IMPROVING THE MACHINABILITY OF HARDENED MATERIAL

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ABSTRACT

The machinability of powder metal (PM) steels depends on the microstructure of the steel. With increasing carbon levels and alloying the machinability of PM steels decreases. Heat treatment only increases the difficulty of machining. To improve machinability of PM steels, machining enhancers are often admixed with the steel powder. In previous studies, the SM3 additive has been shown to greatly improve the machinability of different PM steels while not negatively affecting mechanical properties or corrosion resistance. In this study, the SM3 additive is evaluated in both carburized and sinterhardened materials. The additive will be evaluated on both laboratory and production components. The results of the study show SM3 offers an opportunity to improve both tool life and productivity when machining hardened materials.

INTRODUCTION

When high strength or fatigue performance is required for a powder metal (PM) application, heat treatment can be applied to PM steels to meet performance requirements. PM alloys can be heat treated using a conventional quench and temper process or using the sinter hardening process. Both the heat treatment process and the sinter hardening process manipulate the microstructure using sufficient cooling rates to produce a predominately martensitic microstructure.

Ideally, PM components are net shape and require no secondary machining. However, secondary machining is often required to meet final dimensional tolerances, provide a specified surface finish, or produce a feature which cannot be produced through compaction.[1] The machinability of PM components depends on the microstructure which is generated. Higher hardness microstructures such as bainite and martensite can be difficult to machine resulting in high wear and short tool life.[2] The use of PVD and CVD coatings on carbide or cermet inserts typically is not sufficient to provide acceptable productivity and cBN inserts are required.[2]

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One of the advantages of the PM process is the ability to introduce machining additives into the material system through the blending process. Machining additives have long been used in the PM industry to help improve the machinability of the PM steels.[3] While MnS works well with lower strength iron – copper – carbon materials, as the alloying content of the PM steel increases, the effectiveness of MnS decreases.[4,5] The corrosion issues associated with MnS also restrict it use as a solution for machinability in many cases.

The machining of high strength structures will be critical to the success of the PM industry as it expands into more demanding, high performance applications. For PM producers to be successful, they will require materials which meet the strength requirements while maintaining sufficient machinability. The machining additive SM3 has been demonstrated to provide improved tool life and productivity in high strength materials.[2]

In this study, laboratory testing is used to screen potential materials for a high performance application which requires high temperature sintering in conjunction with a heat treatment step. Based on the laboratory results, a production machining trial was conducted to confirm the results and evaluate the suitability of materials for production.

EXPERIMENTAL

The target application for this trial is shown in Figure 1.

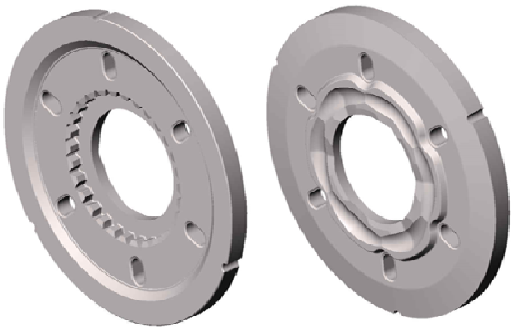


Figure 1. Target application for machining trials.

Due to the mechanical requirements of this application, a martensitic material will be required. The process to produce a martensitic microstructure would be high temperature sintering followed by either carburization or sinter hardening. Three materials were identified as candidates to meet the mechanical performance.

Table 1. Materials selected for study (wt%)

Base Iron	MPIF Code	Copper	Nickel	Molybdenum	Chromium
D.AE	FD-0400	1.5	4.0	0.5	-
Astaloy CrM®	FL-5300	-	-	0.5	3.0
Astaloy CrL®	FL-5200	-	-	0.25	1.5

Note: D.AE is diffusion alloyed, Astaloy CrL & Astaloy CrM are prealloyed

The diffusion alloyed material was selected for carburization, while the chromium prealloys were sinter hardened. For the laboratory machining trials, five materials were evaluated to determine suitable materials for the production machining trials. The materials chosen are shown in Table 2.

