NEW MACHINABILITY ENHANCER FOR IMROVED MACHINING OF IRON-COPPER-CARBON MATERIALS

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ABSTRACT

In the powder metal industry, machining of components is becoming more prevalent as tolerances and features become more demanding. The powder manufacturing processes provide easy and flexible capability in formulating alloying and additives to achieve desired properties including machinability. Manganese sulfide (MnS) has long been the dominant machinability enhancing additive due to its ability to provide improvement in turning and drilling of PM materials, especially in machining of iron-copper-carbon materials. The development of the SM3 machining additive overcame the negative effects of MnS such as stains and corrosion while providing superior performance of turning operations but its performance in drilling of the iron-copper-carbon materials is not as good as MnS. A newly developed machinability enhancing additive aiming for improved performance in both drilling and turning has been evaluated and compared to the commercial additives in machining of iron-copper-carbon materials based on laboratory testing and full scale production trials. Machinability data, mechanical properties and corrosion testing results are presented to demonstrate the effectiveness of the new machining additive named SM4 as a potential machinability improvement solution for replacing MnS without corrosion and stain concerns.

INTRODUCTION

Powder metallurgy (PM) can provide significant benefits in minimizing material and energy waste based on its features as a near-net shape technology compared to other manufacturing technologies. The powder manufacturing processes are simple and have flexible capability in formulating alloying elements and additives into the base metal to achieve desired material properties including machinability. Iron-copper-carbon (Fe-Cu-C) steels are the most common materials used to manufacture PM components. It is a cost-effective, compressible and heat-treatable material system with favorable mechanical strength for most of PM applications. In the as sintered condition, this material system features either a fully pearlitic or a mixture of ferrite and pearlite microstructure with moderate hardness of matrix ($MHV_{-0.1kg}$ 100~300) dependent on the content of diffused carbon. Microstructure and hardness are considered two

key characteristics to determine machinability of PM materials. Compared to low-alloyed and sinter-hardened steels which contain multiphase microstructure including hard phases such as banite and martensite ($MHV_{-0.1kg}$ 300~650), the Fe-Cu-C steels are relatively easy to machine. However, adding machining additives is a common practice to achieve improved productivity and tool life. Furthermore, the selection of an effective machining additive can lead to significant improvement of machinability resulting in substantial reduction of machining costs [1-2].

As a conventional machinability enhancer, manganese sulfide (MnS) at a 0.5% addition is proven to be very effective in improving the machinability of Fe-Cu-C steels. It works well in almost any machining operation. The drawbacks of using MnS are that it tends to easily cause stains on part surfaces and greatly decreases corrosion resistance of component [3]. In many applications, the corrosion resistance and appearance of PM components are important since end customers and users generally consider rust and stains as defects. In these situations, therefore, MnS is either used at a low level or not used at all [4].

For decades, many research and development efforts have been undertaken exploring similar or better machining additives to replace MnS in order to alleviate the stain and rust concerns. Additives such as hexagonal boron nitride, calcium fluoride and magnesium silicates such as talc and enstatite, etc. are commercially used in PM materials for machinability improvement [5]. Although they can provide certain levels of improvement for some PM material systems, none of them can be widely utilized as effective as MnS.

Recent development has realized several new machining additives commercially used in PM materials, resulting in similar or better machinability improvement for low-alloyed and sinter-hardened steels compared to MnS [6-13]. For example, a machinability enhancer named SM3 has been successfully applied into PM materials since 2010. It exhibits superior performances as compared to MnS in terms of better productivity and longer tool life in low-alloyed, sinter-hardened and heat treated steels with lower addition levels [10, 13]. For Fe-Cu-C steels, it can also provide better machinability improvement than MnS in turning operation [11]. For drilling operation, it does improve the machinability but still hasn't reached the level of performance as MnS.

Typical machining operations on PM steels 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 steels. For many PM components, turning may be the only way to achieve required dimensional tolerance and surface finish while in other cases parts require drilling of small holes that are often unable to be made through the PM processes in an economic way or due to engineering difficulty. Components such as variable valve timing rotors and vanes, as well as main bearing cap, often involve heavy interrupted turning, drilling of deep small holes and tapping. Therefore, a machinability enhancing additive is desired to provide both turning and drilling performances that are similar to MnS but without detrimental effects on the PM properties.

In this paper, a newly developed machining additive named SM4 aiming for improved performance in both drilling and turning is examined. Laboratory tests were performed on Fe-Cu-C material to evaluate the performance of the new additive compared to the baseline (without any additive) and the materials containing commercial additives. Mechanical properties and corrosion resistance were also examined. Based on the laboratory test results, full scale production machining trials on a candidate component were conducted to verify the results and evaluate the effectiveness of the new machining additive for commercial use. This paper demonstrates the effectiveness of the new machining additive SM4 as a potential machinability improvement solution for replacing MnS.

EXPERIMENTAL PROCEDURE

Materials

A common Fe-Cu-C material system (MPIF material code: FC-0208) with and without machining additive was selected for evaluations [14]. Commercial machinability enhancers (MnS-E and SM3, North American Höganäs) and the new machinability enhancer (SM4, North American Höganäs) were compared to a mix with no machining additive. The base iron powder (ASC100.29, North American Höganäs) was mixed with the machinability 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 1.

