DEVELOPMENT OF A NEW MACHINABILITY ENHANCING ADDITIVE FOR SINTER-HARDENED AND HEAT-TREATED PM MATERIALS

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ABSTRACT

Sinter-hardened and heat-treated PM materials are considered as the most difficult materials to be machined due to their martensitic structure and high hardness. Machining these types of materials is usually low productivity and/or short tool life. A new machining enhancement additive has been developed aiming to improve the machinability of sinter-hardened and heat-treated PM materials. The performance of the newly developed machinability enhancing additive has been evaluated through designated machinability tests with 6 different sinter-hardened and heat-treated materials that were prepared and tested in actual production conditions. It has been demonstrated as an effective machinability additive for sinter hardenable materials with enabling productive machining and/or extending tool life.

INTRODUCTION

Even though powder metallurgy (PM) is a near-net shape manufacturing process, where complex parts can be produced in an economical manner, secondary operations like machining are still necessary for a large portion of PM parts to reach their final shape, to meet tight tolerance requirements or indeed achieve high levels of surface finish [1].

The machinability of PM materials is mainly determined by their microstructure and hardness, the type of cutting tools and the parameters used in machining. Without changing the machining conditions, one can improve significantly the machinability of PM materials by adding machinability enhancing additives. It is well known that manganese sulfide (MnS) is a very effective machinability enhancing additive for PM parts, especially for Fe-Cu-C steels. It results in dramatic improvement in machinability with limited effect on mechanical properties [2]. In many cases, however, the performances of MnS was found less effective as alloying elements and content

increase in parts and the materials become harder through sinter-hardened or heat treatment [3]. Sinter-hardened and heat-treated PM materials normally consist of >90% martensitic structure with 350~650 microhardness (MHV) and >30HRC apparent hardness so that conventional PVD/CVD coated tools are not able to cut them and expensive cBN cutting tools are typically applied. Machining these types of materials usually results in low productivity and/or short tool life so that it is considered as the most difficult PM materials to be machined.

A new machining enhancement additive named SM-3 has been developed aiming to improve the machinability of sinter-hardened and heat-treated PM materials. The composition of the additive was designed to achieve a combination of the following functions: lubrication, heat reduction and tool protection for high productivity and improving tool life. Furthermore, the new machinability enhancing additive (SM-3) consists of compounds that are chemically stable and environmentally friendly in normal PM manufacturing operations. In this paper, the machinability improvement on sinter-hardened and heat-treated PM materials is demonstrated with the newly developed additive. The materials were manufactured and evaluated in actual PM production conditions.

EXPERIMENTAL PROCEDURE

Materials

Two groups of sinter-hardened and heat-treated PM materials were prepared with and without additives for machinability evaluations. Commercial pre-alloyed iron powders (North American Höganäs, USA) were used as base irons. The base iron powders were mixed with copper (ACu Powder Cu-165), natural graphite (Asbury Graphite SW-1651) and lubricant (0.75% amide wax) to make premix samples. The chemical composition of each premix is shown in Table I. Copper was added into the FL-5208 and FL-4205 in order to achieve more hardenability. The machinability of materials was evaluated with and without additives, where 0.2%SM-3 was typically added in the premixes.

Table I Chemical composition of premixes

Group	MPIF Code	Base Iron	Chemical Composition, %wt				
			Mo	Ni	Cr	Cu*	Graphite
A	FLC-4608	Astaloy A	0.55	1.90		2.00	0.80
	FL-5208M	Astaloy CrL	0.20		1.50	2.00	0.75
	FL-5305	Astaloy CrM	0.50		3.00		0.60
B	FL-4405	Astaloy 85Mo	0.85				0.50
	FL-4208M	Astaloy B	0.60	0.45		2.00	0.90
	FL-5208M	Astaloy CrL	0.20		1.50	1.50	0.65

*admixed in the prealloyed powder

Compaction and Sintering

The two groups of premixes were compacted into two kinds of blank specimens: 1) Group A premixes were compacted into ϕ55 x ϕ35 x 20 H mm rings (~195g) with a green density of 6.9 g/cm^3 and 2) Group B premixes were compacted into ϕ38 x 25H mm slugs (~158g) with a green density of 7.0 g/cm^3.