Table 2. Materials evaluated in laboratory machining trials (wt%)

Mix ID	MPIF Designation	Base Iron	Copper	Graphite	SM3	Lubricant
FD-0405	FD-0405	D.AE	-	0.4	-	0.6
FD-0405 + SM3	FD-0405	D.AE	-	0.4	0.1	0.6
FL-5305	FL-5305	Astaloy CrM®	-	0.75	-	0.6
FL-5305 + SM3	FL-5305	Astaloy CrM®	-	0.75	0.1	0.6
FLC2-5208 + SM3	FLC2-5208	Astaloy CrL®	2	0.8	0.1	0.6

The graphite levels chosen were based on a pre-study to account for the high temperature sintering operation. Natural graphite (Asbury 1651) and water atomized copper (Royal Metal Powder Cu-165) were used in the premix production. From these premixes, ring specimens with dimensions 55 mm □ x 35 mm □ x 20 mm height (2.2 in x 1.4 in. x 0.8 in) were compacted at a pressure of 600 MPa (43.5 tsi). The ring specimens were then processed by Engineered Sintered Components (ESC) using the procedure described in Table 3.

Table 3. Ring specimen processing parameters

Sintering Temperature	1260 °C (2300 °F)	
Sintering Time	180 minutes	
Sintering Atmosphere	90 % Nitrogen / 10 % Hydrogen	
Heat Treatment	Carburzing 2 hours 1.1% $C_{potential}$	Sinter Hardening 2 °C/s cooling rate
Tempering	205 °C (400 °F), 60 minutes, air	

The rings were machined at the North American Höganäs machining center using the parameter listed in Table 4.

Table 4. Laboratory machining parameters

Operation	Facing		
Insert type	cBN		
Condition	Dry machining		
Cutting speed (sfm)	900	600	475
Feed rate (mm / rev)	0.30		
Depth of Cut (mm)	0.2 mm		
Length of Cut (mm)	10 mm		

The machine setup is pictured in Figure 2.



Figure 2. Laboratory facing operation set up

At each cutting speed, a number of cuts were made for each material the wear on the insert was measured using a scanning electron microscope. Microstructure analysis, microindentation hardness, apparent hardness, density and carbon were completed on the machining rings.

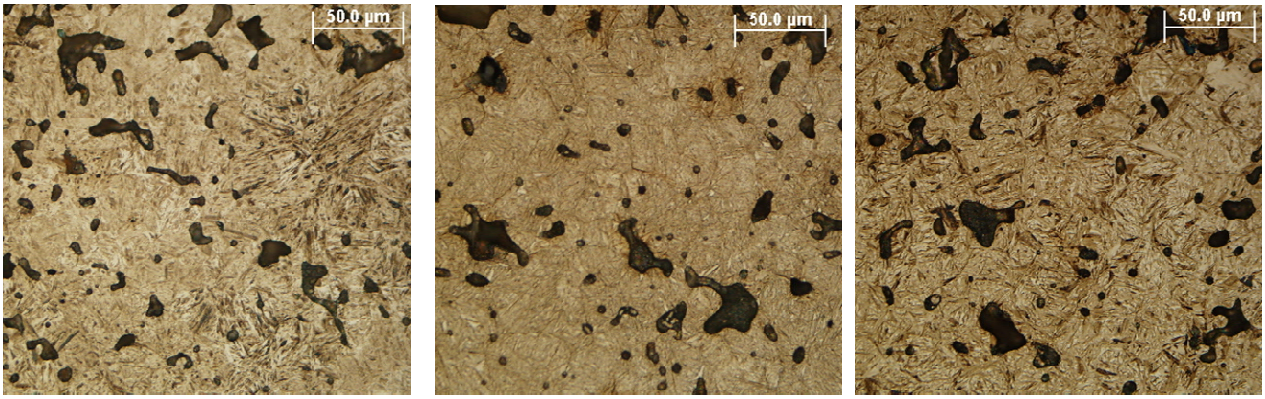
LABORATORY MACHINING RESULTS

The measurements for density, apparent hardness, carbon, and microhardness are shown in Table 5.

