THE EFFECT OF MICROSTRUCTURE ON THE MACHINABILITY OF PM MATERIALS

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ABSTRACT

Sinterhardening is currently being used in the powder metal (PM) industry to meet the demands of high performance components. The alloys used for sinterhardening produce a predominately martensitic microstructure when subjected to rapid cooling. This martensitic microstructure can be challenging to machine due to the particle hardness of the martensite. If the cooling rate is not sufficient, a mix phase microstructure of bainite and martensite will be produced. This mixed phase structure can be equally challenging to machine due to the differences in particle hardness. In this paper, two common sinterhardening alloys (FL-5305 & FLC2-4808) are subjected to two different cooling rates (0.5 °C/s & 2 °C/s) to understand the effect of microstructure on turning and drilling performance. This effect along with options for improving the machinability of these alloys will be discussed.

INTRODUCTION

Sinterhardening has become a popular manufacturing method to obtain high mechanical properties. Alloys with enough hardenability are subjected to rapid cooling (2 – 6 °C/s) in the sintering furnace. The cooling rate is enough so a predominately martensitic microstructure is formed. The process of

completing the hardening operation in the sintering furnace is advantageous as it eliminates another step in the manufacturing process, in this case a secondary heat treatment.

One of the keys to obtaining the optimum properties using this process is to control the cooling rate in the sintering furnace.[1] Understanding the cooling transformation curves of a material system is critical to obtaining the correct microstructure after sintering. Manipulation of the cooling rate can be used to provide optimum performance of an alloying system from a strength, fatigue, or machining point of view.[2]

Even though most PM parts are net shape, a secondary machining operation is often necessary to meet final dimensions or to add a feature which is not feasible during compaction. Sinterhardenable alloys, with their high martensite content, can be difficult to machine.[3] Often times an additive is machining enhancing additive is added to the material to improve machinability. However, an understanding of the effect processing and the resultant microstructure can have on machinability is needed.

In this paper, two common sinterhardening alloys, FLC2-4808 and FL-5305, are examined to understand the effect of microstructure on the machinability of the alloys. Different cooling rates are used to produce similar microstructures in the two alloys. Machinability tests were completed and indicate that even though the microstructure between two materials may appear similar, the machinability performance may be drastically different. A close look at the microstructure indicates small differences in structure can results in very different results.

EXPERIMENTAL PROCEDURE

Materials

Machining evaluation was conducted on two common sinterhardening alloys used in the industry today: FLC2-4808 and FL-5305. The nominal chemical compositions of the base materials used are shown in Table 1.

Table 1. Chemical Composition of Base Irons

MPIF Code	Base Iron	Molybdenum (%Mo)	Nickel (%Ni)	Manganese (%Mn)	Chromium (%Cr)
FL-4800	Astaloy™ MoNi	1.20	1.35	0.40	-
FL-5300	Astaloy™ CrM	0.50	-	0.10	3.0

Premixes were manufactured in the North American Höganäs pilot mixing center for this study. The composition of the material systems manufactured is shown in Table 2.

Table 2. Chemical Compositions of Premixes

Mix ID	Base Iron	Copper (% Cu)	Graphite (% C)	Lubricant (%)
FLC2-4808	Astaloy MoNi	2	0.85	0.6
FL-5305	Astaloy CrM	-	0.55	0.6

The additives used in the premixes were natural graphite (SW-1651, Asbury), elemental copper (Cu-165, ACuPowder) and lubricant (Intralube® E, Höganäs AB).

Compaction and Sintering

The premixes were compacted into □55 x □35 x 20H mm (2.2 x 1.4 x 0.8 in) rings to a green density of 6.90 g/cm^3. The weight of the rings was approximately 275 g (0.6 lb). In addition to the rings, tensile and

impact specimens were compacted to verify mechanical properties of the materials. The rings and test bars were sintered on a mesh belt furnace at 1121 °C (2050 °F) for 30 minutes at temperature in an atmosphere of 90 v/o nitrogen and 10 v/o hydrogen. In order to produce different microstructures and observe the effect on machinability, two different cooling rates were utilized. One set of specimens was subjected to a cooling rate of 0.5 °C/s (1.0 °F/s). The other cooling rate was accelerated using to 2 °C/s (4 °F/s) to sinterharden the alloys. The cooling rates chosen are typical cooling rates which are achievable in a production setting. The cooling rates were measured between the temperatures of 704 °C (1300 °F) and 315 °C (600 °F). The samples subjected to the accelerated cooling rate were tempered at 204 °C (400 °F) for one hour in air.

Sintered Property Testing

The tensile and impact tests were performed according to ASTM E8 and ASTM E23 respectively. The testing was conducted by Westmoreland Mechanical Testing & Research (Youngstown, PA). Three rings from each material and processing condition were randomly selected and tested for apparent hardness, microindentation hardness, sintered density, and sintered carbon. One ring was also evaluated for microstructure.

Machinability Testing

The ring specimens were subjected to inner diameter turning and drilling operations. New rings were used for each machining operation. The parameters used in the machining tests are listed in Table 3.

Table 3. Turning and Drilling Parameters

Parameter	ID Turning	Drilling
Tool	cBN	HSS / coated carbide
Tool manufacturer	Sumitomo	Chicago / Latrobe
Coolant	No (dry)	No (dry)
Cutting speed	1200 / 1800 sfm	2000 rpm
Feed rate	0.1 mm/rev	200 – 400 mm/rev
Depth of cut	0.125/0.25 mm/side	3.5 mm
Length of cut	20 mm	10 mm

Machining tests were conducted with the assistance of Farzati Manufacturing (Greensburg, Pennsylvania).

Machinability was determined for the inner diameter turning and facing operations by measuring the tool wear after a certain number of cuts using a Hitachi S-2600N SEM. The insert then resumed machining. This procedure was continued until the testing was terminated. A depiction of the measurement technique is shown in Figure 1.