The rings (Group A samples) were sinter-hardened in a mesh belt production scale furnace at 2050°F (1120°C) for 25 min. in an atmosphere of 90% nitrogen and 10% hydrogen with cooling rate at 4.0°F/s (~2.2°C/s). The sinter-hardened rings were tempered at 400°F (200°C) for 60min. in air. For the slugs (Group B samples), they were sintered in a mesh belt production scale furnace at 2050°F (1120°C) for 25 min. in an Endo gas atmosphere where the FL-4208M and FL-5208M materials were sinter-hardened with a cooling rate at 2.5°F/s (~1.4°C/s). The FL-4405 material was heat-treated at 1550°F (843°C) for 30min and then quenched in oil after conventional sintering. All slugs were tempered at 350°F (177°C) for 90 min. in air.

Machinability Evaluations

Machinability of the sinter-hardened and heat-treated materials was evaluated through two types of well designed OD turning tests: 1) tool wear measured after certain cutting distance and 2) dimensional tolerances of each part machined measured in actual production manners.

The ring specimens were turned with an engine lathe and the OD of each ring specimen was machined (5 rings as a set so that each pass of the tool will cut through a length of 100 mm). The cutting tools used for this OD turning are a silicon nitride ceramic insert (Sandvik, CC6090). Machinability was evaluated by measuring the insert wear after cutting a certain distance or number of passes.

The slug specimens were turned with CNC lathe and the OD of each slug specimen was machined with one rough cut and one finishing cut (length of each cut was 0.625 in or ~16 mm). The cutting tools used for this OD turning are a cBN insert (Sandvik, CBN7050). No offsets were made during the tests. Machinability was evaluated by measuring the dimensions of OD after each slug to be cut, total 200 pieces were measured for each tested materials.

All machinability tests were performed in a dry condition without any coolant.

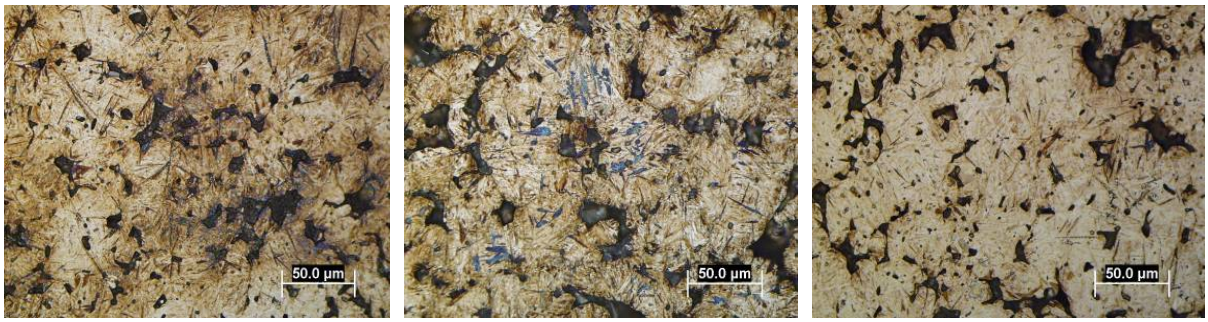
Corrosion Resistance Evaluations

In some applications, corrosion resistance of PM parts is very critical. The effect of machining additives on surface corrosion of sintered PM materials was investigated in a humidity chamber at 43 °C and an environment of 100% humidity.