Table 5. Laboratory machining specimen properties

Material	Apparent Hardness (HRC)	Sintered Density (g/cm^3)	Sintered Carbon (%C)	Microhardnes ($HV_{0.1}$)
FD-0405	41	7.21	0.48	630
FD-0405 + SM3	42	7.22	0.49	632
FL-5305	43	7.05	0.55	657
FL-5305 + SM3	44	7.05	0.57	663
FLC2-5208 + SM3	42	7.01	0.74	648

Microstructure photographs are shown in Figure 3.



a.) **b.)** **c.)**

Figure 3. Laboratory machining specimen microstructure photographs: (a.) FD-0405, (b)FL-5305, (c)FLC2-5208).

The pore structure of the materials was rounded due to the high temperature sintering. The FD-0405 materials had little nickel rich areas indicating good diffusion due to the long sintering cycle. The microstructure of all the materials rings was martensitic throughout.

The machining results are summarized in Table 6.

Table 6. Results of laboratory machining evaluation

Cutting speed	900 sfm		600 sfm		475 sfm	
Mix ID	No. cuts	tool wear	No. cuts	tool wear	No. cuts	tool wear
FD-0405	225	150nm	1200	300nm	-	
FD-0405+SM3	225	55um	1200	95um	-	
FL-5305	24	broken	165	broken	460	broken
FL-5305+SM3	38	broken	600	163um	900	139
FLC2-5208+SM3	233	broken	600	143um	900	79

The insert photographs at 900 sfm machining speed are shown in Figure 4.

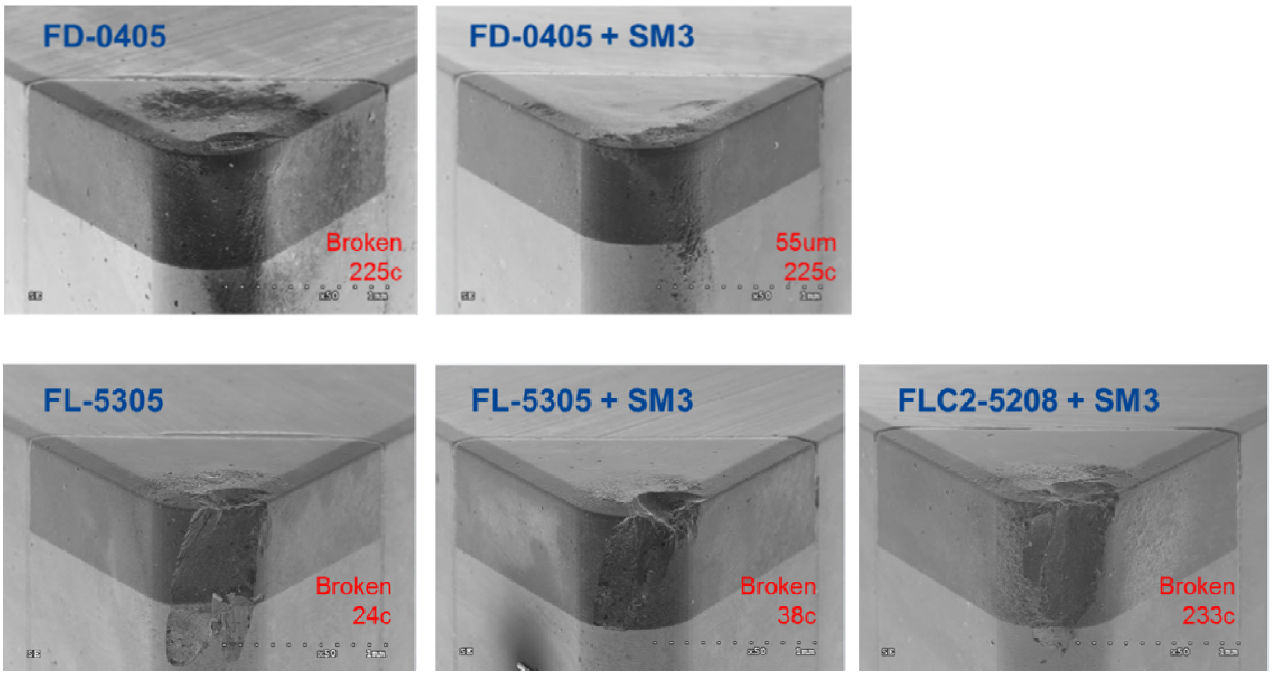


Figure 4. Laboratory insert analysis at 900 sfm.

