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Machinability of Sinter-hardening PM materials with experimental machining enhancers

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Abstract

Although powder metallurgy is an economical method for production of near net shape components, machining operations are often required to deliver desired geometrical features, dimensional tolerances, and surface finish of PM parts. Machining enhancers are used to improve the machinability of PM components and to increase tool life. MnS is the most common machinability enhancer used for PM steel parts. However, it is less effective for harder materials and, especially, for sinter-hardening grades. It has also shown to stain steel parts and make them susceptible to corrosion. In this study the machinability of sinter-hardening materials with new experimental machining enhancers was investigated. Different additive formulations were evaluated and their performance was compared to that of the materials without machining enhancer and with MnS. Specimens were compacted, sintered, and cooled down at two cooling rates to evaluate the effect of post-sintering cooling rate on sintered properties and machinability. The results of the material characterization including dimensional change, static and dynamic properties, microstructural analysis, and machinability by drilling test are presented in this paper.

Keywords: Machinability, Machining enhancers, Sinter-hardening, Mechanical properties

Introduction

Machining enhancers (additives) are added in the initial powder mixture to enhance the machinability of PM parts after sintering especially in high strength steels. They should in general fulfil these requirements: mechanical and physical properties as well as dimensions of the sintered parts should be retained at the same values as for material without machining additives, and machinability should be improved [1].

Machining additives perform several functions during the cutting process: they promote microcracking and fracture of the chip/workpiece interface ahead of the cutting tip and prevent welding of the hot chips to form continuous swarf the removal of which is very complicated. They also prevent build-up edge formation in the area where local cutting forces and temperatures promote welding. A third function is to act as complex lubricant and a barrier to diffusion in the region of the tool face behind the cutting edge where crater wear normally occurs. In general, machining additives have to decrease tool/chip friction thereby decreasing the cutting forces and the temperature in the cutting zone. This can result in improved surface finish and improved machinability [1-3].

The most common machining enhancer in PM industry is MnS. The beneficial effect of machining additives can be explained by the role of MnS which has been most frequently investigated. MnS inclusions act as stress concentration risers in the machining shear zone to initiate cracks that subsequently lead to fracture of the chip. These inclusions are also known to deposit a layer on the surface of the cutting tool. It means that MnS acts as lubricant in machining operation by minimizing tool/chip friction, reducing tool wear [1].

While MnS has many beneficial attributes, it has some limitations and potentially negative effects. The use of MnS may damage the sintering furnace through the production of a sulfur containing gas. In addition, MnS becomes less effective as alloy content increases and for sinter-hardening steel grades. It can also be detrimental to the mechanical properties of such grades. The other issue with MnS is that it can stain the PM parts after sintering and make them susceptible to corrosion [1,4]. In this context, alternative machining additives have been developed to enhance the machinability of PM steel components. Some examples of additive materials include oxides (CaO, $MgSiO_3$), fluorides (CaF_2), and temperature stable lubricants like talc, hexagonal boron nitride, and mica/bentonite [5-6].

As mentioned above, MnS is less effective to improve the machinability of sinter-hardening materials. One example of such materials is FLC-4608 that can be sinter-hardened or heat-treated with a microstructure mainly consisting of martensite with apparent hardness values ≥ 30HRC. Therefore, these materials are very hard to be machined using conventional coated tools and often expensive cBN cutting tools are required. In this study the effect of new experimental machining additives on the machinability, physical and mechanical properties, and fatigue strength of sinter-hardening FLC-4608 was investigated and compared to the materials without additive and with 0.5% MnS.

Experimental methods

The master mix was prepared using ATOMET 4601 powder the composition of which is shown in Table 1.To the base powder 2% Cu, 0.9% graphite, and 0.75% wax were added to reach the MPIF FLC-4608 grade. The materials evaluated as machining additives were two non-sulfide conventional additives, lithium metaborate ($LiBO_2$), and lithium tetraborate (LiB_4O_7). The borate glasses were used as it is believed that they can melt during machining where local temperatures are higher than their melting point being 850 and 917°C, respectively. The molten glasses can then act as lubricant on the tool during machining thereby improving tool life [7]. Different formulations of machining enhancers were prepared with at least one of the materials named above using Taguchi 8 arrays and added to the master mix. Two series of experiments using Taguchi 8 arrays were done giving a total of 16 new formulations of experimental additives. The mix without additive was used as reference and the one with 0.5% MnS was used for comparison.

