhancer



No enhancer (failed at 5 holes) 0.5%MnS (stop at 180 holes) 0.3%SM4 (stop at180 holes)

Figure 5. Status of tool wear after cutting the FC-0208 materials with and without machining enhancer in wet machining (drilling with plain HSS, f 0.15 mm/rev)

Machining responses of the FC-0208 materials in turning operation

Turning tests with the FC-0208 materials without machining enhancer

The sintered ring specimens were cut at three different cutting speeds in dry and wet conditions and the results of tool wear are presented in Figure 6. After cut the same amount of material (90 cuts) in dry machining, significant effect of porosity was observed in fast cutting but the effect gradually decreased as the cutting speed was reduced. At the slow cutting speed, the effect of porosity on the tool wear was not significant. In wet machining, however, no effect of porosity was observed at the tested cutting speeds. Figure 7 presents the status of tool wear in dry and wet machining.

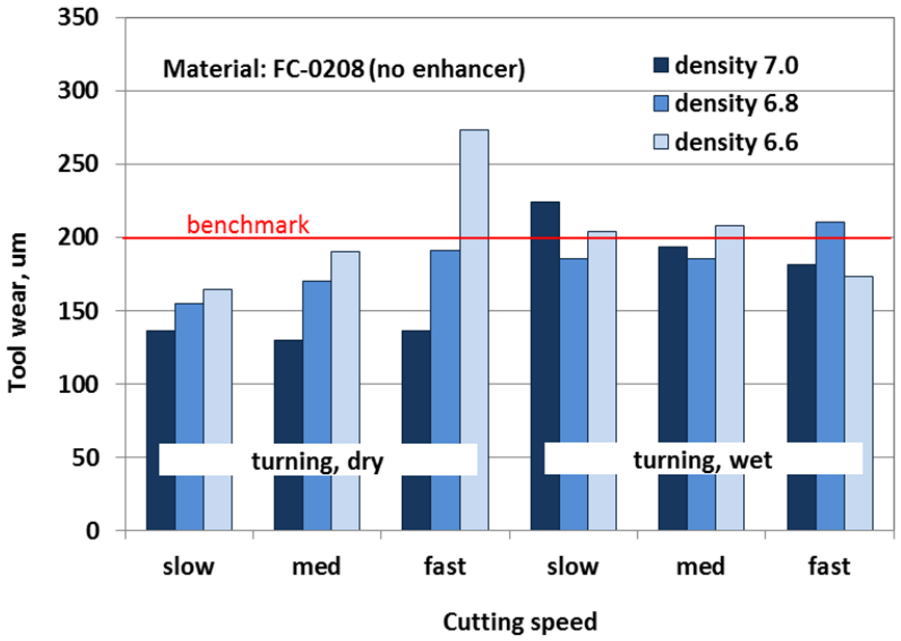
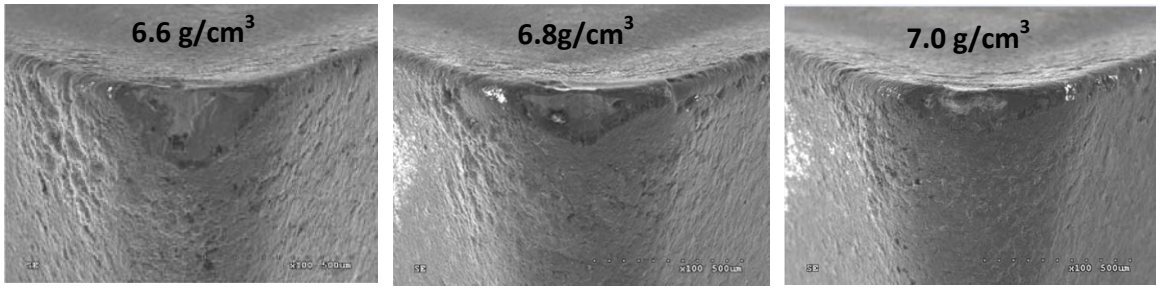
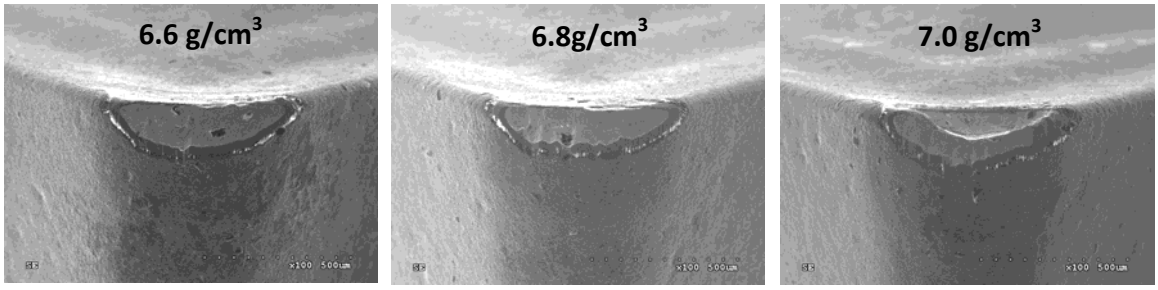