Table 1 Chemical compositions of premixes used for laboratory tests

Premix	ID	Base iron	Chemical Composition, %wt			
			Cu	Graphite	Lubricant	Additive
FC-0208	**A**	ASC100.29	2.0	0.8	0.75	None
	B	ASC100.29	2.0	0.8	0.75	0.5%MnS
	C	ASC100.29	2.0	0.8	0.75	0.3%SM3
	D	ASC100.29	2.0	0.8	0.75	0.3%SM4

Compaction and Sintering

For performance evaluations in laboratory machining tests, the mixes were compacted into ring specimens with dimensions ϕ55 x ϕ35 x H20 mm and a green density of 6.9 g/cm^3. The rings were then sintered in a mesh belt furnace at 1120 °C (2050 °F) for 20 minutes at temperature in an atmosphere of 90% nitrogen and 10% hydrogen with a normal cooling rate of 0.5 °C/s (1°F/s). In addition, specimens for transverse rupture strength were compacted to a green density of 6.9 g/cm^3 and sintered in the same sintering conditions.

A target application component was selected for performance verification in full scale production trials. Figure 1 shows the schematic diagram of the component which is currently made by a Fe-Cu-C material (FC-0208) with a commercial additive SM3 as the machinability enhancer. For the full scale production trials, components made with the same mix where the SM3 was replaced by the new machining additive SM4 were compacted and sintered according to the manufacturing specifications.

Laboratory Machining Tests

The machinability of the Fe-Cu-C materials made from the mixes listed in Table 1 was evaluated with the sintered ring specimens in two types of machining operations: drilling and turning. For drilling, a CNC mill was used with a coated tungsten carbide drill bit to drill ϕ3mm blind holes in a depth of 18mm with a feed rate of 0.1mm/rev. For turning, a CNC lathe was used with a coated tungsten carbide insert to cut the inner diameter (ID) of the ring specimen with a feed rate of 0.2mm/rev. The depth of each cut was 0.25mm. All machinability tests were performed in a wet condition using coolant. Machining performance was evaluated by measuring the tool wear after a number of holes and cuts were made using a scanning electron microscope (SEM).

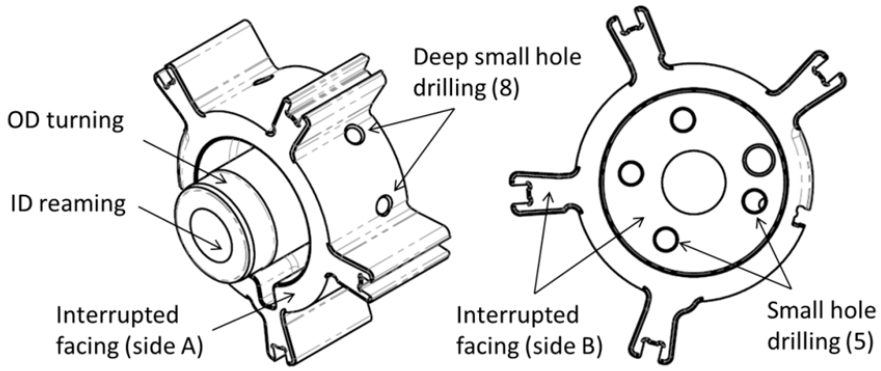


Figure 1 Schematic diagram of component used for full scale production trials

Full Scale Production Machining Trials

The components made with the current Fe-Cu-C mix with SM3 and the trial mix with the new machining additive SM4 were machined in a fully automatic production line involved drilling and turning operations. A 5-axis CNC mill was used for the drilling with a coated tungsten carbide drill bit to drill deep small holes on the outer diameter of the component. A total of 8 holes were drilled for each component. The turning operation was performed in a CNC lathe equipped with a cBN insert, a coated tungsten carbide insert and a coated cermet insert respectively used for OD turning, interrupted face cutting in two sides (Figure 1). The cutting parameters were specified based on the type of tools and the manufacturing specifications. All machining was conducted in a wet condition using coolant. Machining performance was verified by measuring the tool wear and surface finish after a number of components were machined.

Material Property Tests

Transverse rupture specimens were used to evaluate apparent hardness, dimensional change and transverse rupture strength according to MPIF standard test methods [15]. The transverse rupture strength bars were also tested for sintered density and diffused carbon content. In addition, analysis for microstructure and hardness were completed on the application components.

The effect of machinability enhancers on surface stains and corrosion was investigated using a humidity chamber at 45°C with 95% relative humidity (RH) on sintered ring specimens. The amount of corrosion (rust) was examined by photography every 24 hours for 5 days.

RESULTS

Performance evaluations in laboratory machining tests

Drilling test with ring specimen

The results obtained from drilling tests on the Fe-Cu-C materials with and without machinability enhancing additive are shown in Figure 2. The tool wear was measured on the two cutting edges of the drill bit after it drilled 360 and 720 holes respectively. For the material without additive, excessive wear was observed on the cutting edges after it drilled 360 holes and the drill broke after 613 holes were

drilled. By adding a machinability enhancing additive, the machinability of the Fe-Cu-C material was improved. The SM3 containing material could be drilled 720 holes without tool failure even though excessive tool wear was observed. The material with MnS addition presented good machinability in drilling with much less tool wear than the material with SM3 addition. Compared to the commercial additives SM3 and MnS, the newly developed machining additive, SM4, exhibited great improvement in machinability with the least tool wear after 720 holes were drilled. Figure 3 shows the status of tool wear after the drilling operation.