Table 1 Composition of ATOMET 4601

Element	Fe	Mn	Mo	Ni	S	O	C
Wt. %	Bal.	0.19	0.54	1.84	0.009	0.1	0.008

To evaluate the green and sintered properties, standard TRS specimens were compacted from each mix to 7.0 g/cm^3 density. For drilling machinability tests, ½ in thick (12.7 mm) TRS specimens were compacted to 7.0 g/cm^3 density. The bars pressed with the first eight additive formulations were sintered at two conditions to evaluate the effect of post-sintering cooling rate on their properties. The first sintering was done in 90% N_2–10% H_2 atmosphere for 25 min at 1120°C with a slow cooling rate of 0.3°C/s between 400 and 250°C. Second sintering parameters were 90% N_2–10% H_2 atmosphere, 35 min at 1130°C with a faster cooling rate of 1°C/s between 400 and 250°C. The specimens with the second series of additive formulations (ME11 – ME18) were sintered using only the fast cooling profile. All properties were evaluated after tempering at 200°C for 60 min.

The drilling tests were performed using Champion 705C cobalt HSS drill, ¼ in (6.35 mm) diameter, at rotating speed of 500 RPM, and feed rate of 0.64 mm/s. Three holes were drilled on each specimen with a cutting depth of 0.47 in (12 mm). Average and maximum thrust forces were measured for each hole until tool failure or until reaching the maximum number of holes for each material.

After the initial evaluations and the selection of more efficient additive formulations, tensile tests were performed on dog-bone specimens pressed to 7.0 g/cm^3 density from the mixes containing the new additives, 0.5% MnS, and no additive. Also plane bending fatigue test was performed with R=0.1 load ratio and the fatigue limit at 50% survival value was determined using the staircase method with a run out limit of 2.5 million cycles. The microstructures were observed using optical microscope after metallography preparation and Nital etch.

Results and discussion

Fig. 1 shows the difference in the dimensional change (DC) of the mixes containing the first series of new additive formulations with that of the reference material without additive (DC=0.215 %). The most similar DC to the reference was achieved for the mix 3 followed by mixes 4 and 2. The transverse rupture strength (TRS) and hardness of these mixes are also presented in Fig. 2. All machining enhancers reduced the mechanical properties of FLC-4608 material with some formulations (mixes 2,4, 6, and 8) having less detrimental effect than others.

The FLC-4608 material without machining enhancer had low drilling performance as the tool broke only after three holes with a high average thrust force (Fig. 3). The machining enhancers improved the drilling machinability in terms of the average thrust force and number of holes drilled. Another measure of machinability is the slope of the average thrust force versus number of holes which is an indication of tool life. The experimental enhancers improved also the tool life as this slope decreased significantly compared to the reference. Additives of mix 8 and mix 5 showed the highest performance among the formulations tested. Based on the results of the preliminary tests with the eight experimental formulations, four mixes (2, 5, 7, and 8) were selected for further evaluation of the effect of post sintering cooling rate on mechanical properties and machinability.

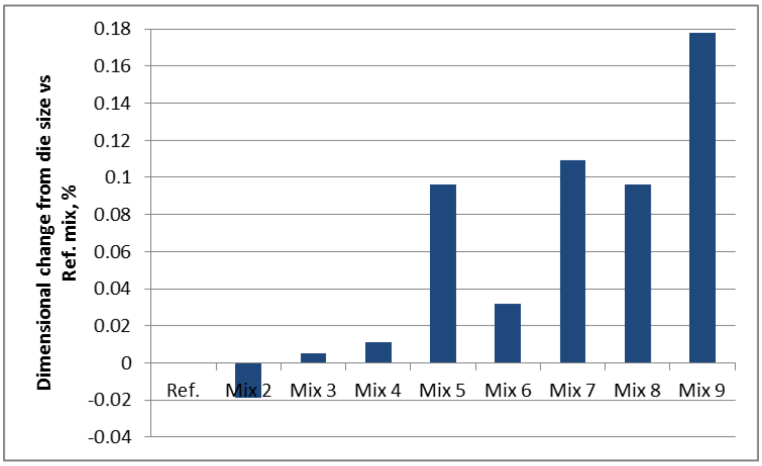


Fig. 1 Dimensional change from die size: difference with the reference material without machining enhancer