Figure 6. Tool wear after cutting the same amount of the FC-0208 materials without machining enhancer at different cutting speeds in dry and wet machining (turning)



a) fast turning, dry



b) slow turning, wet

Figure 7. Status of tool wear after cutting the same amount of the FC-0208 materials without machining enhancer in dry and wet machining (turning)

Turning tests with the FC-0208 with machining enhancer

Figure 8 presents the machining responses of the FC-0208 materials containing machining enhancers in dry and wet turning compared to the material without enhancer. Both of the machining enhancers, MnS and SM3, improved the machinability of the FC-0208 materials with longer tool life either in dry or in wet machining without the effect of porosity. The machining responses of the material without enhancer were also independent from the porosity when it was turning with coolant. For SM3, it exhibited superior performances to MnS in turning operation even though it was added at 3 times less amount. Figure 9 presents the status of t tool wear after cutting the FC-0208 materials with and without machining enhancer in dry machining. Compared to the excessive tool wear after cut the material without enhancer for 90 cuts, MnS improved the machining with normal tool wear at the same cuts of machining but the tool failed after cut additional 30 cuts. Compared to MnS, SM3 provided further improvement and normal tool wear was still maintained after cut 180 cuts.

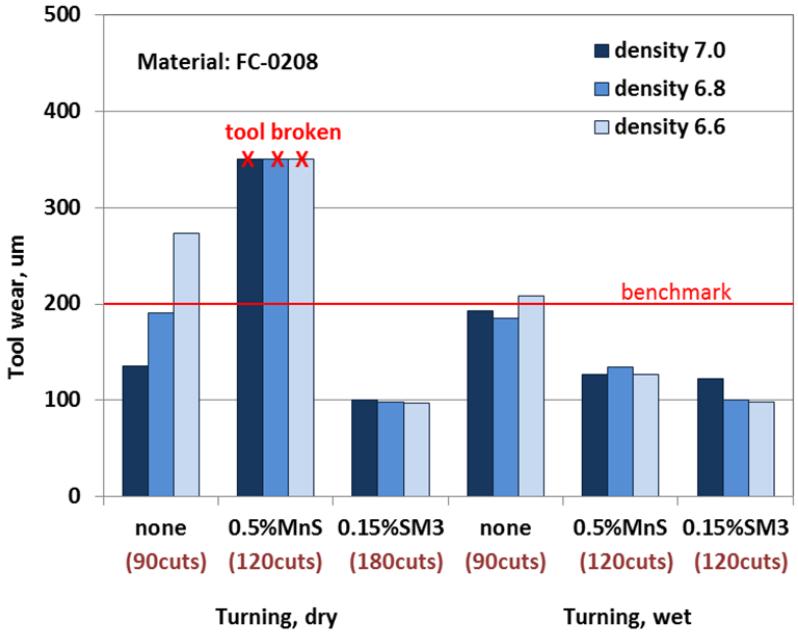
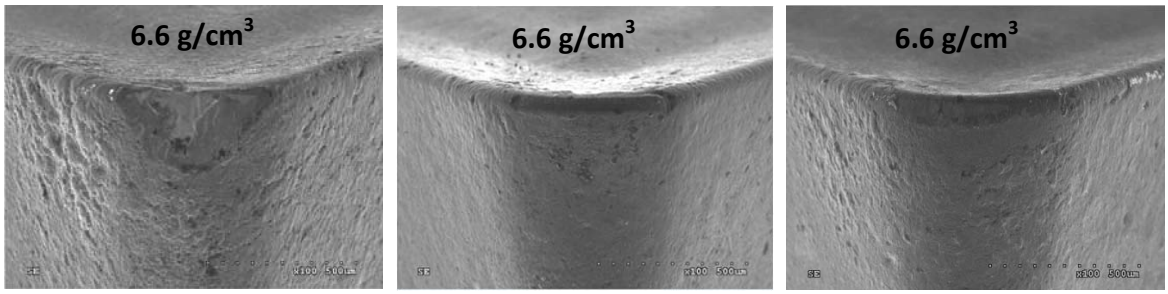