RESULTS AND DISCUSSIONS

Microstructures and Hardness Evaluations

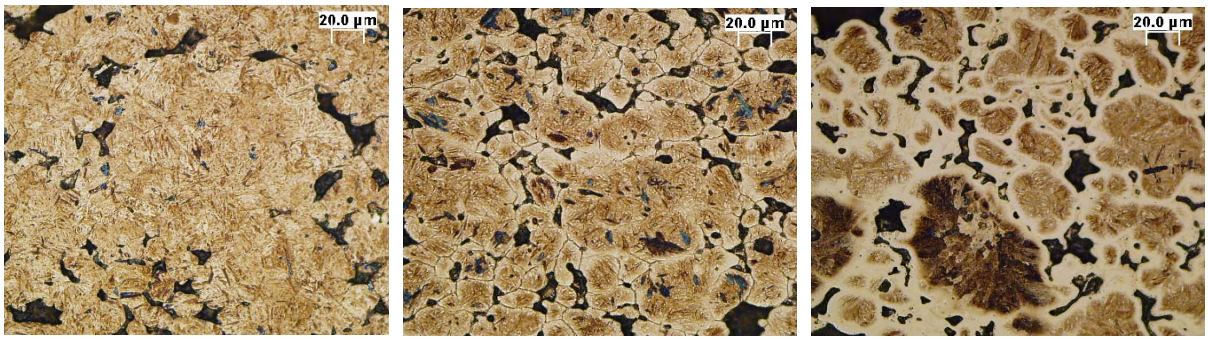
The microstructures were examined for all of sinter-hardened and heat-treated materials with and without machinability enhancing additives prior to machinability evaluations. There is no effect on the microstructure formation when the machining enhancing additives are added. Figure 1 presents the microstructures of sinter-hardened materials with containing machinability enhancing additives except the FLC-4405 materials which was sintered and heat treated. An almost full martensitic microstructure was achieved with microhardness ($MHV_{-100g\ load}$) above 350 and below 650 after sinter-hardened and heat-treated operations. The apparent hardness of each material is shown in Table II. All of materials used for machinability tests have the hardness that was close to 35HRC or higher.



MHV 505~626 MHV 353~461 MHV 547~637

(1) FLC-4608 with 0.2%SM-3 (2) FL-5208M with 0.2%SM-3 (3) FL-5305 with 0.2%SM-3

Group A



MHV 538~637 MHV 353~594 MHV 378~405

(1) FLC-4405 with 0.2%SM-3 (2) FL-5208M with 0.2%SM-3 (3) FL-4208M with 0.2%SM-3

Group B

Figure 1 Microstructures of sinter-hardened materials with containing the new machinability additive

Table II Hardness (HRC) of sinter-hardened and heat-treated materials to be machined

	Group A			Group B		
Materials	FLC-4608	FL-5208M	FL-5305	FL-4405	FL-4208M	FL-5208M
no additive	33-34	33-35	35-37	NA	NA	NA
0.2%SM-3	35-38	33-36	34-38	40-41	32-35	32-35

Note: FL-4405 was heat-treated and all others were sinter-hardened

Machinability Evaluations

1) Tool wear evaluations with Group A materials

Lathe turning tests were performed on the OD of ring specimens (5 rings per setting) with a cutting length of 100mm. The cutting speed was 1800 rpm (271-305 m/min) with a feed rate of 0.004 in/rev (0.1 mm/rev) and the cutting depth was 0.02 in (0.5 mm). The tool wear was measured on the insert flank by using a new insert as a baseline.

Due to its extremely high hardness compared to conventional PM materials, the sinter-hardened and heat-treated materials are basically not able to be cut with tungsten carbide and/or PVD/CVD coated solid carbide tools that were used in previous studies [4]. High Performance & expensive cBN tools are generally used for machining this type of materials with high productivity and long tool life in fast machining (>750 sfm or >250 m/min). In this study, ceramic inserts are found to be able to cut the materials with a reasonable tool life when it is used at slow cutting speeds (<450 sfm or <150m/min) while it will wear fast at high cutting speed (>750 sfm or >250m/min).

Figure 2 shows the tool wear after 10, 20, 30 and 50 ring specimen of the sinter-hardened materials were cut with using ceramic inserts at a cutting speed of 1800rpm (271~305m/min). All of three sinter-hardened materials without machinability enhancing additive created more than 200 um tool wear after 10 ring specimens were cut and serious tool wear (>1500 um) after 20 rings were cut. With added 0.2%SM-3, the sinter-hardened materials could be cut up to 50 rings with a tool wear less than 200 um. The results demonstrated that the new machinability enhancing additive, SM-3, exhibited significant machinability improvement for sinter-hardened materials. It is expected that the machining on sinter-hardened materials with 0.2%SM-3 can achieve at least 5 times longer tool life than the machining on the materials without additive based on this study.