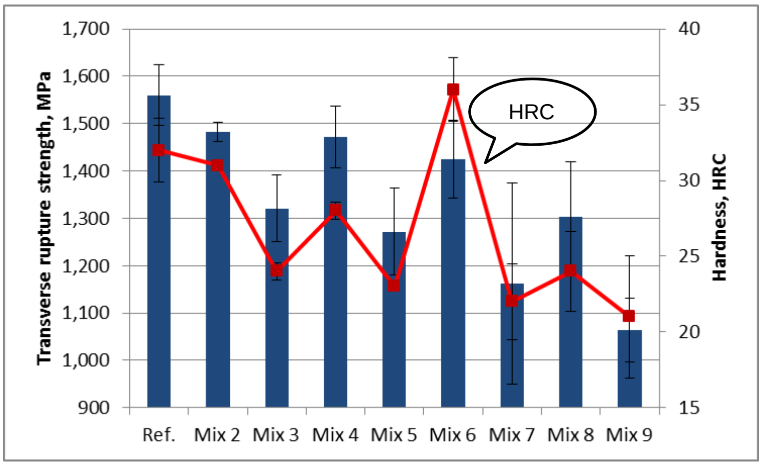


Fig. 2 Mechanical properties of the mixes containing new additive formulations

For the specimens produced from mixes with the select additive formulations and fast cooled after sintering, the dimensional change from die size was very similar (less than ± 0.04 % difference) to that of the reference FLC-4608 material without additive, being 0.316 %. Fast cooling also reduced the negative effect of the experimental additives on the mechanical properties, as shown in Fig. 4. Both TRS and hardness increased for the mixes with machining enhancers after fast-cooling. As illustrated in Fig. 5, drilling machinability of all materials tested decreased in terms of the average thrust force, and the slope of thrust force vs number of holes. For instance, the highest average thrust forces for the mix 8 increased from 75 lbf to 168 lbf, and the slope of average thrust force increased from 0.366 to 5.36 lbf/hole after sinter-hardening. Although the thrust forces increased for the sinter-hardened materials, the machining additives still improved the drilling performance of FLC-4608 material.

Additive of mix 8 was selected for further evaluation of tensile and fatigue properties based on both its machining performance and its effect on the sintered properties.

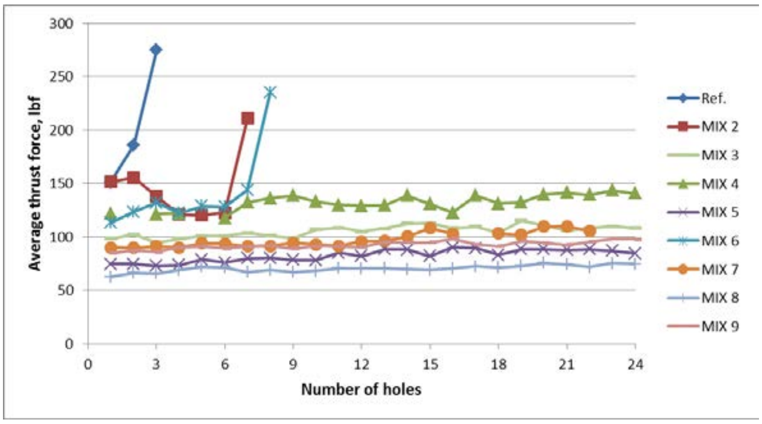


Fig. 3 Drilling machinability of the mixes containing new additive formulations compared to the reference without additive: materials with slow cooling