At 900 sfm cutting speed, the tool life was poor for cutting the FD-0405, FL-5305 and FL-5305 + SM3 materials. These materials showed difficulty to machine which resulted in fracture of the insert after a small number of cuts (< 50 cuts). The FLC2-5208 + SM3 material was able to achieve 233 cuts before failure. For this material, a large amount of crater wear was observed on the failed insert. The only material able to achieve good tool life was the FD-0405 + SM3 material. For this material, only 55 µm of tool wear was observed after 225 cuts compared to the material without SM3 addition which caused excessive tool wear on the face and crater. The amount of wear on the FLC2-5208 + SM3 insert indicates further machining could have been completed with this insert.

The cutting speed was reduced to 600 sfm. The insert photographs are shown in Figure 5.

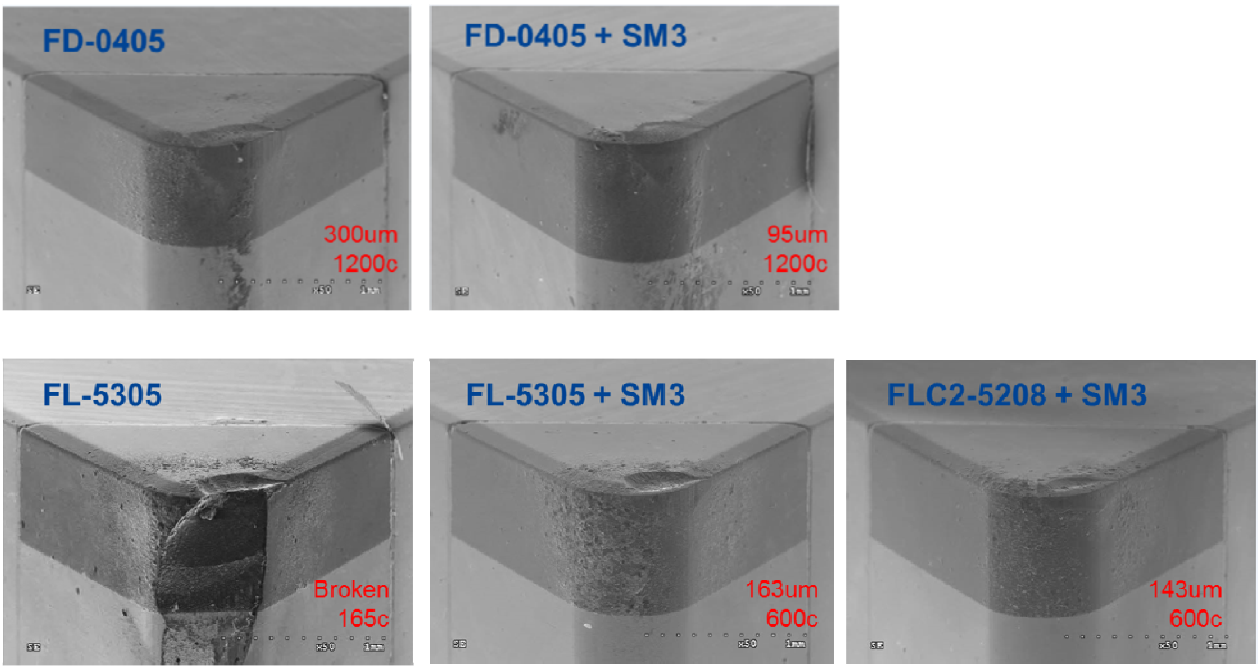


Figure 5. Laboratory insert analysis at 600 sfm.