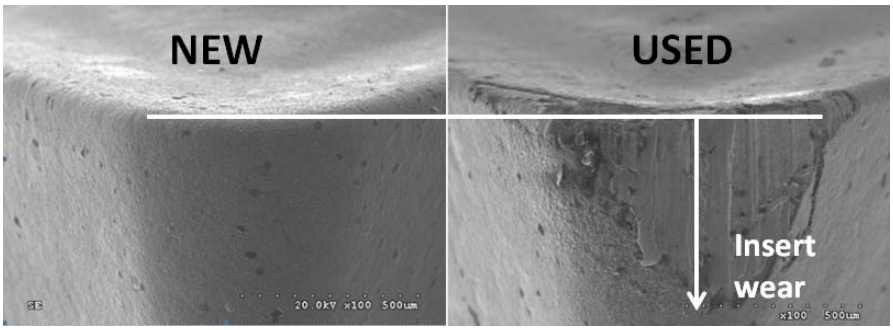


Figure 1. Tool wear measurement technique

For the drilling tests, machinability was determined by drilling holes until breakage or until excessive heat was noted on the component.

RESULTS – ACCELERATED COOLING RATE

Since both of these materials are used primarily as sinterhardened materials, testing was first completed using the accelerated cooling rate. A summary of the mechanical properties in this condition are presented in Table 4.

Table 4. Mechanical Properties – Accelerated Cooling (2.5 °C/s)

Material	Sintered Density (g/cm^3)	Carbon (%C)	Hardness (HRA)	UTS (MPa)	YS (MPa)	E (%)	IE (J)	$HV_{0.1}$
FLC2-4808	6.66	0.78	63	750	N/A	< 1	7	N/A
FLC2-4808	6.85	0.77	66	858	N/A	< 1	9	709
FLC2-4808	6.98	0.78	69	967	N/A	< 1	12	N/A
FL-5305	6.64	0.50	64	803	N/A	< 1	11	N/A
FL-5305	6.84	0.50	66	922	N/A	< 1	13	697
FL-5305	6.97	0.51	68	1001	N/A	< 1	14	N/A

The FL-5305 material system achieved higher tensile and impact properties. Similar apparent and microindentation hardness levels were observed for both materials.

The results of the ID turning at 1200 sfm are shown in Figure 2.

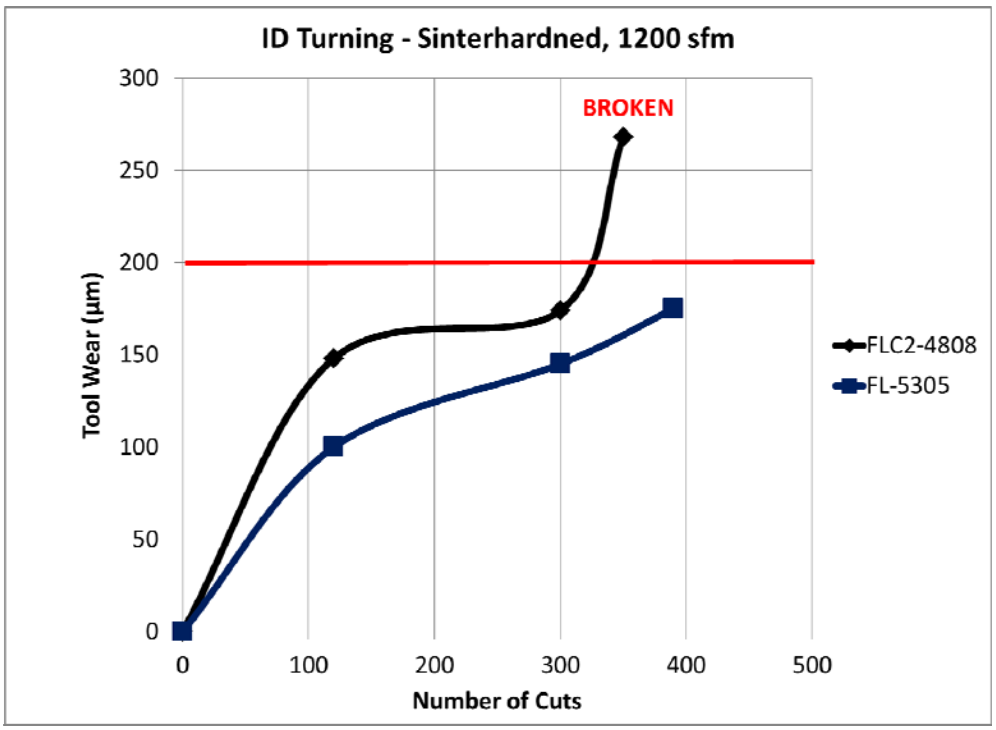


Figure 2. ID turning, 1200 sfm, sinterhardened

Under these conditions, both materials showed a steady increase in wear through the first 300 cuts. However, as cutting continued the FLC2-4808 material quickly wore until failure of the insert was occurred at cut 350. The FL-5305 material continued to cut and have a steady increase in wear. At 400 cuts, the FL-5305 material still was below the wear criteria of 200 µm maximum wear (red line).

SEM photographs of the machining inserts are presented in Figure 3.