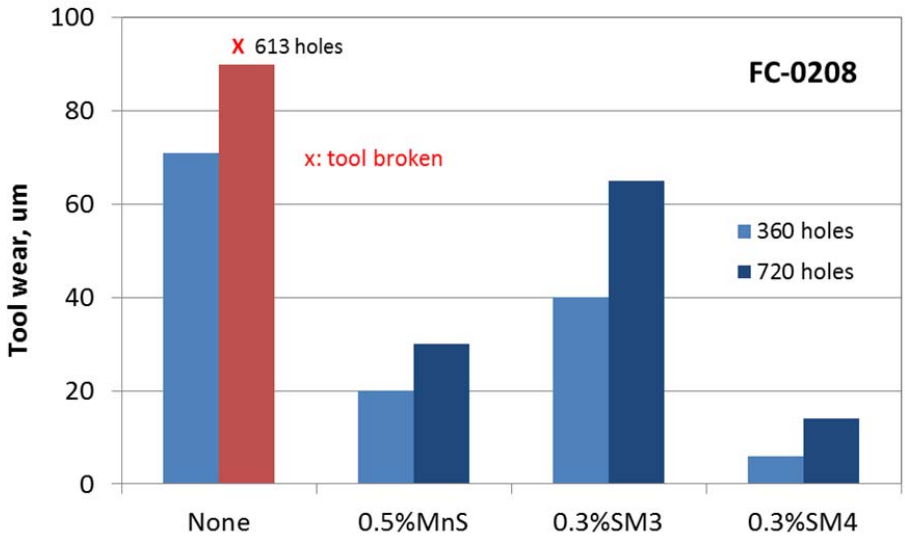


Figure 2 Comparison of tool wear after drilling the Fe-Cu-C materials with and without additive. ϕ3mm drilling (wet): 0.1mm/rev feed, 18mm depth blind hole

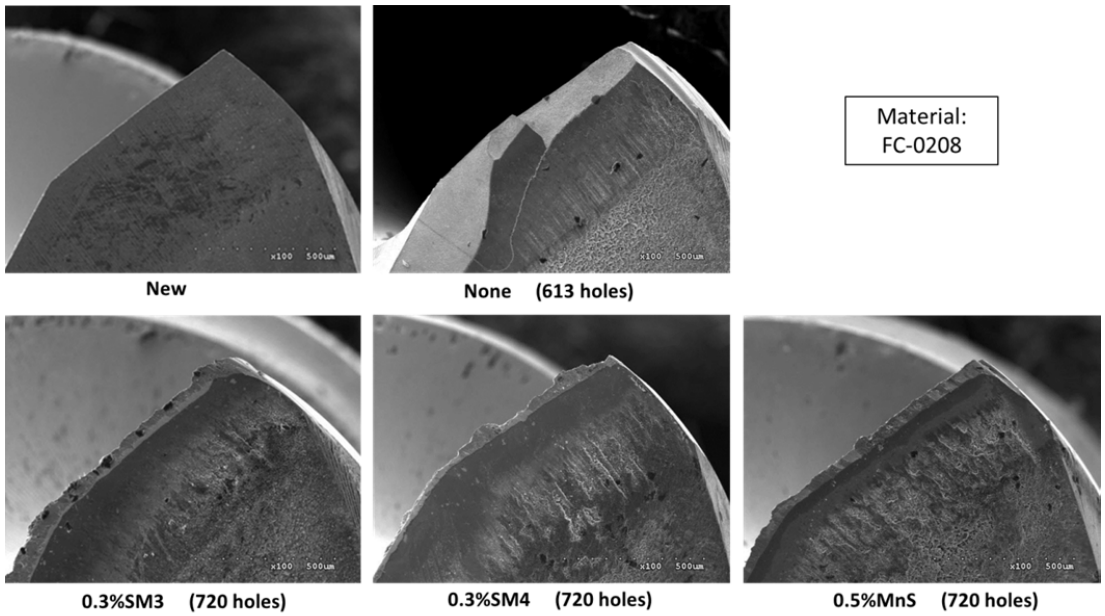


Figure 3 Status of tool wear after drilling on the Fe-Cu-C materials with and without additive

Turning test with ring specimen

The results obtained from turning tests on the Fe-Cu-C materials with and without machinability enhancing additive are shown in Figure 4. The tool wear was measured as flank wear on the insert after it cut 180 and 240 cuts respectively. When the material without additive was cut, excessive wear was observed on the insert after 180 cuts. By adding a machinability enhancing additive, the machinability of the Fe-Cu-C material was significantly improved with longer tool life (more cuts) and much less tool wear. Compared to the MnS, the SM3 and SM4 provided superior performance in improving machinability. After 240cuts, they were still maintaining normal tool wear (100μm or less) while the MnS exhibited more tool wear (>200μm). Again, the new machining additive SM4 demonstrated its potential for improving the machinability of Fe-Cu-C material in turning operation. Figure 3 shows the status of tool wear after the turning operation.

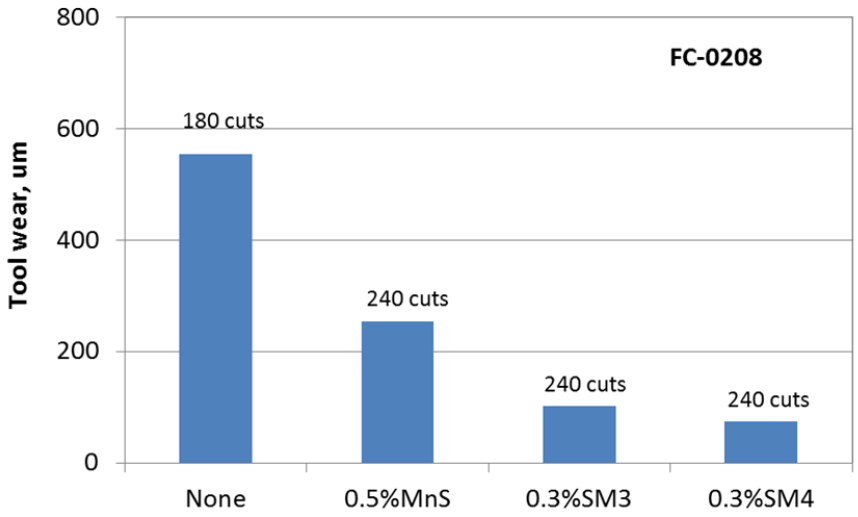


Figure 4 Comparison of tool wear after cutting the Fe-Cu-C materials with and without additives. ID turning (wet) : 0.2 mm/rev feed, 0.25 mm depth per cut