The machining performance of all materials improved at this reduced speed. For the FD-0405 material, 1200 cuts were made before the tool failed due to excessive wear (300 µm). With the SM3 addition, the amount of tool wear after 1200 cuts was drastically reduced to only 95 µm. A similar trend was observed for the chromium materials. The FL-5305 insert broke after 165 cuts. With the SM3 addition, 600 cuts were able to be made and only 163 µm of tool wear was observed. The FLC2-5208 + SM3 material after 600 cuts had 143 µm of tool wear.

The machining speed was further reduced to 475 sfm. Since a high number of cuts were achieved for the FD-0405 based materials, they were not included in this round of testing. At this slow cutting speed, their tool life would be expected to increase dramatically. The insert photographs for the chromium materials are shown in Figure 6.

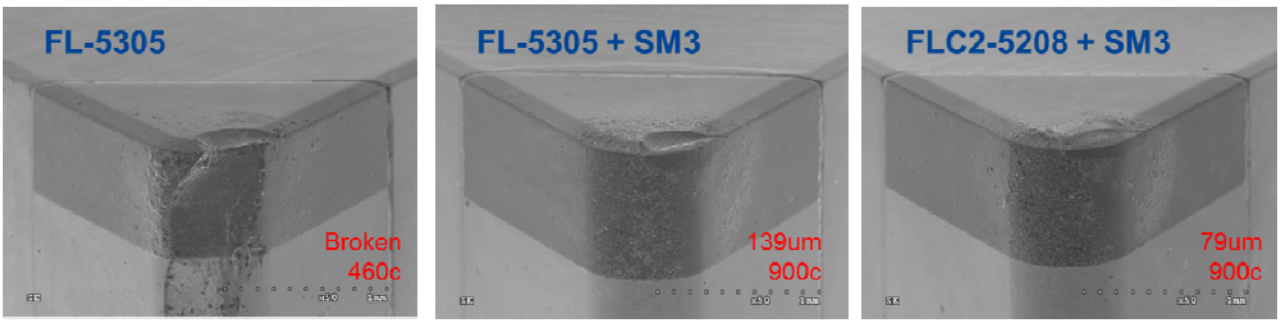


Figure 6. Laboratory insert analysis at 475 sfm.

Again, slowing down the cutting speed increased the machinability of the materials. All of the materials were able to achieve 300 cuts with a low amount of wear. The FL-5305 insert broke after 460 cuts. Both the FL-5305 + SM3 and the FLC2-5208 + SM3 were able to achieve 900 cuts with low wear. The FL-5305 + SM3 after 900 cuts had 139 µm of tool wear, mostly crater wear. The FLC2-5208 + SM3 had a very low amount of tool wear after 900 cuts: 79 µm with minor crater wear. Both of the materials with SM3 would have been able to continue cutting based on the tool wear observed.

Based on the laboratory results, only the materials with the machining additive were chosen for the production study. It was clear for these materials and processing conditions, good productivity in machining operations could not be achieved unless a machining additive was utilized.

PRODUCTION MACHINING RESULTS

The mixes from the laboratory machining study were chosen for the production trial. The production parts (Figure 1) were compacted, sintered and heat treated using the same process as the laboratory machining specimens. The components were machined by ESC in their production line using the conditions listed in Table 7.

Table 7. Production machining parameters

Operation	Facing
Insert type	cBN
Condition	Dry machining

A facing operation is completed on both sides of the component. A two-step operation is employed where each side receives a rough cut and then a finishing pass. Separate inserts are used for the facing operations of each side..