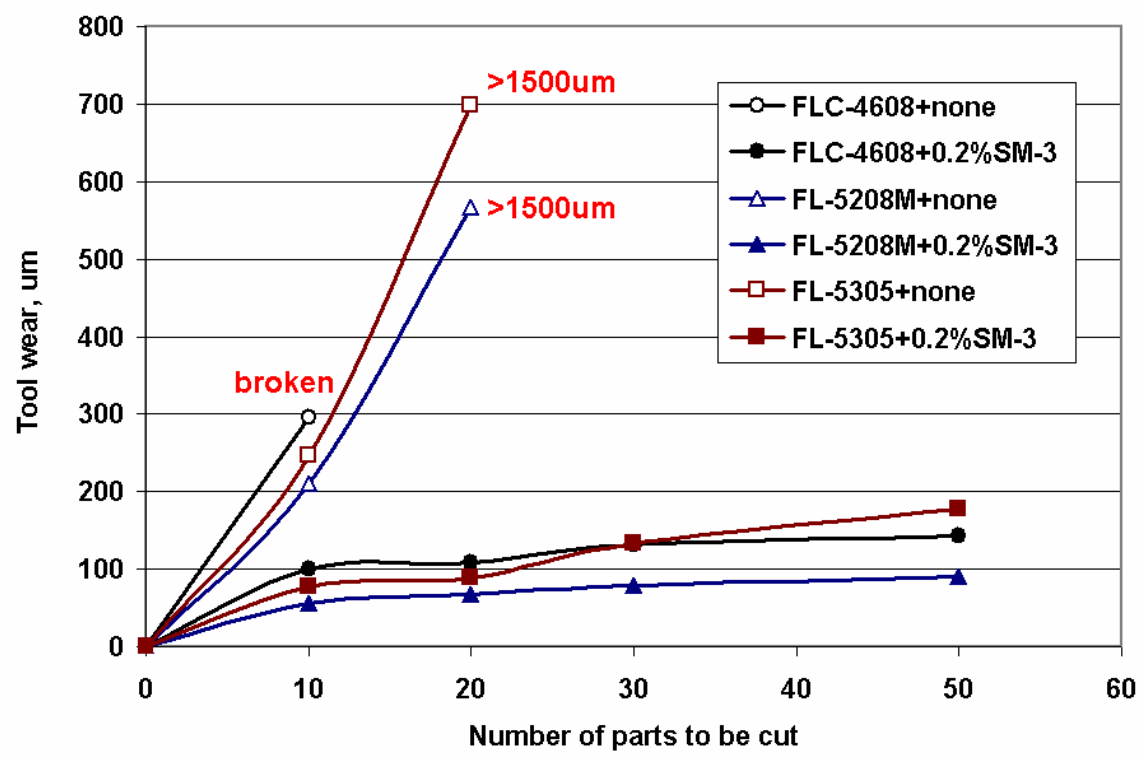


Figure 2 Comparison of tool wear between the sinter-hardened materials with and without additives. Turning conditions: ceramic insert, 1800rpm, 0.1mm/rev, 0.5mm depth

Figure 3 shows the status of tool wear after it cut 10 parts (rings) of the materials without additive and 50 parts (rings) of the materials with 0.2%SM-3. The materials without additive presented obvious crater and flank wear after 10 rings were cut while the materials with 0.2%SM-3 presented some wear in the crater area only. A protection layer can be found in the flank area of the inserts used to cut the materials with the new machinability additive.