Figure 8. Machining responses of the FC-0208 materials containing machining enhancers in dry and wet turning compared to the material without enhancer



No enhancer (90cuts) 0.5%MnS (90cuts) 0.15%SM3 (180cuts)

Figure 9. Status of tool wear after cutting the FC-0208 materials (6.6g/cm^3) with and without machining enhancer in dry machining (fast turning)

DISCUSSION

Machining is a process where momentum energy is converted to cutting forces to make elastic and plastic deformation on the workpieces in order to remove the unwanted portion of the material. Friction and thermal effects created during machining play important roles in tool wear and machined surface roughness since the temperature on the tool face greatly affect to the size and stability of the built-up edge (BUE) [7]. It also causes chemical reactions such as diffusion and oxidation to make harder machined surfaces when the cutting temperature is high enough. Therefore, machining is a complex tribological process that involves the performance of surfaces related to lubrication, friction and wear described in multiple mechanisms.

For PM materials, the following theories were developed to explain poorer machinability of porous components compared to the more dense ones [8]:
1) Micro-interrupted cutting theory
2) Hard-inclusion theory
3) Deformation cutting theory
4) Thermal conductivity theory

The micro-interrupted cutting theory is the most common one used to explain the poor machinability of PM materials for decades [9]. It is based on the porosity of PM materials leading to interrupted cutting continuously on the micro-level, as shown in Figure 10. However, this schematic figure used to describe this theory doesn't truly reflect the behaviors of real machining as the pore size existed in common PM components is significantly smaller than the contact area of cutting tool with the workpiece material.

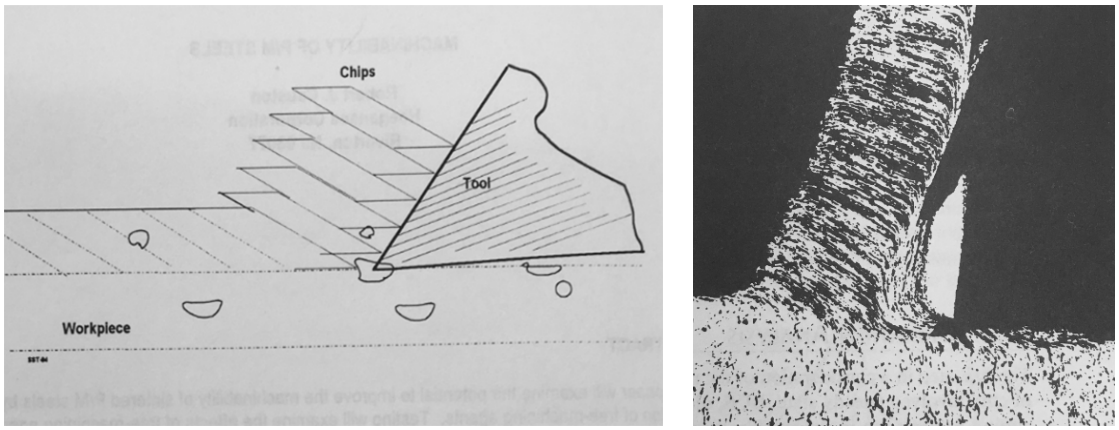


Figure 10. Schematic of the effect of porosity on metal cutting (left) [9] and photomicrograph of chip formation with partially formed chip, material deformation and built-up edge when cut AISI 1020 steel at a depth of 0.2 mm (right) [7]