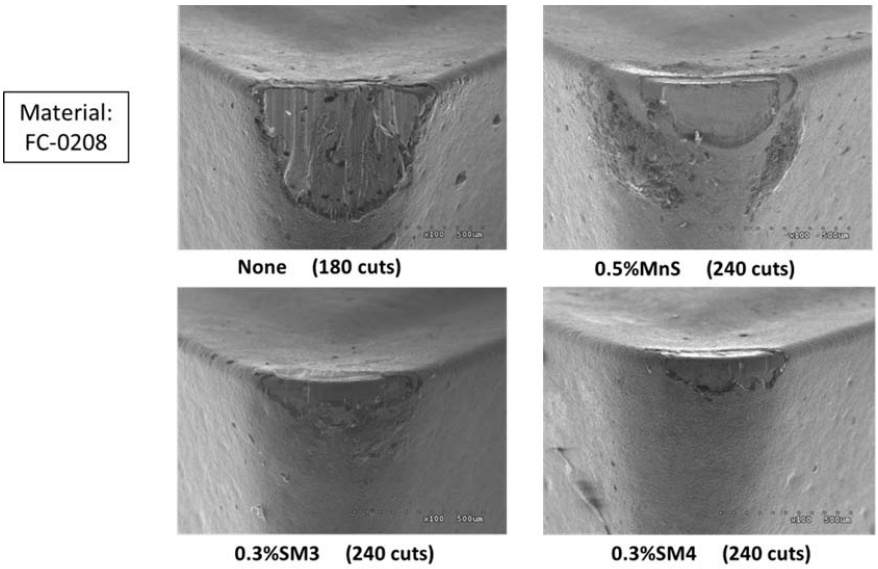


Figure 5 Status of tool wear after turning on the Fe-Cu-C materials with and without additive

Performance verification in full scale production machining trials

The laboratory machining tests demonstrated the capability of the new machining additive, SM4, in improving the machinability of Fe-Cu-C material not only for drilling operation but also for turning operation. For the performance verification, therefore, full scale production trials were conducted by selecting an application component which requires both drilling and turning operations. The component is currently made by a Fe-Cu-C mix (MPIF FC-0208) containing SM3 as the machinability enhancing additive. The MnS additive is not an option for this application due to its propensity to stain and rust. The machining operations are fully automatic, including heavy interrupted face cutting on the two sides and deep small hole drilling on the outer diameter. Figure 6 illustrates the major machining steps performed on the components.

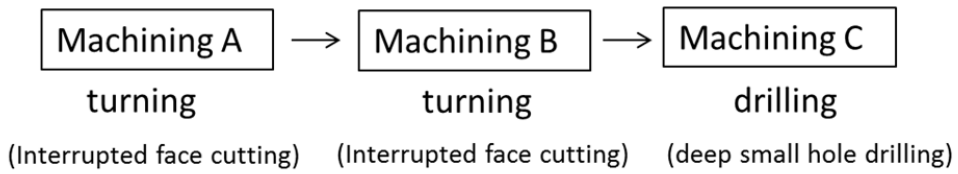


Figure 6 Flowchart of major machining operations for production trials

The results obtained from the full scale production trials to compare the performance between the current additive SM3 and the new additive SM4 are presented in Table 2.

Table 2 Results from full scale production machining trial comparing the performance of SM3 and SM4 machining additives used in the Fe-Cu-C material

Material	Operation	type	tool life, pcs	tool wear, μm	remarks
FC0208-SM3	machining A	turning	500	61, 118	tool changed at 500pcs as scheduled
	machining B	turning	500	76, 71	tool changed at 500pcs as scheduled
	machining C	drilling	299, 371	broken	drill edge chipped with oversize holes
FC0208-SM4	machining A	turning	1000	82, 106	terminated at 1000pcs without issues
	machining B	turning	1000	95, 56	terminated at 1000pcs without issues
	machining C	drilling	1000	417	terminated at 1000pcs without issues

In current production, the typical tool life is 500pcs in both turning and drilling operations. During the trials, the current material with SM3 could be cut for 500pcs in turning without severe tool wear, as expected. However, there were two occurrences of tool breakage during drilling at 299pcs and 371pcs respectively. The chipped drill edges caused the hole to be oversized and out of print tolerance. When the trial material with SM4 was machined, the part was able to be cut for 1000pcs in turning and the tools still maintained the similar level of wear as the current production. For drilling, the SM4 containing material could be drilled for 1000pcs without tool breakage. No oversize holes were found even though the cutting edge was severely worn after 1000pcs. Overall of the machining met the specifications. The trial

was terminated after 1000pcs since the machining line needed to resume regular production. Figure 7 summarized the results of the production trials comparing the tool life in machining of the components when the SM3 and SM4 were respectively added as the machinability enhancing additive. The status of tool wear in each machining operation used in the full scale production trials is shown in Figure 8~10.

The production trials verified that the new machinability enhancing additive SM4 could provide significant improvement in machinability for both turning and drilling operations. Compared to the current machining solution using SM3, the SM4 could extend two times of the tool life.