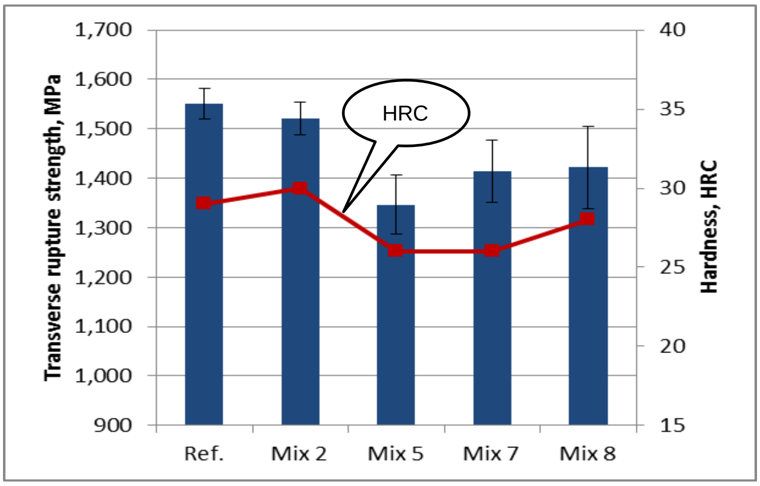


Fig. 4 Transverse rupture strength and hardness of the materials containing experimental additive compared to the reference without additive: sinter-hardened materials

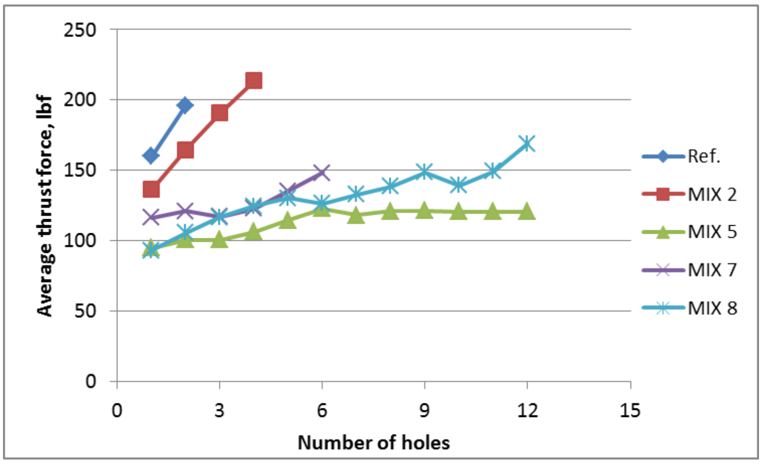


Fig. 5 Drilling machinability of the materials containing select additive formulations compared to the reference without additive: sinter hardened materials

Based on the results of the first series of experiments, another series of eight additive formulations was developed and tested. The materials containing these new additives were only tested in sinter-hardened condition. The drilling performance of these materials is illustrated in Fig. 6. Additive of mix 14 was selected from this series as it improved the machinability of FLC-4608 with acceptable sintered properties (DC=0.351%, TRS=1351 MPa, Hardness=27 HRC) compared to that of the reference without additive (DC=0.316%, TRS=1550 MPa, Hardness=29 HRC).

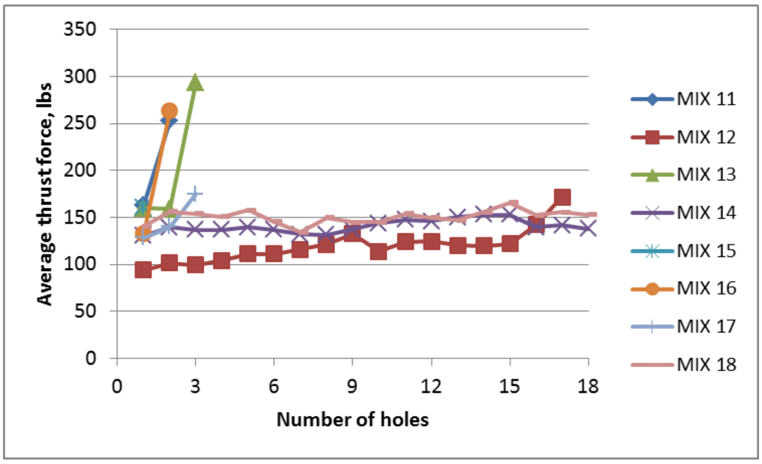


Fig. 6 Drilling machinability of the materials containing the second series of experimental additives

In the next step, the materials containing machining enhancers of mixes 8 and 14 (ME 8 and ME 14) were tested for tensile and fatigue properties and the results were compared to the materials without additive and with 0.5% MnS. Ultimate tensile strength was lower for all materials containing machining enhancers compared to the reference, as shown in Fig. 7, while the material with ME 8 showed the lowest decrease of 9%. Yield strength also decreased slightly for the materials containing machining additives. Fig. 8 presents the dimensional change from die size of different FLC-4608 materials. DC was measured on TRS samples compacted to 7.0 g/cm^3 density and sintered for fatigue testing from each material. All machining additives caused growth in FLC-4608 specimens compared to the reference without additive.