In this study, the sintered Fe-Cu-C samples were prepared at a density ranged from 6.6 to 7.0 g/cm^3 (porosity: approx.12~17%) which covers the majority of PM components produced today. As shown in Figure 11, the pores were in very irregular shapes with a pore size not larger than 50 um even in the lowest density (6.6 g/cm^3). In contrast to the pores, the radius of insert used for ID turning was 406 um (0.016 in) so that the contact area of cutting tool is larger than the pore size, i.e. there is no continuous interrupted cutting during the machining. Furthermore, material deformation with a cutting depth compress the pore structure to become denser or to fill the pores so the micro-interrupted cutting is

minimal if there is any (Figure 10 right). In this study, surface deformation layer was examined after the material was cut. As shown in Figure 12, a deformed surface layer (approx. 50~100 um) was created after the machining. The layer became thicker as the density decreased since it is easier to deform in a less dense structure so that no micro-interrupted cutting exists in any density level according to this study. Therefore, the micro-interrupted cutting theory doesn't apply to the common machining of PM materials.

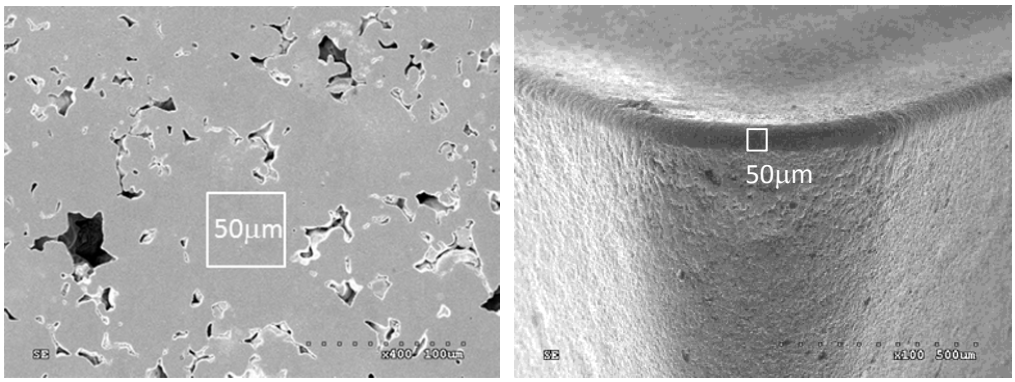


Figure 11. Comparison between the pore size of sintered samples at 6.6 g/cm^3 and the cutting edge of insert used for ID turning

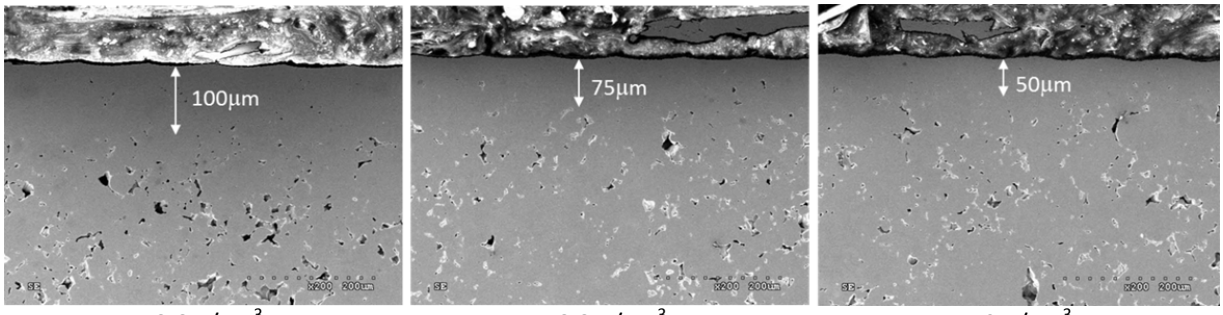


Figure 12. Deformation layer created on the surface of FC-0208 material in wet machining (turning)

The hard-inclusion theory also doesn't explain the behaviors of machining found in this study with the sintered materials which have the same full pearlitic microstructure at different density levels. The base iron was a high purity atomized iron powder with no excessively hard-inclusions. The impurities measured as acid-insoluble for such type of iron powder is usually less than 0.05%.