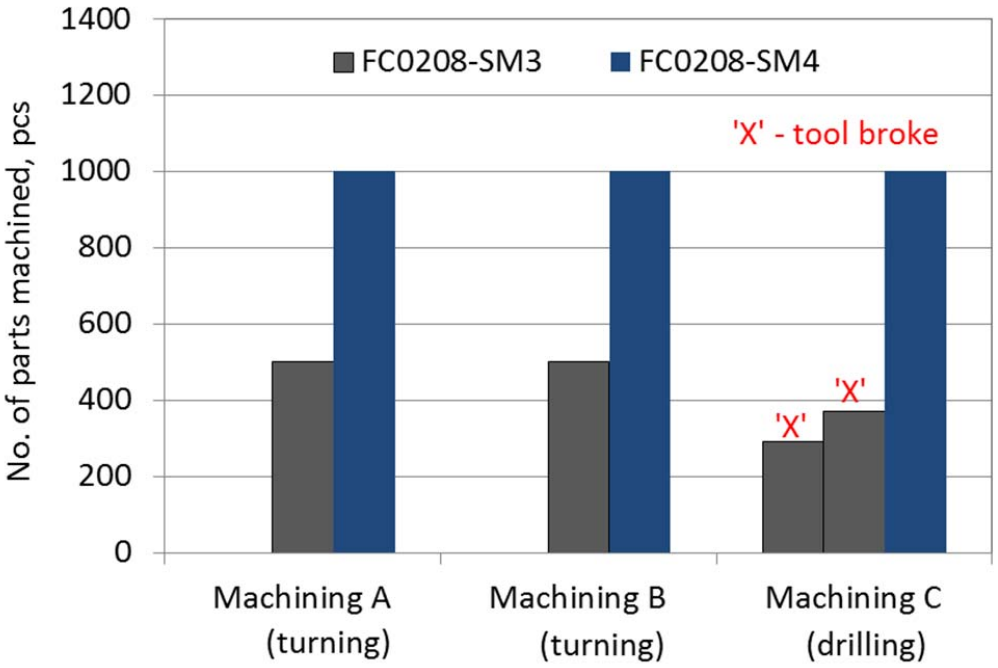


Figure 7 Comparison of tool life in machining of the Fe-Cu-C material with adding SM3 and SM4 additives respectively