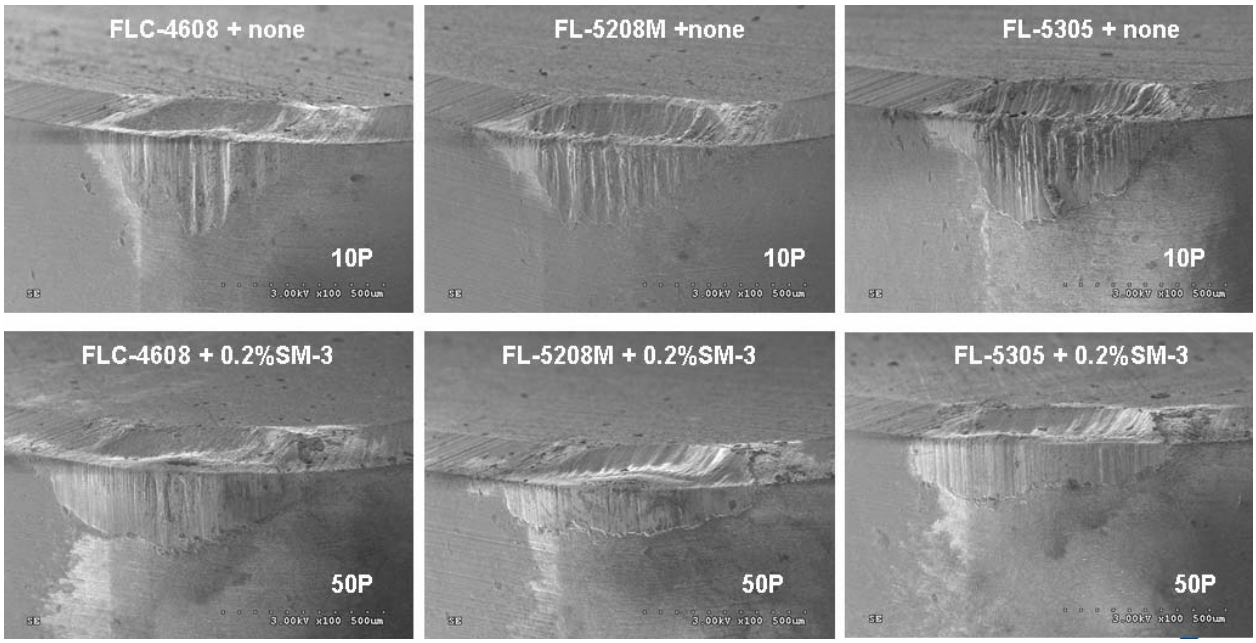


Figure 3 Status of tool wear after cut 10 and 50 parts of the sinter-hardened materials with and without machining enhancing additive (SM-3).
Turning conditions: ceramic inserts, 1800rpm, 0.1mm/rev, 0.5mm depth

During machining, heat is generated due to friction between tool and work piece. The harder the material is the more heat will be generated. When the generated heat reaches a certain temperature level, it would cause premature tool failure. This is why conventional PVD/CVD coated tools are not able to cut the sinter-hardened materials, and high temperature resistant tools such as cBN are required.

Figure 4 shows the state of heat generation during dry turning. The machining of sinter-hardened materials without additive created many sparks at each cut due to excessive heat generation. With the addition of SM-3, the turning was very smooth and almost no sparks were observed during machining. This observation demonstrates that the new machinability enhancing additive provides benefit in reduction of heat generation during machining.



1) without additive 2) with 0.2%SM-3

Figure 4 Observation of heat generation during machining of sinter-hardened materials

2) Dimensional tolerance Evaluations with Group B materials

CNC turning tests were performed on the OD of slug specimens (one slug per setting) with using a cBN insert for a cutting length of 0.635 in (~16 mm) per each cut. Each slug specimen was turned with one rough cut and one finishing cut where the cutting depth was 0.03 in (~0.76 mm) for rough cut and 0.01 in (~0.25 mm) for finishing cut respectively. The cutting speed was 1884 rpm (225 m/min) with a feed rate of 0.006 in/rev (0.15 mm/rev). Machinability was evaluated by measuring the dimensions of OD after each slug to be cut, total 200 pieces were measured without offsets were made for each tested materials.

As machining operations are applied to provide required dimensional tolerance of parts, this test method is considered as a closest way to the actual production machining. It can detect the tool wear through monitoring the dimensions of parts for each cut and maintain the machined parts within the dimensional tolerance range through offsetting the tool wear. When a material is difficult to cut with the selected machining conditions, the cutting tool will wear more. As the tool wear can not be managed by offsetting of tool, the dimensions of machined parts will be out of the limits after certain amount of parts are cut.

Figure 5 presented the dimensional tolerance of heat-treated materials with 0.2% SM-3 after each slug was machined. For the FL-4405 (heat-treated) and FL-4208M (sinter-hardened) materials, the dimensions of machined slugs are within the tolerance range except early edge wear as noted in Figure 5 was observed in the beginning machining. The early edge wear can be corrected by using heavier edge preparation. For FL-5208M (sinter-hardened) material, continuous increased dimensions of parts, i.e. a continuous tool wear, are observed over entire test run. The difference in dimensions is judged to be acceptable as it is stable & predictable, therefore, can be adjusted by offsetting the tool during machining. Except several points, all of three heat-treated materials have the moving range of dimensions within the specification limits when 200 pieces of parts were evaluated.