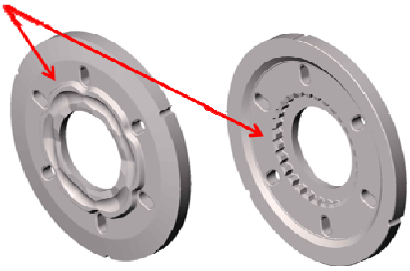
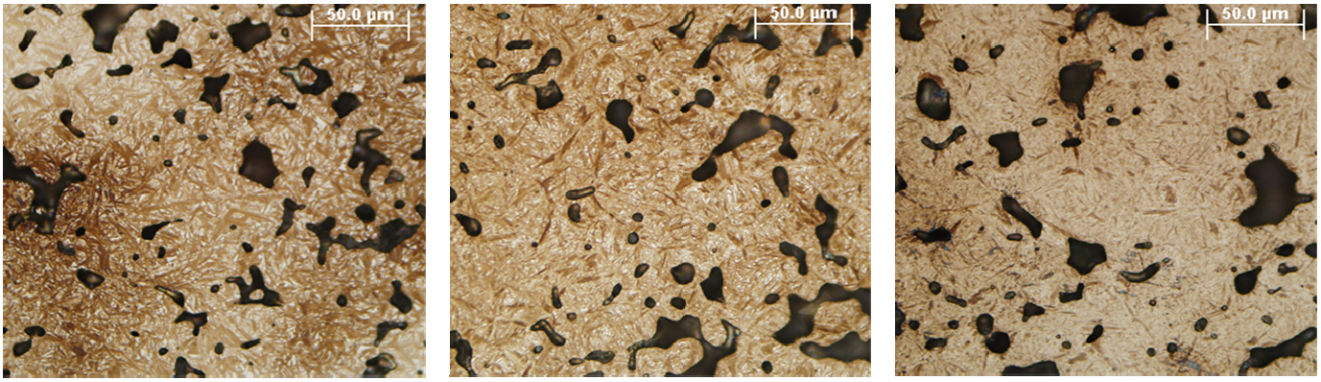


Figure 7. Areas on component which are machined

Based on the laboratory results, 200 components were machined for each material. The inserts for each side and operation were then collected and measured for tool wear using the same method as the laboratory specimens. Components were collected for apparent hardness, microstructure, and microhardness measurements.

The microstructures of the components are shown in Figure 8.



a.) **b.)** **c.)**

Figure 8. Microstructure of production components: (a) FD-0405, (b) FL-5305, (c) FLC2-5208

The FD-0405 material was martensitic with a good distribution of the nickel due to the high temperature sintering with very little nickel rich austenitic regions observed. Both of the chromium materials were martensitic throughout. The properties of the components are shown in Table 8.

Table 8. Properties of components used in production machining trial

Material	Apparent Hardness (HRC)	Carbon (%C)	Microhardness ($HV_{0.1}$)
FD-0405	41	0.51	626
FL-5305	43	0.54	660
FLC2-5208	43	0.77	640

The properties of the production components were similar to the laboratory specimens which were produced under the same conditions. The results of the machining are summarized in Table 9.

Table 9. Summary of tool wear for production machining trial

Mix ID	FD-0405	FL-5305	FLC2-5208
Additive	**0.1% SM3**	**0.1% SM3**	**0.1% SM3**
Side A			
Rough Cut	75 µm	146 µm	92 µm
Finish Cut	69 µm	107 µm	75 µm
Side B			
Rough Cut	33 µm	61 µm	40 µm
Finish Cut	56 µm	broken	108 µm

The production machining results mimicked the results observed in the laboratory testing. The FD-0405 material had the best overall performance from a wear perspective followed by the FLC2-5208 and the FL-5305. The FL-5305 had higher wear and the finishing insert on side B broke during the trial. This material also had the highest wear during the laboratory testing. The SEM photographs of the inserts for the machining of side A are shown in Figure 10.