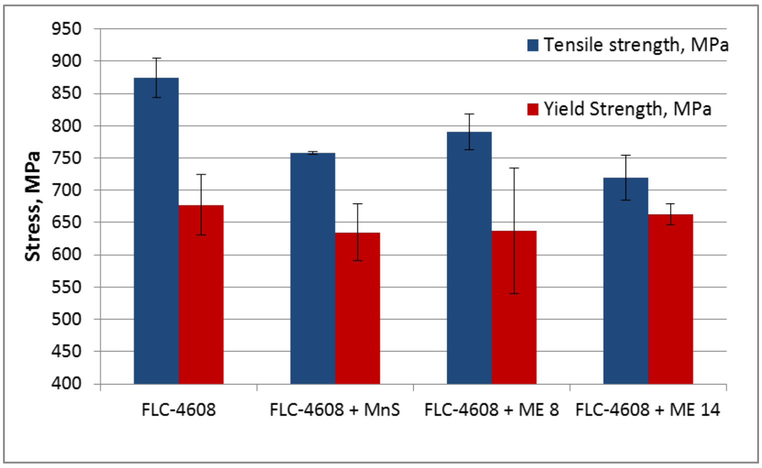


Fig. 7 Ultimate tensile strength and yield strength of FLC-4608 materials with different machining enhancers

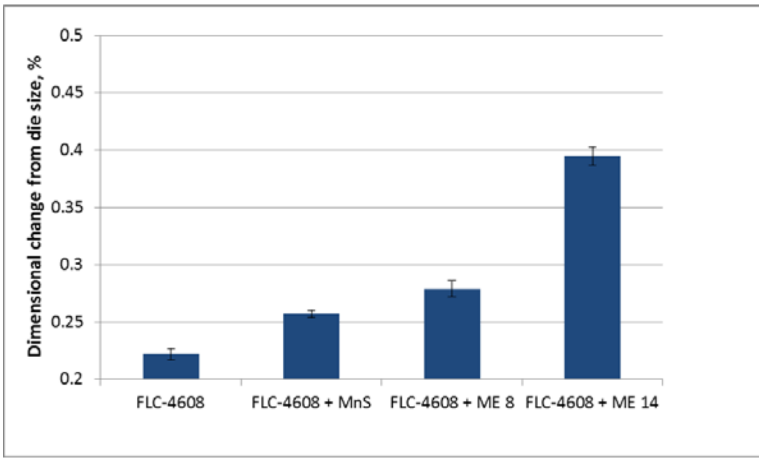


Fig. 8 Dimensional change from die size of FLC-4608 materials with different machining enhancers

The results of bending fatigue test performed on TRS bars from materials with no additive, MnS, ME 8 and ME 14 are shown in Fig. 9. The reference material and the one containing MnS showed similar fatigue strength values, 418 and 414 MPa, respectively. The material containing ME 8 showed a 7% lower fatigue strength compared to the reference, 390 MPa, while the material with ME 14 had the lowest fatigue strength of 347 MPa, 17% below the reference.