The deformation cutting theory describes a harder layer generated on the machined surface when the porous structure is deformed. Studies showed that this deformed and work-hardened surface layer was very thin (<60 um) [8]. However, a cutting depth in machining is normally more than 100 um. Therefore, this theory couldn't be used as an explanation.

The thermal conductivity theory is considered the most dominant one that explains the effect of porosity on machining of PM components. As porosity increases, the thermal conductivity of the PM materials decreases linearly [10]. The friction between the cutting tool and workpiece material generates heat. If the heat can be quickly transferred from the cutting area, thermal effects that cause tool wear can be reduced. In dry machining, the heat transfer relies on the thermal conductivity of the workpiece material

while in wet machining most of heat is removed by the coolant. The results obtained in this study strongly support this theory. Both drilling and turning performed in three different cutting speeds demonstrated the effect of porosity on machining when it was run in dry condition. The difference in machining performance was correlated to the difference in thermal conductivity of the sintered materials. The materials with higher porosity tend to have poorer machinability compared to the ones having less porosity. With coolant, however, the difference in thermal conductivity was minimized so that the effect of porosity couldn't be observed in either drilling or turning operations. Compared to turning, drilling is more sensitive to thermal effects as it is performed in a closed environment. However, drilling with coolant didn't display any effect of porosity even the machining was run at faster feed rates (Table 4) due to the removal of heat by the coolant.

This study also demonstrated the effectiveness of machining enhancers in eliminating the effect of porosity by providing either lubrication to reduce the heat generation or protect the tool from the thermal effects. When the machining enhancers were used, the thermal effects caused by porosity in dry machining were eliminated (Figure 3). The machining enhancers provided exceptional performance in improving the machining of PM materials in both drilling and turning operations (Figure 4 and Figure 8). Figure 13 provides evidence how the machining enhancers used in this study greatly reduced the heat generation during a dry machining.



Figure 13. Appearance of machined chips of FC-0208 materials (6.6 g/cm^3) with and without machining enhancer in dry drilling with TiN coated HSS (f 0.1 mm/rev)

Based on the findings obtained in this study, the effect of porosity on machining of PM materials is often overestimated [11]. Under direction of the micro-interrupted theory, the performance achieved by resin-impregnation and copper-filtration was simply explained as closure or sealing the porosity. This study indirectly demonstrated that the thermal conductivity theory is more useful to explain the functions of resin-impregnation and copper infiltration. Also, past studies on investigating the machinability of PM steels were often performed in a dry condition without coolant. Drilling was usually the only operation used to evaluate the machinability of PM materials in a single cutting condition [12]. This study demonstrated that the porosity has no detrimental effect on the machining of PM materials when an effective machining enhancer is used and/or the thermal energy can be effectively removed by coolant. In fact, the majority of machining is operated with coolant and thus the thermal effects contributed from porosity are minimal, especially in turning where it is operated in an opened environment.

CONCLUSION

The effect of porosity on machinability of a common Fe-Cu-C material has been evaluated in both of drilling and turning operations 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. Thermal effects generated from friction on the machined surfaces play an important role on tool wear and failure. As porosity increases, the thermal conductivity of the PM material reduces which results in larger thermal effects on tool wear. The thermal effects are more severe in drilling compared to turning as drilling is performed in a closed environment

2. When a coolant is used to remove the heat generated from machining, the thermal effects are eliminated and thus no detrimental effect from porosity contributes to the machining

3. Commercial machining enhancers provides high temperature lubrication and tool protection to reduce the thermal effects so that their effectiveness is not affected by porosity

4. Since the pores are much smaller than the tool cutting edges, the micro-interrupted cutting theory doesn't explain the poor machining of PM materials. The thermal conductivity theory can explain the phenomena in dry machining as was demonstrated in the machining tests of this study

5. In practice, most machining is performed with a coolant. Poor machining with a short tool life shouldn't be simply linked to the porosity of PM materials if the coolant acts effectively

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