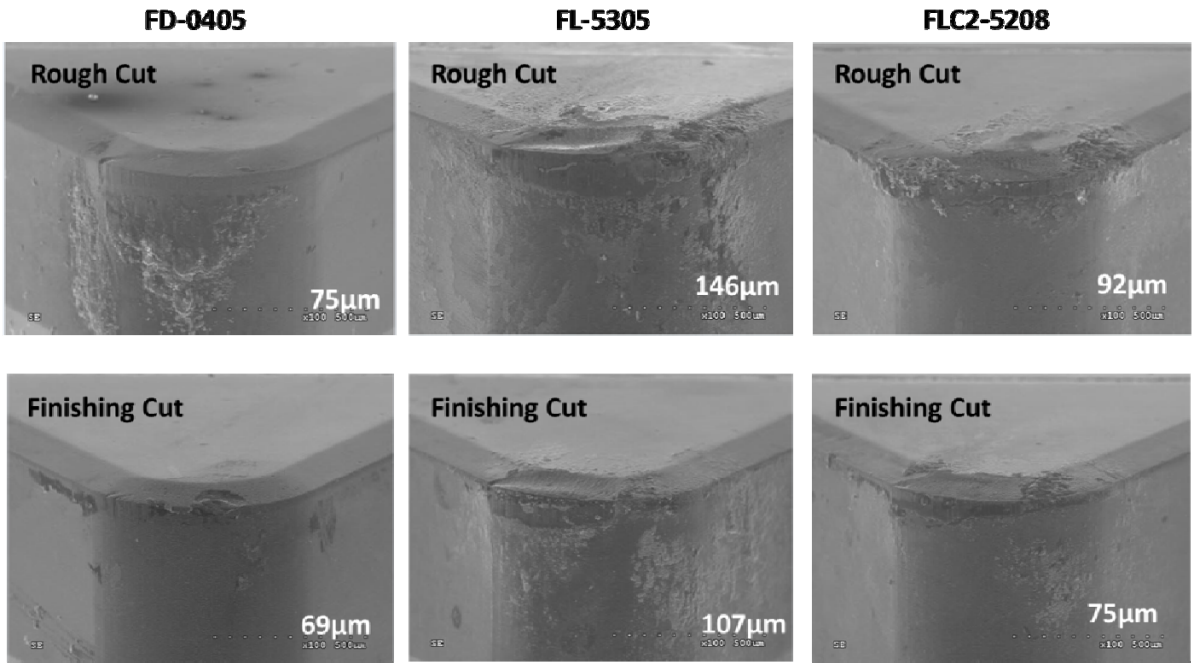


Figure 10. Production machining trial: Side A inserts analysis.

The FD-0405 material had a small amount of wear on the face of the rough cutting insert. The finishing insert had a small amount of wear; however a chip was observed indicating the start of crater wear. The FL-5305 material had more wear on the face and crater of the rough cutting insert. Based on the amount of wear, this insert would be expected to fail shortly if more cutting continued. The finishing insert had wear on the face and the start of crater wear was observed. The FLC2-5208 material had similar wear compared to the FD-0405 material.

The SEM photographs of the inserts for the machining of side B are shown in Figure 11.