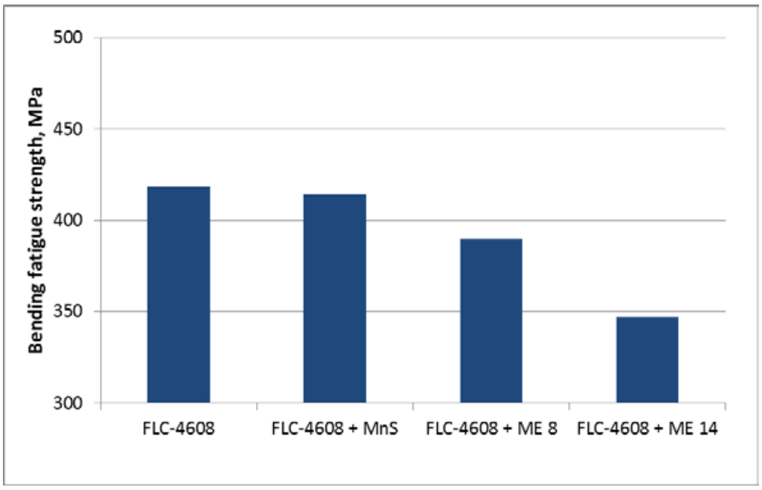


Fig. 9 Bending fatigue strength of FLC-4608 materials with different machining enhancers: maximum stress at 50% survival rate, loading ratio of 0.1

Fig. 10 shows the variation of the average thrust force as a function of number of holes drilled for different FLC-4608 materials. As shown, the tool broke after two holes for the reference material and after 4 holes for the material containing MnS. Therefore, MnS was not efficient to improve the machinability of the evaluated sinter-hardened material. Machinability improved significantly with the use of both select machining enhancers with ME 14 being more efficient in general. The thrust forces were initially lower for ME 8 containing material compared to ME 14 but increased rapidly after a certain number of holes. The slopes of average thrust force versus number of holes curves for different materials are also compared in Fig. 11. The slope values were 40 and 36 lbf/hole for the materials without additive and with MnS showing a very short tool life for these materials. The slope was significantly lower for the materials containing both select machining enhancers and ME 14 could potentially provide longer tool life compared to ME 8. The microstructure of different sinter-hardened FLC-4608 materials is shown in Fig. 12. These microstructures were taken from the center of TRS bars where the effective cooling rate was the lowest and the difference in the evaluated materials could be better seen. For all materials, the microstructure was composed of tempered martensite and bainite. A higher proportion of martensite to bainite is seen for the reference material without additive and the one with MnS compared to the materials with select experimental additives. This is in accordance with the higher hardness of these materials presented in the parentheses. The material with ME 14 was composed of martensite and bainite with some retained austenite.

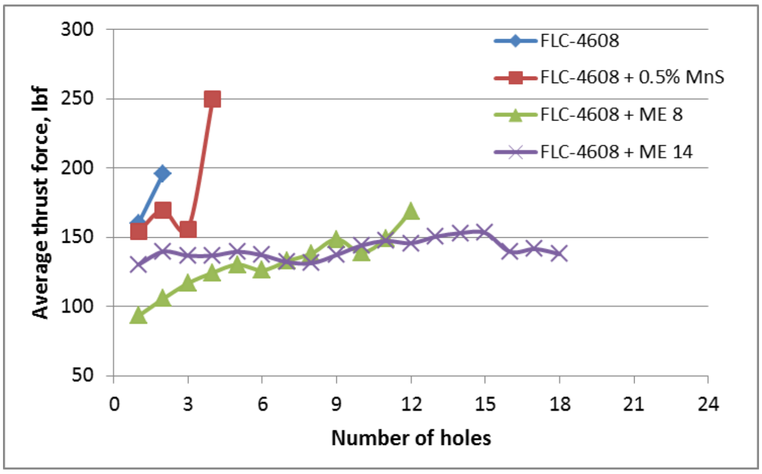


Fig. 10 Drilling machinability in terms of average thrust force of FLC-4608 materials with different machining enhancers