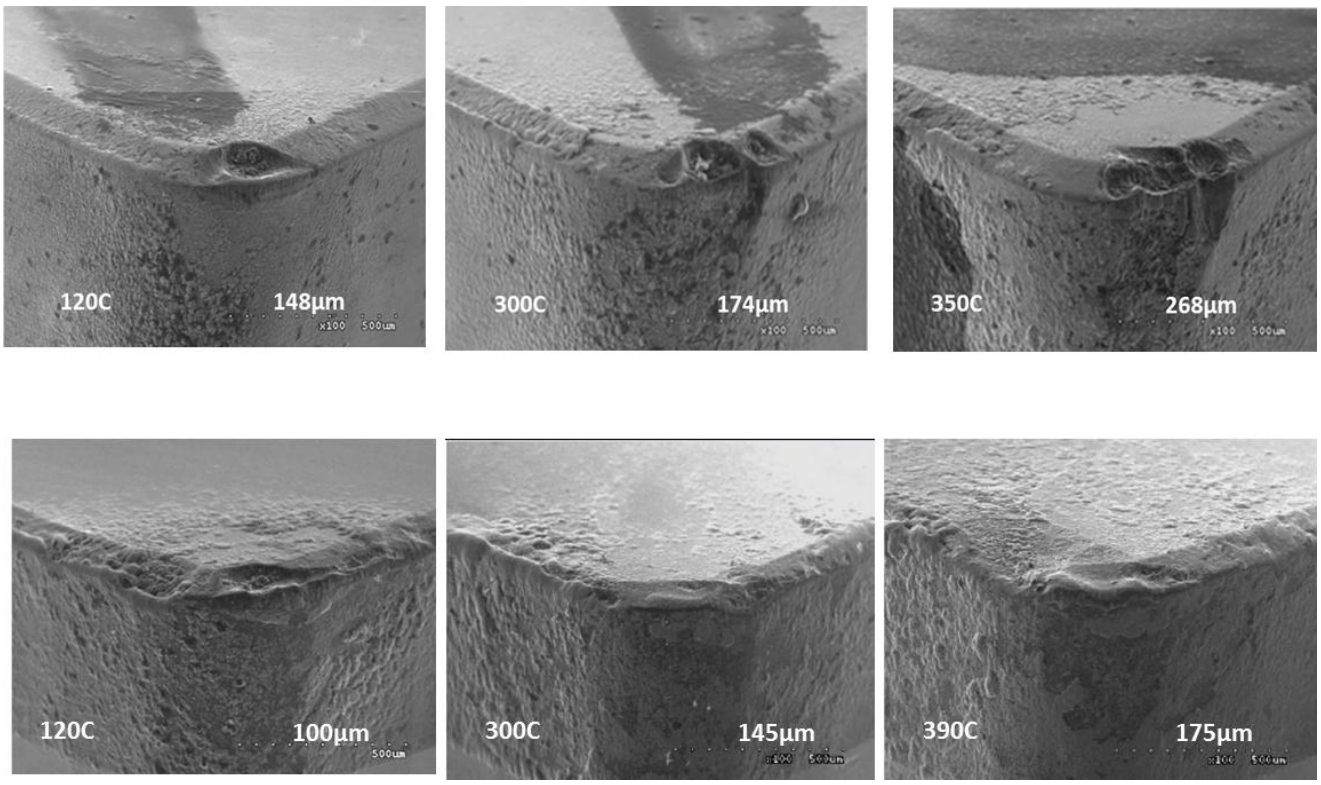


Figure 3. Machining inserts after various cuts, 1200 sfm: Top – FLC2-4808, Bottom: FL-5305

The machining speed was increased to observe its effect on machining performance. The results of the ID turning at 1800 sfm are shown in Figure 4.

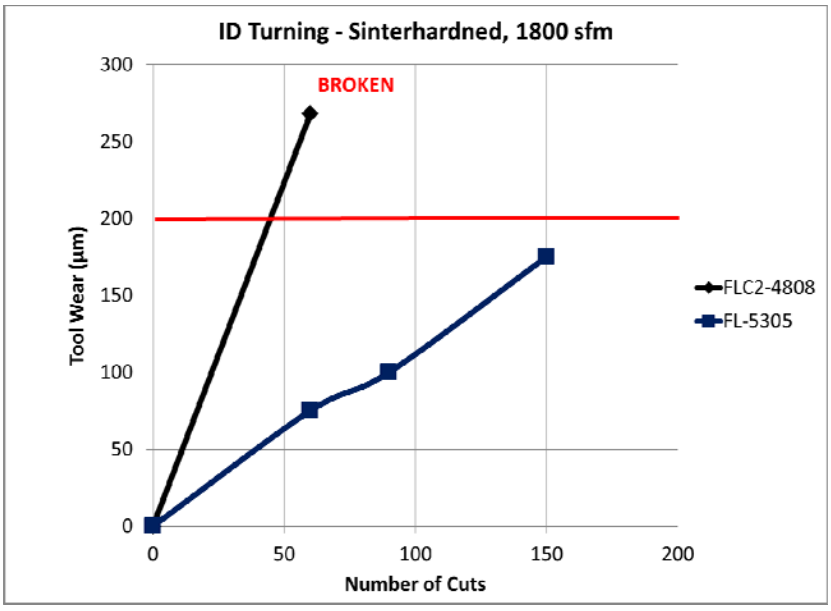


Figure 4. ID turning, 1800 sfm, sinterhardened

Machinability decreased for both materials at this higher speed as expected. The FLC2-4808 material suffered an extreme amount of wear and the insert suffered catastrophic failure after just 50 cuts. The FL-5305 material achieved stable wear as the number of cuts increased. After 150 cuts, the FL-5305 material still met the wear criteria of 200 µm maximum wear. SEM photographs of the inserts are shown in Figure 5.

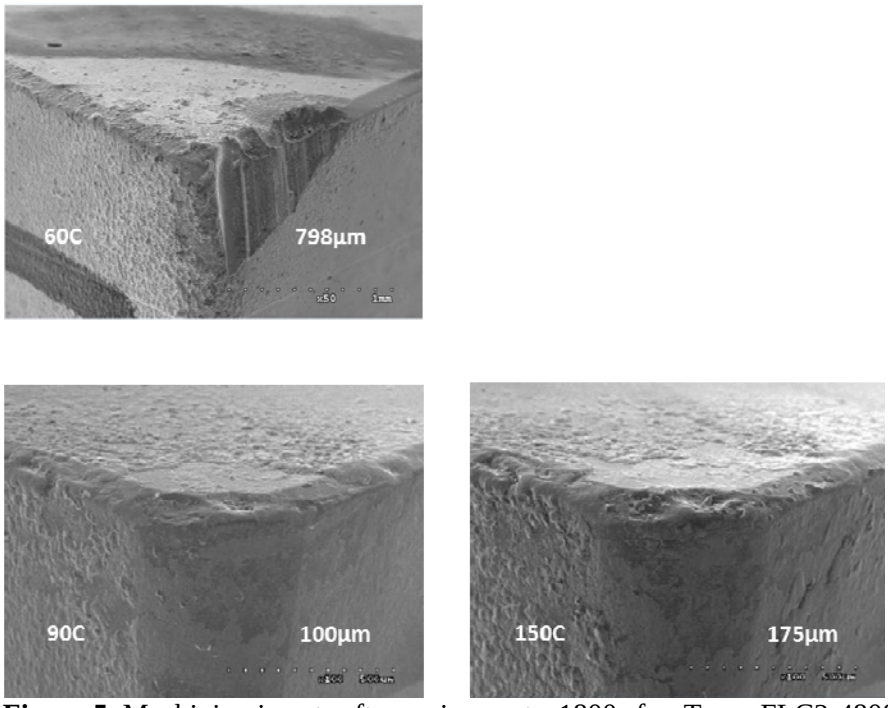


Figure 5. Machining inserts after various cuts, 1800 sfm: Top – FLC2-4808, Bottom: FL-5305

Machinability of the materials was also tested by a drilling operation. The results of the drilling test are shown in Figure 6.