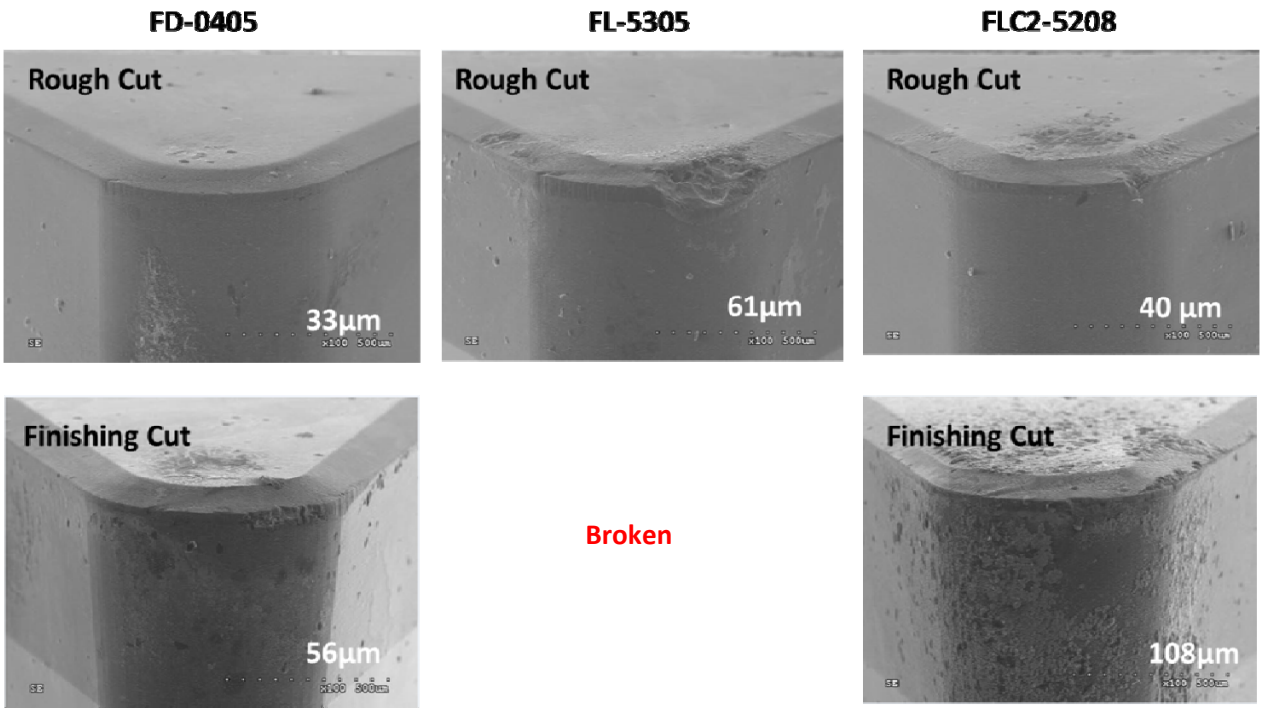


Figure 11. Production machining trial: Side B inserts analysis. (Note: FL-5305 finishing cut insert broke)

The amount of machining on side B of the component was less than side A. Only a small amount of wear was observed on both inserts for the FD-0405 material. The FL-5305 material had wear on the face of the rough cutting insert. The finishing insert fractured before 200 parts were machined. The FLC2-5208 material had minimal wear on the rough cutting insert similar to the FD-0405. The finishing insert had more wear than the FD-0405 on the face of the insert.

DISCUSSION

The machining of martensitic materials can be challenging due to the difficult nature of the microstructure. The martensite, due to its high hardness, wears the machining insert quickly as it passes through the material. At high cutting speeds, only a small number of cuts can be made before high amounts of wear are observed or insert failure occurs. For these materials, slow cutting speeds are required to minimize the amount of wear on the insert. These slower speeds result in lower productivity for the machining process. The use of the machining additive, SM3, provided a large benefit in the amount of wear on the insert. Even at high cutting speeds, a larger improvement in insert wear was observed compared to the same material with no additive addition.

In this study, a laboratory study was conducted to select possible candidates for the production trial. The study showed the FL-5305 material was the least machinable. By adding a small amount of the machining additive SM3, the amount of wear was reduced compared to no additive. The results of the laboratory study indicated that machining of the materials without the additive would result in high tool wear and low productivity.

The results of the laboratory study correlated with the results observed in the production environment. In the production environment, the same order of materials with regards to machinability was observed. The FL-5305 had the highest amount of wear during production machining and in one case tool failure occurred. The FD-0405 and FLC2-5208 had similar machinability with low amounts of wear observed on the inserts.

CONLCUSIONS

The following conclusions were drawn from this study:

- Machining of martensitic materials can be difficult requiring slower cutting speeds to minimize high amounts of tool wear. At faster cutting speeds, high amounts of tool wear were observed after only a small amount of cuts were made.
- The machining additive SM3 dramatically increased the machinability of the alloys evaluated. Using the additive decreased the amount of tool wear observed compared to the same material with no additive. The additive allows for increased productivity through faster cutting speeds and less down time due to tool changes.
- Laboratory machining testing can be a useful tool to screen candidate materials and conditions before full production testing is conducted. The laboratory testing in this study produced results which directly correlated to the results achieved in the production setting. The laboratory testing also showed that the materials without the machining additive would have high amounts of tool wear and were not worth testing in the production setting saving time and resources.

ACKNOWLEDGEMENTS

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