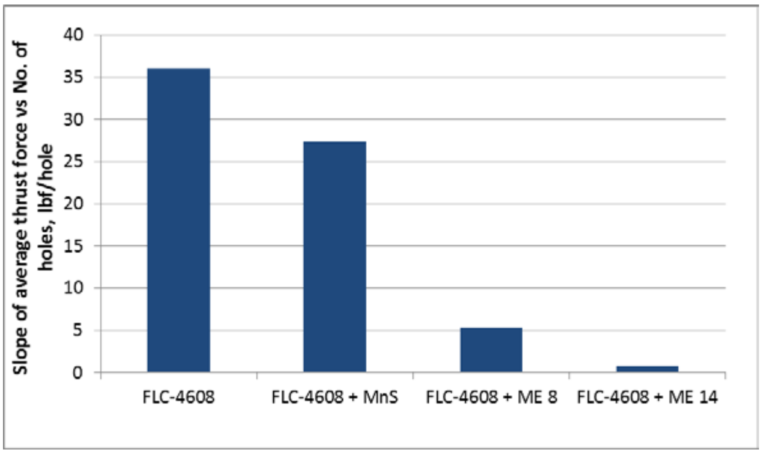
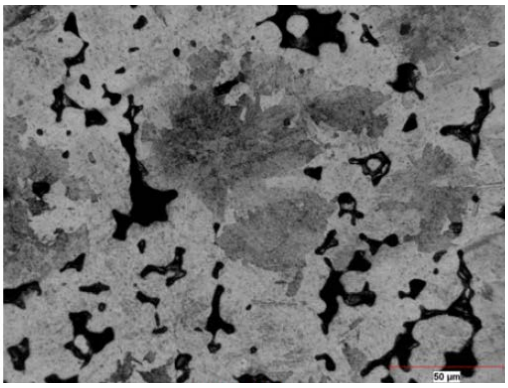


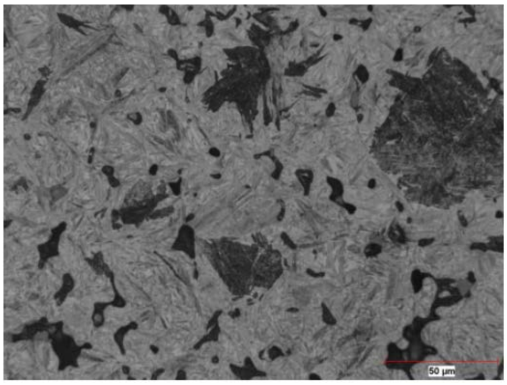
Fig. 11 Slope of average thrust force versus number of holes for different FLC-4608 materials

Conclusion

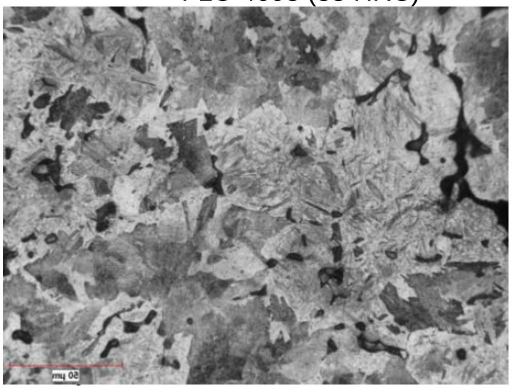
The new experimental machining enhancers ME 8 and ME 14 improved the drilling machinability of sinter-hardened FLC-4608 material while MnS was not an effective enhancer for this system. ME 8 had less negative effect on the mechanical properties of FLC-4608 compared to ME 14, while the latter showed better machining performance. Accelerated cooling also reduced the negative effect of machining enhancers on the sintered properties. Further evaluation of the machining performance of these new experimental enhancers should be done by performing turning test to validate their improving effect on the machinability of FLC-4608 material as this study was limited to drilling of certain number of holes for each material.



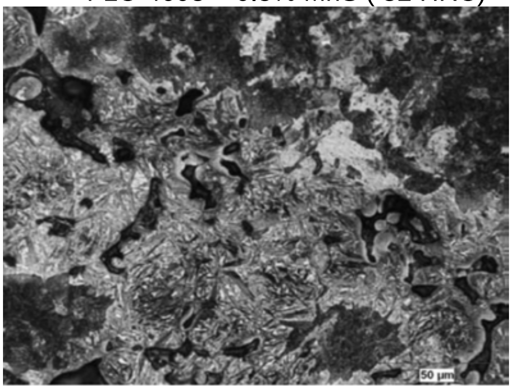
FLC-4608 (33 HRC)



FLC-4608 + 0.5% MnS (32 HRC)



FLC-4608 + ME 8 (27 HRC)



FLC-4608 + ME 14 (26 HRC)

Fig. 12 Microstructure of different sinter-hardened FLC-4608 materials: center of ½” TRS bars; hardness values in parentheses

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