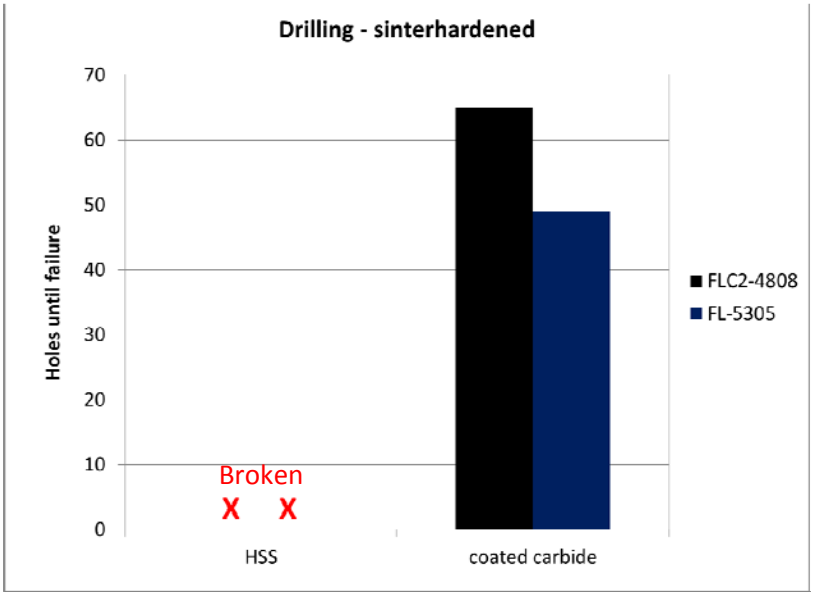


Figure 6. Drilling test, sinterhardened

Neither material was able to drill a hole using the high speed steel drill. When a coated carbide drill was used, a number of holes were able to be drilled for both materials. For drilling, the FLC2-4808 material was able to drill 15 more holes compared to the FL-5305. Both materials suffered from excessive heat as the drill failure mode.

Photomicrographs were taken of the unetched structure. They are presented in Figure 7.

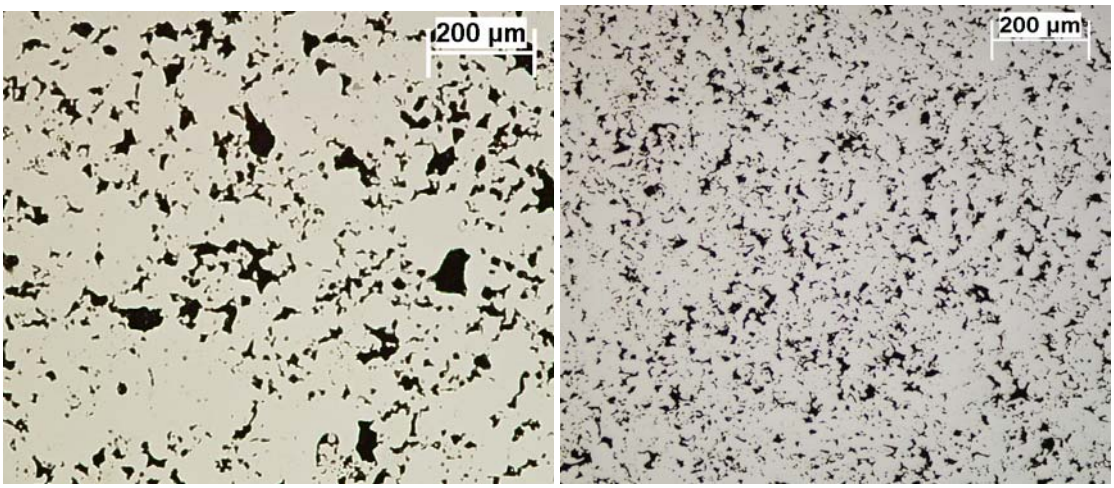


Figure 7. Unetched photomicrographs: Left – FLC2-4808, Right: FL-5305

Both materials showed acceptable sintering. Good sinter necks were observed between the particles. The FLC2-4808 material contained large pores as a result of the copper addition. This structure was similar for both cooling rates. The etched photomicrographs are shown in Figure 8.

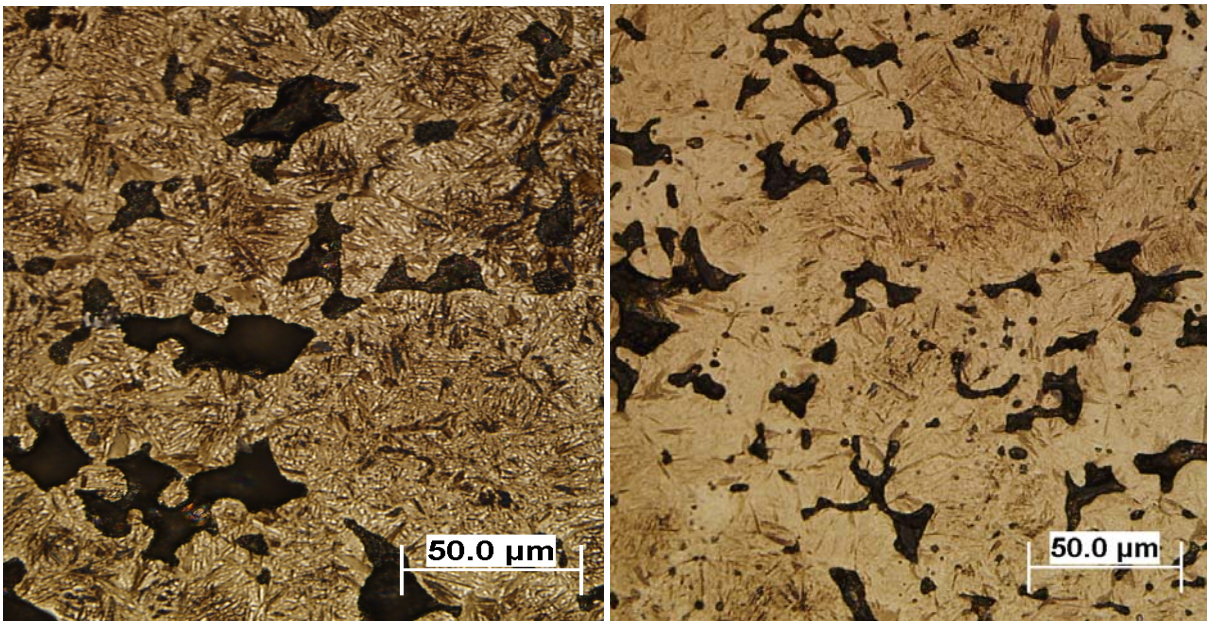


Figure 8. Sinterhardened microstructures: Left – FLC2-4808, Right: FL-5305 (Nital / Picral)

Both materials were completely martensitic. The microindentation hardness of both materials was also similar.