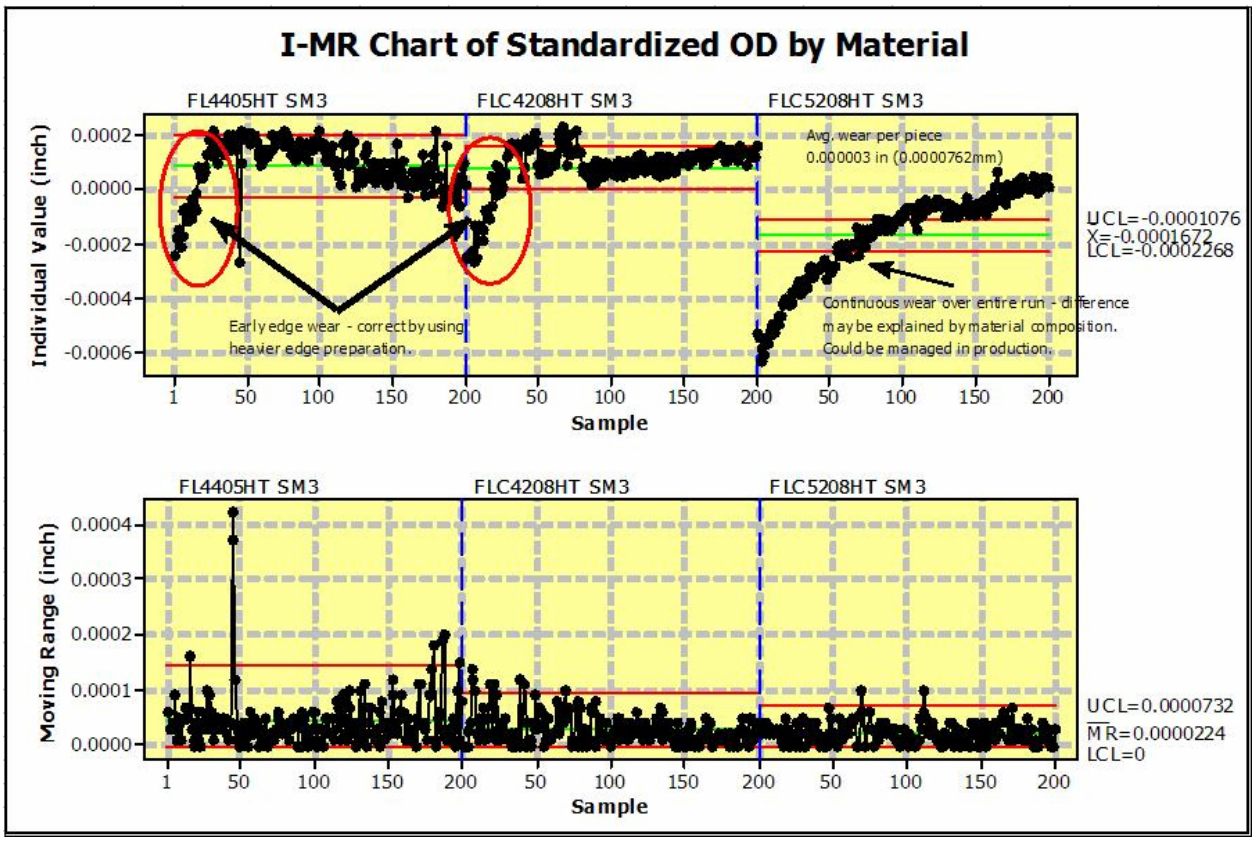


Figure 5 Dimensional tolerance of the FL-4405 heat-treated, FL-4208M sinter-hardened and FL-5208M sinter-hardened materials with 0.2%SM-3 after dry turning 200 pieces of each material. Turning conditions: cBN insert, 1884 rpm, 0.15 mm/rev, 0.76 mm (rough cut) and 0.25 mm (finish cut) depth

Overall, the new machinability enhancing additive, SM-3 is recognized to be able to provide great machinability improvement for sinter-hardened and heat-treated materials. The different behaviors of machinability improvement observed in different hardened materials in this study are manageable during production.