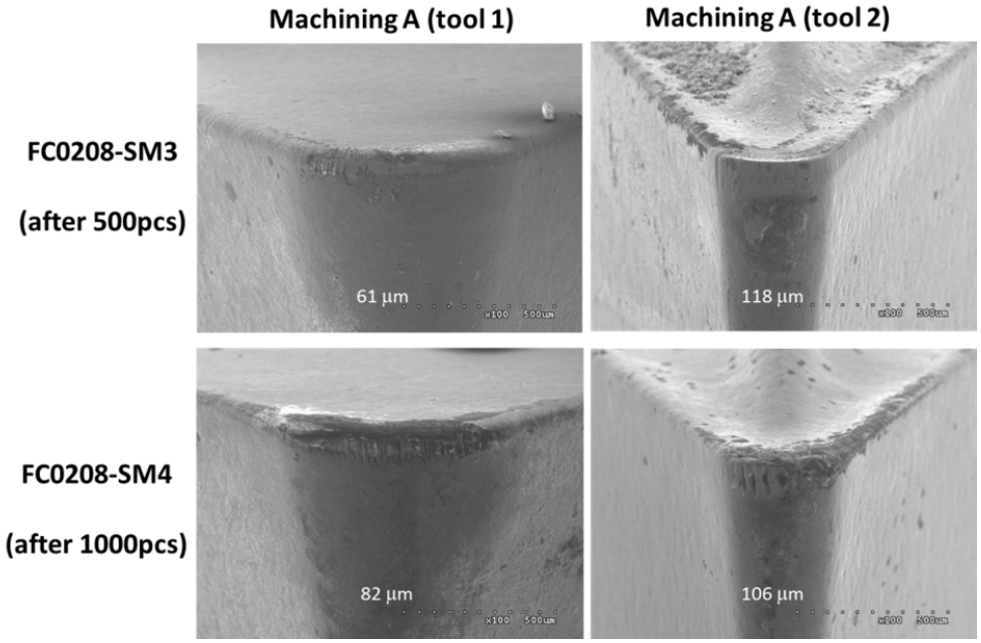


Figure 8 Status of tool wear in machining A (turning) of the Fe-Cu-C materials

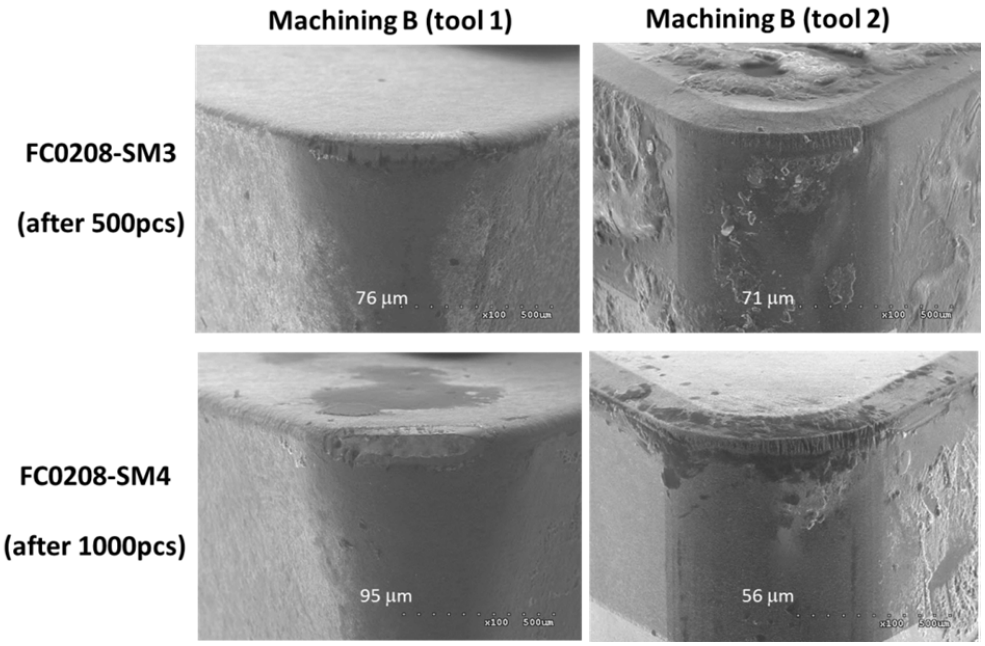


Figure 9 Status of tool wear in machining B (turning) of the Fe-Cu-C materials

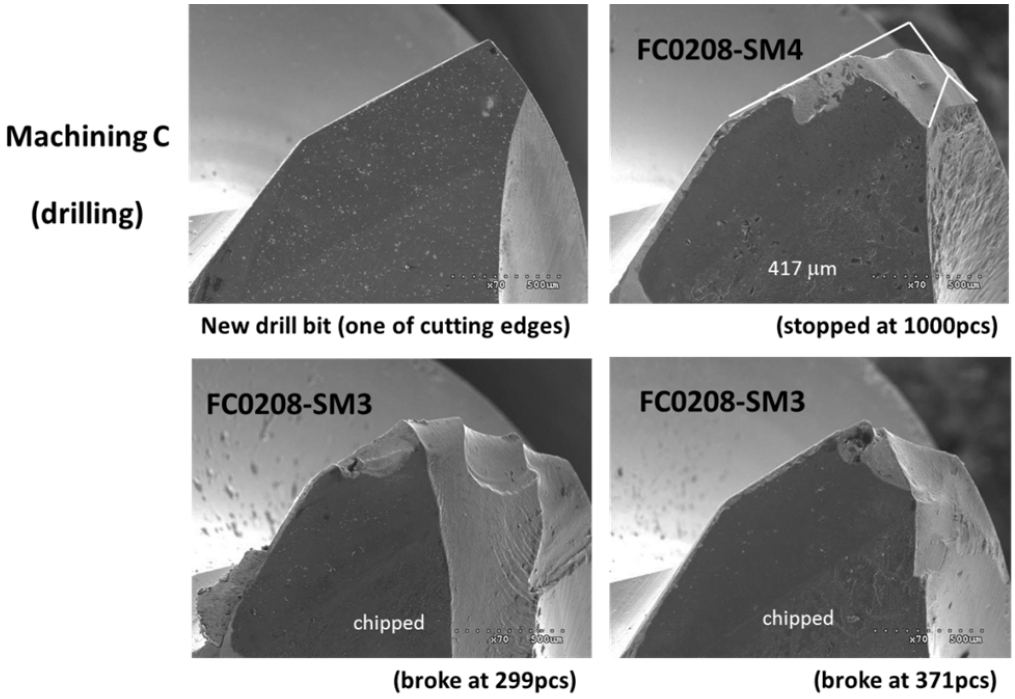


Figure 10 Status of tool wear in machining C (drilling) of the Fe-Cu-C materials

DISCUSSIONS

As a machinability enhancing additive, manganese sulfide (MnS) has been recognized as an outstanding agent to improve the machining of PM materials, especially for Fe-Cu-C materials. However, it is often prohibited to use in many applications due to stringent visual criteria regarding stain and surface rust. The principal of MnS in improving the machinability is a combination of solid lubricant, chip breaker and tool protector [16]. In commercially available machining additives, few of them could provide such combined features as seen with MnS. Common additives such as hexagonal boron nitride, calcium fluoride and talc are considered as good solid lubricants and appear to provide good drilling performance for some of PM materials but their turning performance is usually limited.

The commercial additive SM3 is a recent answer to the application without the concerns found with MnS. The additive is proprietarily formulated as engineered composites based on tribological concepts. It can significantly improve the machinability of PM materials, especially for turning operation where its performance exceeds to the MnS. In this study, it has clearly demonstrated the performance of SM3 in turning operation compared to the MnS. During machining, it is considered to provide tool protection through a favorable transfer film generated by friction heat between the tool and work piece. The new machining additive SM4 was developed under the same concepts but it was specifically formulated for use in machining of Fe-Cu-C materials, a material composition widely used for manufacturing PM components.

Drilling and turning are two very different machining processes. Drilling is performed in a closed environment while turning is performed in an open environment so the heat generation and removal are totally different. When a deep, small hole is drilled, the coolant has difficult time to penetrate into the drilled hole under high drilling speeds (rpm) so that the drilling becomes more difficult and less efficient.