RESULTS – CONVENTIONAL COOLING RATE

The materials were tested for mechanical properties after conventional sintering. The results are presented in Table 5.

Table 5. Mechanical Properties – Conventional Cooling (0.7 °C/s)

Material	Sintered Density (g/cm^3)	Carbon (%C)	Hardness (HRA)	UTS (MPa)	YS (MPa)	E (%)	IE (J)	$HV_{0.1}$
FLC2-4808	6.65	0.76	66	352	N/A	< 1	5	N/A
FLC2-4808	6.85	0.77	69	409	N/A	< 1	7	695
FLC2-4808	6.96	0.77	71	467	N/A	< 1	8	N/A
FL-5305	6.64	0.51	54	703	573	1	12	N/A
FL-5305	6.83	0.50	57	848	678	1	17	588
FL-5305	6.98	0.51	59	913	736	2	21	N/A

A sharp decrease in properties was observed for the FLC2-4808 material. The impact energy was extremely low under these conditions. The microindentation hardness did not change much compared to the accelerated cooling rate. The FL-5305 material showed good strength and impact resistance. The microindentation hardness decreased under the conventional cooling conditions.

Inner diameter machining was conducted on the as sintered materials. The results of machining at 1200 sfm are shown in Figure 9.

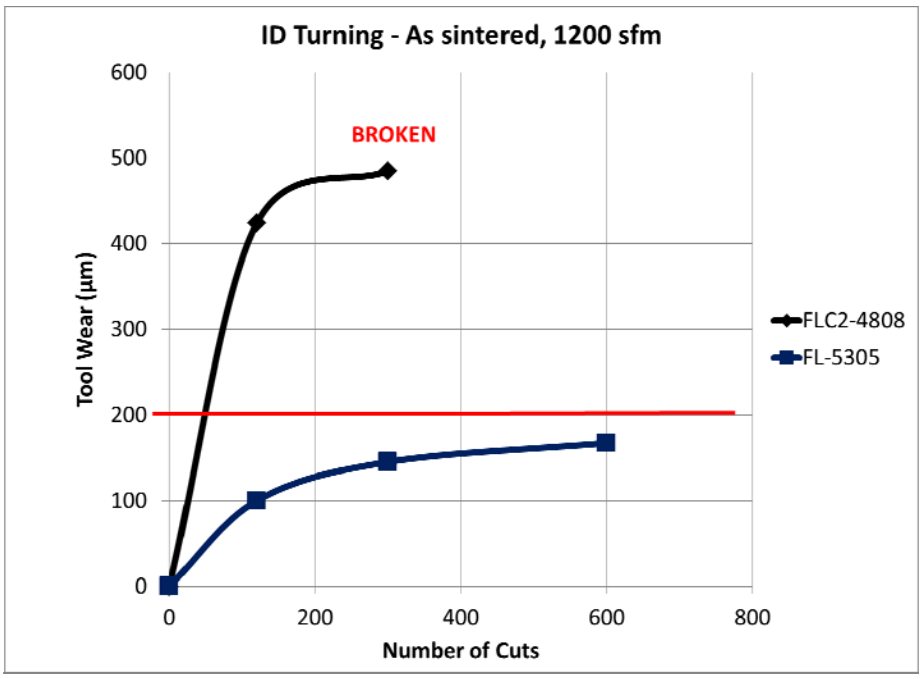


Figure 9. ID turning, 1200 sfm, conventional cooling

The FLC2-4808 material had a large amount of initial wear exceeding the wear criteria very quickly. At 300 cuts the insert failed. The FL-5305 showed initial wear, then a slow but stable increase in wear until the testing was stopped at 600 cuts. SEM photographs of the inserts are shown in Figure 10.

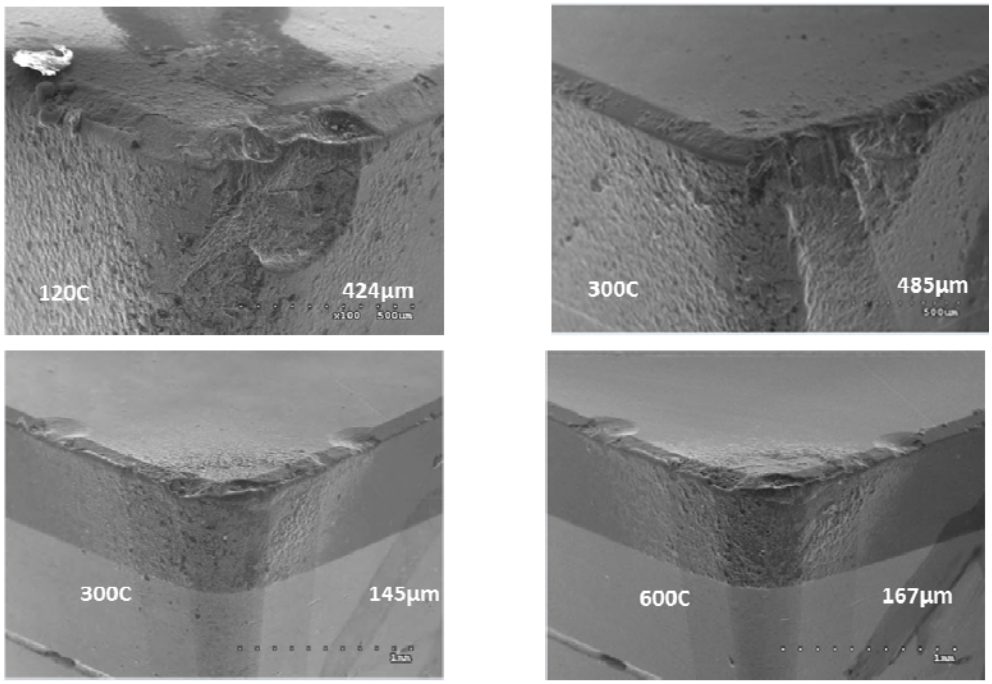


Figure 10. Machining inserts after various cuts, 1200 sfm: Top – FLC2-4808, Bottom: FL-5305

Since the results of the machining were very different for the two materials, another machining speed was not completed. Drilling tests were conducted and the results are presented in Figure 11.