Sintered Properties Evaluations

The effect of the new machinability enhancing additive on the sintered properties of PM materials was investigated with a typical sinter-hardenable material (FLC-4608). The results are shown in Table III. Compared to the materials without additives, the materials with the newly developed additive (SM-3) have no detrimental effect on mechanical strength. In addition, there are no significant differences in hardness and dimensional changes between the materials with and without additives.

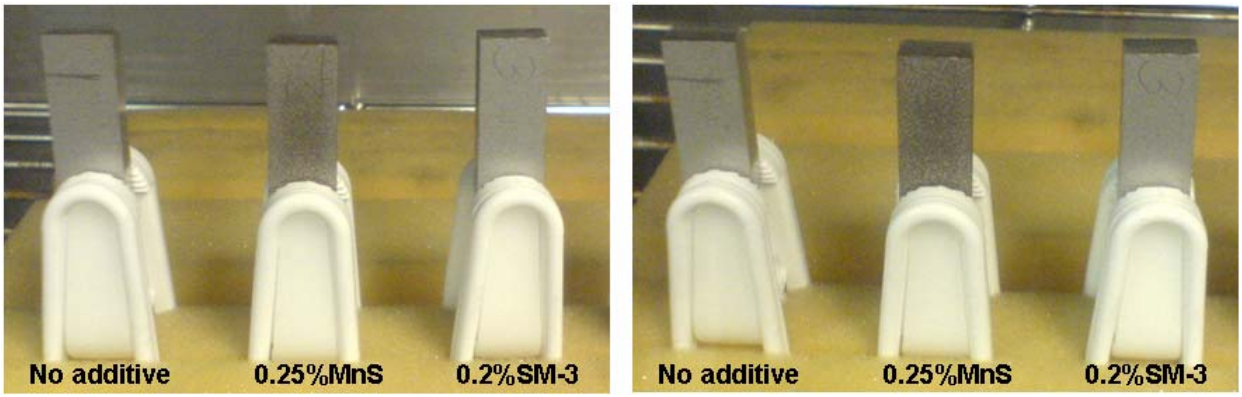
Table III Sintered properties of sinter-hardened materials with and without machining additive

Material	Additive	Density	%DC	HRC	TRS, kpsi (MPa)
FLC-4608 Untempered	None	6.8	0.43	39-40	118 (813)
	0.2%SM-3	6.8	0.46	38-39	129 (892)
FLC-4608 Tempered	None	6.8	0.36	30-32	193 (1328)
	0.2%SM-3	6.8	0.40	30-32	194 (1339)

Note: tests were performed with TRS bars

Corrosion Resistance Evaluations

The effect of machining additives on surface corrosion of PM parts was investigated with the as-sintered FLN2-4408 material (Astaloy 85Mo +2%Ni + 0.7%C) in a humidity chamber. Figure 6 shows the status of surface rusting of the material without additive, with 0.25%MnS and with 0.2%SM-3 after placed in an environment of 100% humidity at 43 °C for 9 days. Corrosion happened over the whole surface of the material containing MnS additive while no rust was visible in the material with SM-3, same as seen in the material without additive. The results indicated that the newly developed machinability enhancing additive, SM-3, has no detrimental effect on the corrosion resistance of PM materials.



1) after 4 days 2) after 9 days

Figure 6 Surface corrosion of as-sintered FLN2-4408 material in a humidity chamber at 110°F (43°C) with 100% humidity

CONCLUSIONS

The performance of the newly developed machinability enhancing additive (SM-3) has been evaluated through designated machinability tests with 6 different sinter-hardened and heat-treated materials. Compared to the materials with and without additive, the following conclusions can be made from this study.

1. The new machinability enhancing additive, SM3, is an environmental friendly substance. It is a chemically stable additive that is suitable to be used in PM processing operations. No detrimental effect on the mechanical properties and corrosion resistance of PM materials is observed.
2. The new machinability enhancing additive reduces heat generation and provides tool protection during machining. This combination function greatly helps in enabling high productive machining and/or extending tool life
3. The new machinability enhancing additive can provide significant improvement in machinability of sinter-hardened and heat treated materials. The required addition (0.2% or less) is much less than the usage of conventional additive such as MnS. The current study has demonstrated SM-3 as an effective machinability enhancing additive for sinter hardenable materials

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