The tool geometry and available tool materials for drilling are limited compared to turning operation. A drill bit uses two and more sharp cutting edges to do the job. The available matrix materials are limited to either high speed steel or tungsten carbide. For an insert, however, it can be made more durable for a single point cutting and it can be made from a wide selection of matrix materials such as carbide, cermet, ceramic and cBN, etc. Due to differences in the machining operations, therefore, the extent of machinability enhancement by a machining additive is not equal in drilling and turning operations, usually it presents a large difference. For example, a machining additive which performs well in drilling doesn't mean it will perform well in turning. Commercial practices in machining Fe-Cu-C materials indicate that MnS performs much better in drilling than in turning while SM3 acts as the opposite. In this study, the new machining additive SM4 demonstrated its capability to combine the machinability enhancing features from MnS and SM3, i.e. it provide significant improvement in machinability for Fe-Cu-C material not only for drilling but also for turning operations.

The laboratory tests evaluated the performances of the new additive under accelerated wear conditions with simplified work pieces and controlled parameters to determine its effectiveness in machinability improvement, optimal addition and suitable machining environment. This study presented a good example how a pre-assessment under laboratory conditions is essential to ensure successful production trials using actual components. The results obtained in the laboratory tests provided effective information that resulted in a successful production trial.

The production trials performed in a full scale automatic machining line provided verification of performance with the new additive. In drilling operation, the SM4 containing material could be continually drilled for 1000pcs (i.e. 8000 deep small holes) without tool failure while the SM3 containing material is typically drilled for <500pcs (i.e. <4000 deep small holes) in current production. Figure 11 illustrates the appearance and size of holes drilled on the two materials.

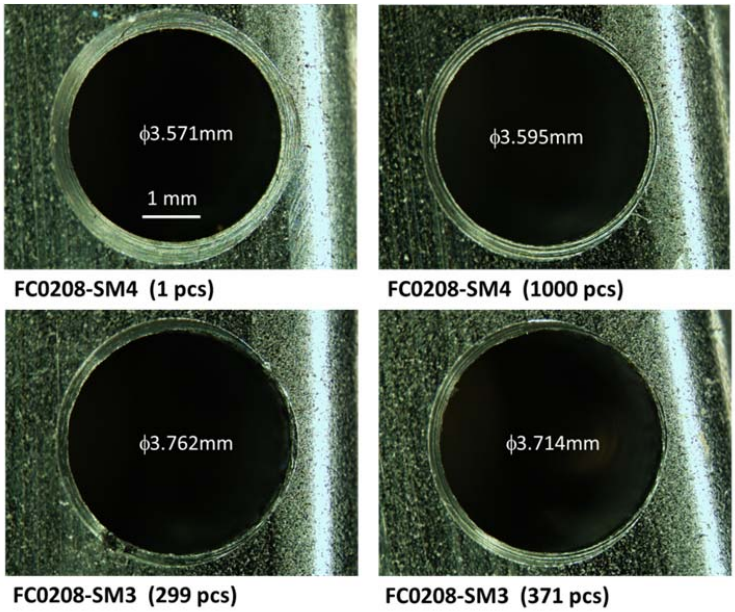


Figure 11 Comparison of hole size after the drilling of Fe-Cu-C materials with SM3 and SM4 additives. Oversize holes are found in the materials with SM3 due to the chipped tools

Compared to the holes made in the first part, there is no large difference in size after drilled 1000pcs of the material with SM4. For the current material with SM3, however, oversize holes were observed due to the tool breakage after drilling 299pcs and 371pcs respectively. In the turning of this component with the current material, the inserts are typically changed every 500pcs in order to meet the thickness specification. When the material with SM4 was machined, the inserts cut 1000pcs without offset and the dimensions were still within the specifications. Figure 12 shows the dimension measurement on the machined parts containing SM3 and SM4 respectively. The thickness was measured in two locations apart from 180° of the part. The trial material with SM4 showed consistent dimension in the machined thickness after the inserts were stabilized from initial wear.

In conclusion, the improved machinability achieved with the new additive for this component is not only to extend tool life but also to increase productivity through reducing downtime and tool change caused by unpredictable tool breakage or short tool life, resulting the total machining cost is reduced.

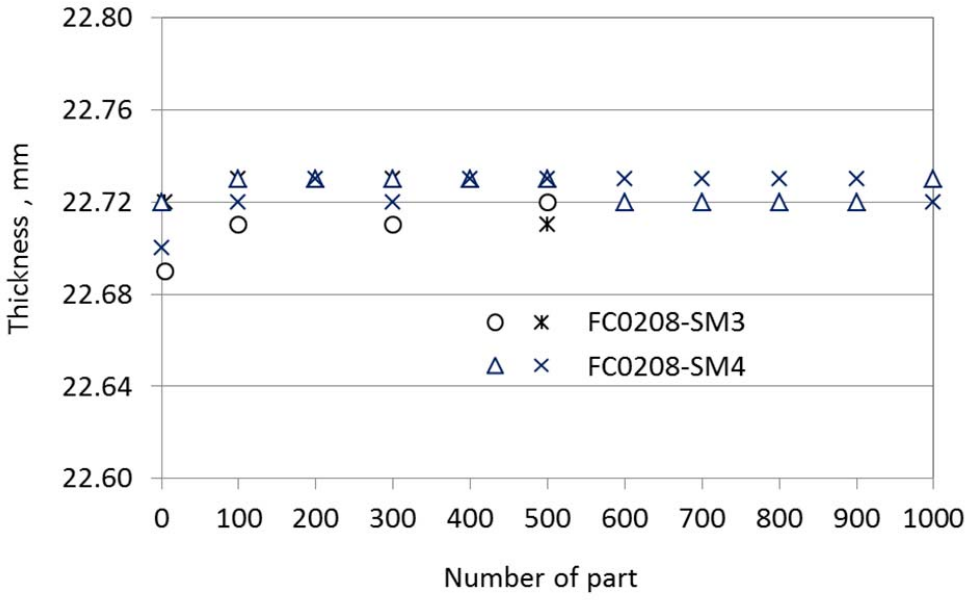


Figure 12 Thickness of machined parts without tool offset after the turning of Fe-Cu-C materials with SM3 and SM4 additives

Prior to the machining, the trial components were examined for all manufacturing processes based on the same procedure for the production of current material. The SM4 containing material met all QC specifications in compaction and sintering and was found to be identical to the current material. Figure 13 presents the microstructures and hardness of the trial material compared to the current material. Both of the materials have a full pearlitic microstructure with identical microhardness (MHV).