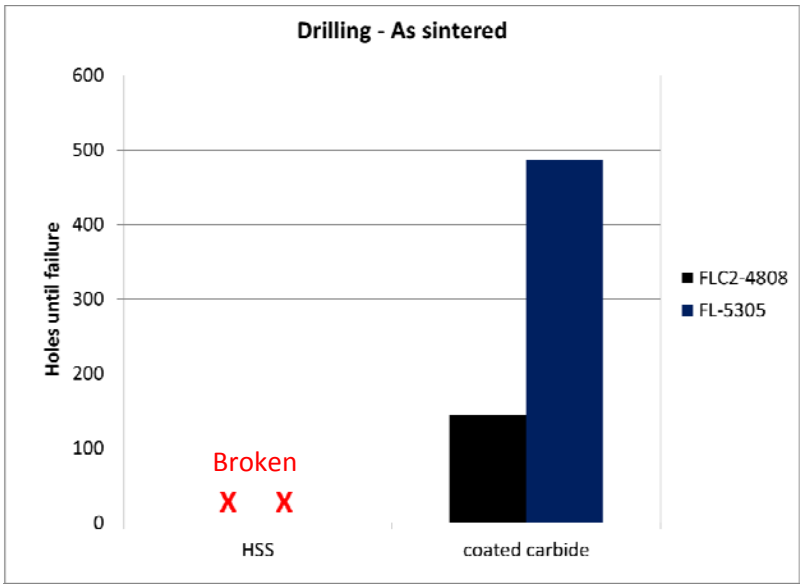


Figure 11. Drilling test, conventional cooling

Similar to the sinterhardened materials, the high speed steel drill was not able to drill even a single hole. Compared to the sinterhardened condition, the drilling performance of both materials improved with the coated carbide drill. However, the FL-5305 material had a dramatic improvement in drilling performance. Almost 500 holes were able to be drilled before excessive heat was observed. For the FLC2-4808 material, 150 holes were able to be drilled before drill failure occurred.

The etched microstructures are shown in Figure 12.

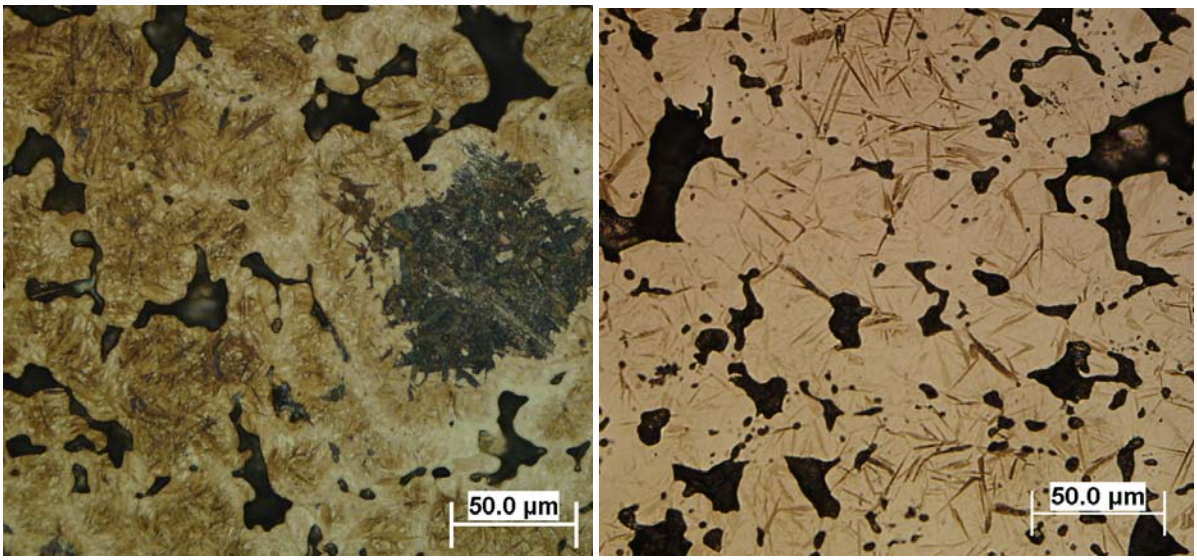


Figure 12. As sintered microstructure: Left – FLC2-4808, Right – FL-5305

For the FLC2-4808, a predominately martensitic microstructure was observed. Large bainitic islands were present throughout the structure. The amount of bainite was estimated to be 25 – 30%. A large amount of retained austenite was observed in between the martensitic needles. FL-5305 microstructure was a mix of lower bainite and martensite. The amount of bainite was more than the FLC2-4808 at approximately 40-45%.

DISCUSSION

The FL-5305 material had good machinability in the sinterhardened condition and the machining improved once the cooling rate was lowered. The resultant microstructure went from a completely martensitic microstructure to a mixture of bainite and martensite. As the martensite level decreased the machinability of the material improved.

However, the FLC2-4808 material had the opposite result. Once the microstructure moved from entirely martensitic to a mixture of bainite and martensite the machinability became much worse. This is in contrast to previous studies completed on this material.[4] While their study used different conditions and inserts, they showed that increasing amounts of martensite leads to a decrease in machinability. In order to confirm the results observed for the FLC2-4808 material, more testing was completed.

Using the same rings, a facing operation was completed on both the sinterhardened and as sintered rings. The parameters for the facing operation are shown in Table 6.

Table 6. Facing Parameters

Parameter	Facing
Tool	ceramic
Tool manufacturer	Sandvik
Coolant	No (dry)
Cutting speed	800 / 1200 sfm
Feed rate	0.1 mm/rev
Depth of cut	0.5 mm/side
Length of cut	10 mm

Two cutting speeds were used: 1200 and 800 sfm. For both materials, at the 1200 sfm condition, tool failure occurred quickly. Once the speed was reduced to 800 sfm, stable wear was observed for the sinterhardened material, while the as sintered material had tool failure. The SEM photographs of the inserts are shown in Figure 13.

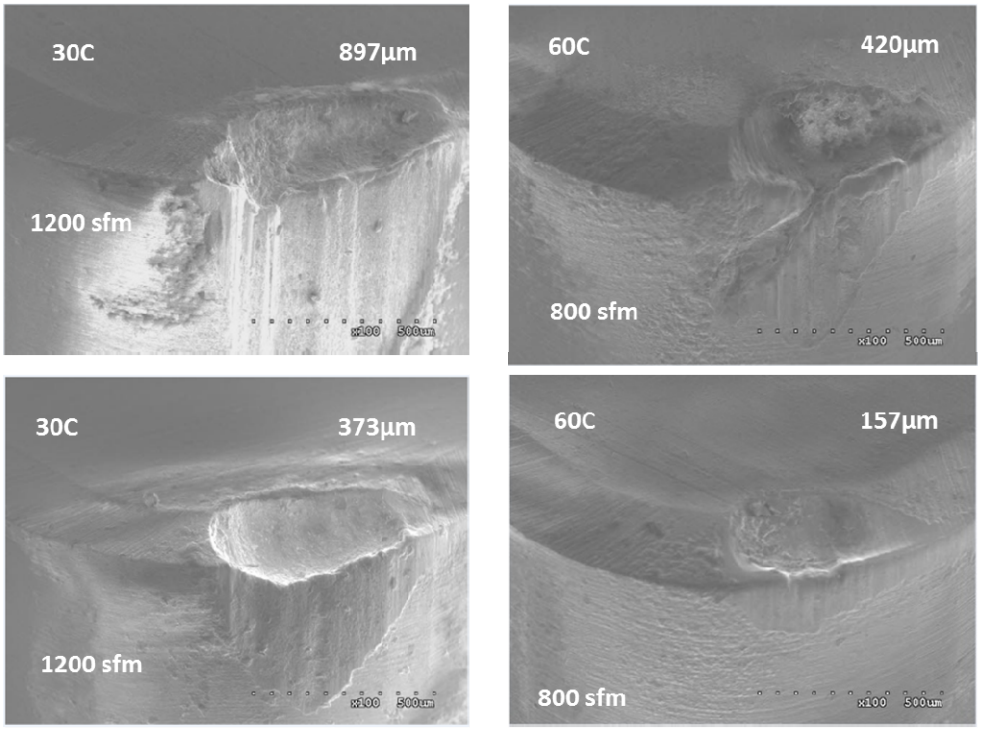


Figure 13. Machining inserts: Top – FLC2-4808 as sintered, Bottom: FLC2-4808 sinterhardened

A closer look at the microstructures of the two material systems was conducted. In the sinterhardened condition, both the FL-5305 and FLC2-4808 are entirely martensitic with similar microindentation hardness levels. However, a closer look at the microstructure shows some subtle differences.

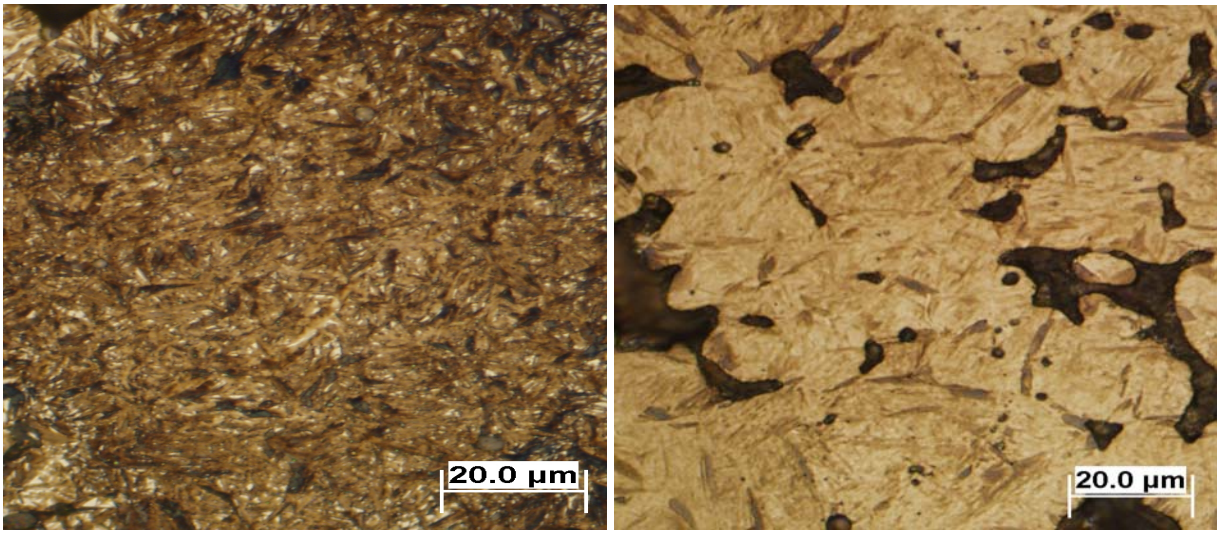


Figure 14. Sinterhardened microstructures: Left – FLC2-4808, Right: FL-5305 (Nital / Picral)

The martensite formed by the FLC2-4808 is coarser compared to the FL-5305. Retained austenite is also observed between the martensite needles of the FLC2-4808. This could explain the difference in machinability observed between the two materials.

Looking at the as sintered microstructures, more differences can be observed. The as sintered FL-5305 is a mixture of bainite and martensite. The bainite is evenly distributed throughout the martensite. The FLC2-4808 on the other hand has bainitic islands throughout the martensite. There is also a large amount of retained austenite between the martensitic needles and at the particle boundaries. This amount of retained austenite could explain the brittle nature of the mechanical testing and machinability testing.