In addition, the sintered and mechanical properties of the Fe-Cu-C material (FC-0208) with and without additives were also examined based on MPIF standard procedures. The results are shown in Table 3. As same as the commercial additive MnS and SM3, the new machining additive SM4 has no significant detrimental effect on the sintered and mechanical properties. Figure 14 presents the results obtained from corrosion tests performed in a humidity chamber at 45°C in 95% relative humidity (RH). As described

before, MnS promoted the rust on the component and became fully rusted after 4 days in the humidity chamber. Under the same conditions, the SM4 containing part was observed to be the same as the part with no additive, i.e. the SM4 has no detrimental effect on the corrosion resistance of Fe-Cu-C materials.

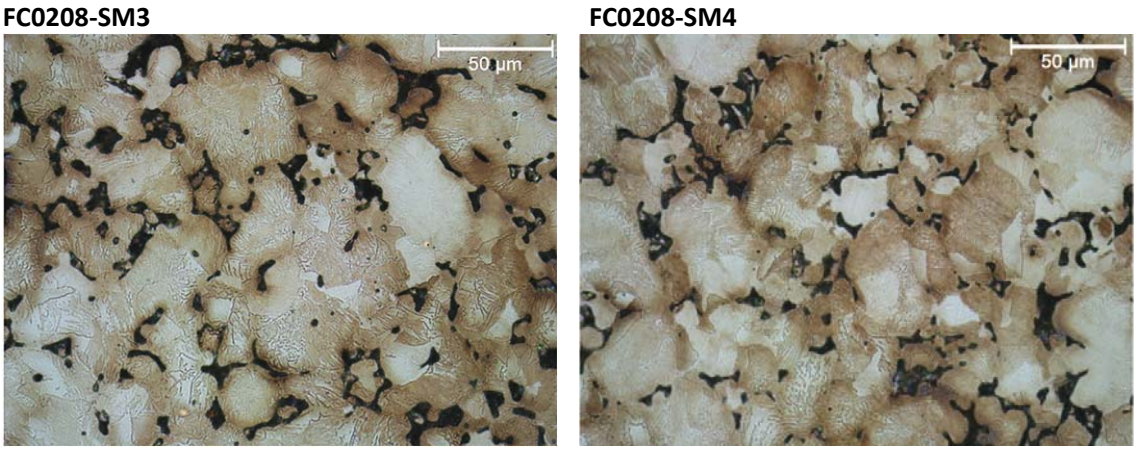


Figure 13 Microstructures and hardness of the Fe-Cu-C materials used in production trials

Table 3 Sintered and mechanical properties of Fe-Cu-C materials with and without additive

Material: FC0208

Material ID additive	**A** none	**B** 0.5%MnS	**C** 0.3%SM3	**D** 0.3%SM4
GD, g/cm^3 SD, g/cm^3	6.84 6.74	6.84 6.72	6.86 6.72	6.84 6.71
TRS, MPa (kpsi) HRB	1000 (145) 77	951 (138) 74	1014 (147) 76	986 (143) 75
%DC %C	0.28 0.73	0.30 0.74	0.29 0.71	0.30 0.72

Note: TRS bars were compacted at 414 MPa (30 tsi) and then sintered in 1121°C (2050°F) in 90/10 N_2/H_2 for 20min.

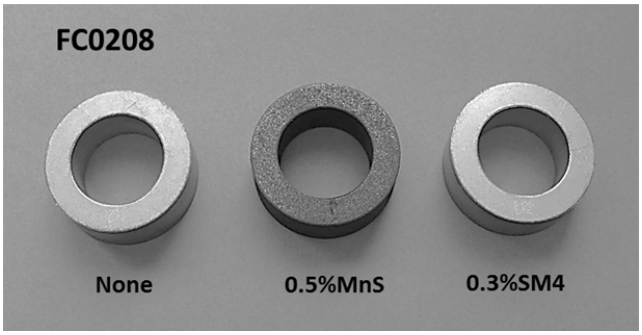


Figure 14 Corrosion test on the Fe-Cu-C materials after 5 days at 45°C in 95%RH

CONCLUSION

The performance of the newly developed machinability enhancing additive has been evaluated in laboratory machining tests with a common Fe-Cu-C material. The improved drilling and turning performance was further verified through full scale production machining trials with actual application component. Comparing the materials with and without additive, the following conclusions can be made from this study:

1. The new machinability enhancer SM4 is proven to be able to provide significant improvement in the machinability of Fe-Cu-C materials for both drilling and turning operations. This improvement can result high productivity machining and/or extended tool life so that the reduction of total machining cost can be achieved

2. Compared to the commercial additives, the new machining additive exhibits better performance than MnS in turning and superior performance to SM3 in drilling. With a smaller addition, it provides similar performance to MnS in improving drilling of Fe-Cu-C materials. The improved machinability performances are achieved by its ability in tool protection during machining

3. The new machinability enhancer is found to have no detrimental effects on the sintered and mechanical properties of the material system. Unlike the commercial additive MnS, no stains and no rust promotion are observed when this new machining additive is used

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