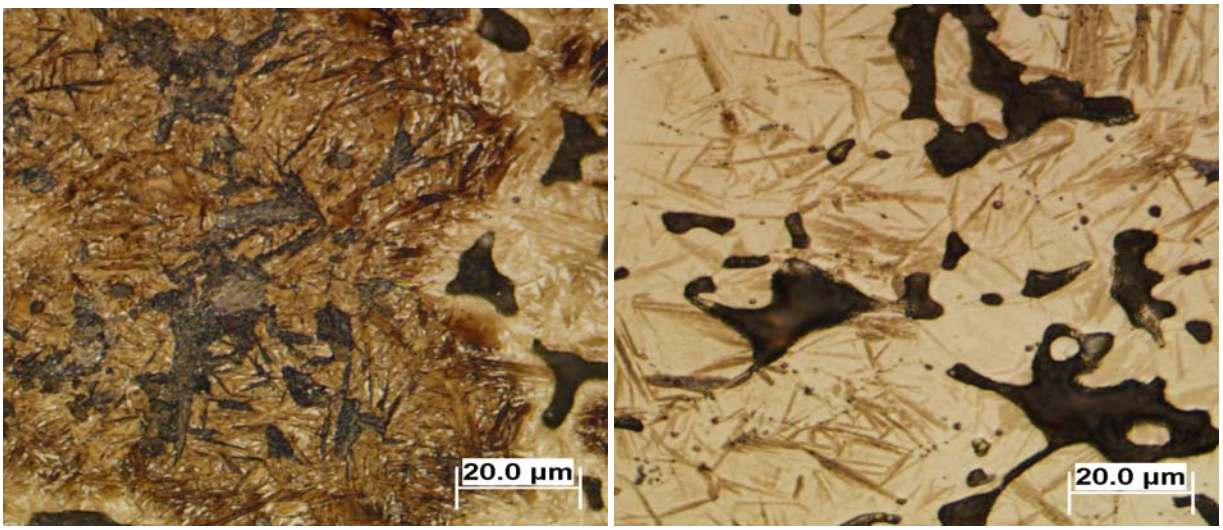


Figure 15. As sintered microstructure: Left – FLC2-4808, Right – FL-5305 (Nital/Picral)

To observe if the retained austenite in the as sintered material could be a factor in decreasing the machinability, some of the as sintered rings were tempered using the same conditions as the sinterhardened rings. Since only a few rings remained, drilling tests were conducted. The results are shown in Figure 16.

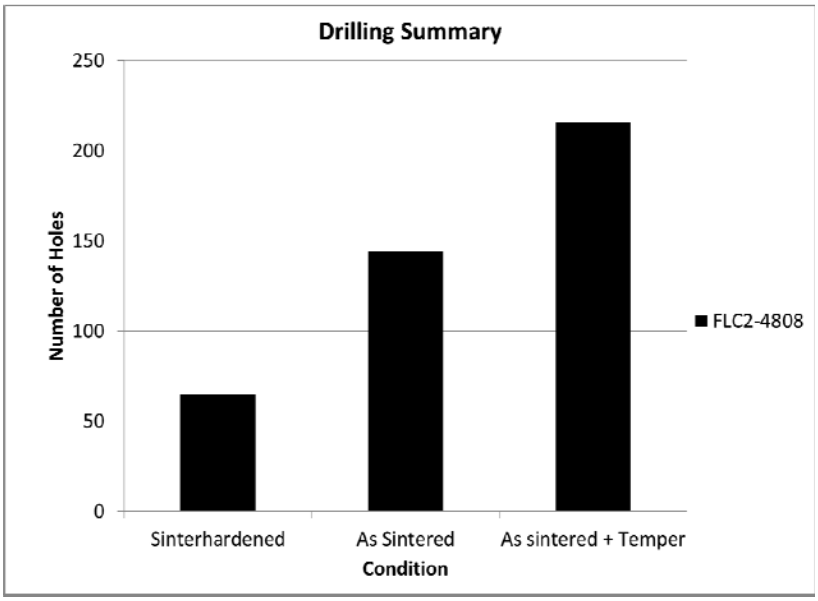


Figure 16. Drilling tests, effect of tempering as sintered FLC2-4808

By tempering the FLC2-4808, an improvement in the machinability was observed. More holes were able to be drilled compared to just the as sintered condition. Looking at the microstructure, the result of the tempering operation was to relieve some of the stress in the as sintered structure. The microstructure of the as sintered plus tempered material is shown in Figure 17.

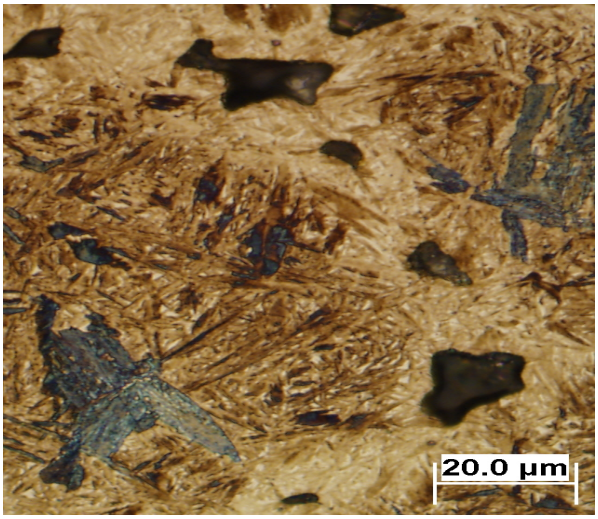


Figure 17. As sintered plus tempered FLC2-4808 (Nital / Picral)

Compared the tempered microstructure to the as sintered structure, a decrease in the amount of retained austenite was observe. While it is still present, the amount at the particle boundaries was decreased. Reducing the amount of retained austenite should improve the machinability and the mechanical performance of this alloy in the as sintered condition. However, even with tempering, the machinability and mechanical properties will be less than the FL-5305 material.

CONCLUSION

Evaluating the microstructure of a material system is crucial to understanding how the material will perform. Clearly, not all microstructures are the same even is they can be described similiary. The FLC2-4808 and FL-5305 materials both had martensitic microstructures after sinterhardening. However the FLC2-4808 did not achieve the level of machinability that the FL-5305 did due to differences in the martensite and retained austenite levels. Likewise in the as sintered condition, a martensitic / bainitic structure was observed for both materials. The FL-5305 contained a mixture of martensite and bainite with the bainite being evenly distributed throughout. The FLC2-4808 contained islands of bainite and large amounts of retained austenite at the particle boundaries. These two factors led to poor machinability of the material. By lessening the amount of retained austenite through a tempering operation, the machinability of the FLC2-4808 was improved.

ACKNOWLEDGEMENTS

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