Example

Selecting Productive and Cost-Effective Machining Solutions for Powder Metallury (PM) Materials

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ABSTRACT: Machining is a tribological process which involves friction, lubrication and wear. It is important to understand the basic machining principles and link them to the actual machining of components. Powder metalallurgy (PM) components are commonly considered to be more difficult to machine compared to wrought steels due to their inherent porosity and differences in the material compositions required to achieve similar performance. Machinability enhancing additives are a commonly used solution to improve machining. However, to utilize the benefits provided by the additives for specific or multiple machining operations is a challenging subject due to the complexity of machining. Therefore, developing an effective laboratory testing procedure based on specific machining operations is critical to avoid failures in production trials when introducing a machining enhancer into the material. In this study, the basics of machining PM materials and the ways to improve machining are discussed. The effectiveness of recenttly developed machining enhancers is demonstrated for improving productivity and increasing tool life through application case studies.

*Key words***:**
Machinability
Machining enhancers

1. Introduction

Despite Powder Metallurgy (PM) being recognized as a net-shape manufacturing technology, machining is often required to achieve desired dimensional tolerances, surface finish or features which are unable to be made through the PM process in an economic way, or due to engineering difficulty. PM materials are commonly considered more difficult to machine compared to wrought steels due a number of factors. Porosity is inherent to PM materials. However, the pore structure decreases thermal conductivity resulting in difficulty in removing the heat generated during machining. In order to overcome the effect of porosity with regards to mechanical performance, PM steels are typically more heavily alloyed. This results in harder microstructures which are more difficult to machine[1]. But, one of the advantages of PM technology is the flexibility in material formulation, i.e. formulating functional ingredients to achieve desired performance. If increased machinability is required for an application, an addition of a machinability additive can result in significant improvement.

Manganese sulfide (MnS) is a well-known conventional machining enhancer which has been proven to be very effective in improving the machinability of copper steels. With a typical addition level of 0.5%, a large improvement can be observed in many different machining operations. While large

improvements can be achieved, caution is required due to a decrease in corrosion resistance and the formation of surface stains after sintering[2]. In some applications, the corrosion resistance and appearance of PM components are a critical aspect as many end-users consider surface stains or corrosion to be defects. In these situations, therefore, MnS is either used at a reduced level or not at all[3]. In higher alloyed materials, such as low-alloyed steels, heat treated steels and sinter hardened steels, MnS also provides improvement in machinability, although at reduced levels[4]. In general, this additive is commonly used to solve many machining issues.

Many research and development efforts have been undertaken to explore new additives to replace MnS. Additives such as hexagonal boron nitride, calcium fluoride and magnesium silicates such as talc and enstatite are commercially used in PM materials today for machining improvements[5]. Although these additional additives provide a certain level of improvement for some PM material systems, none of them are as widely utilized and effective as MnS.

Recent development activities have realized several new machining enhancing additives for PM materials[6-14]. For example, a machining enhancer named SM3 has been successfully applied for numerous PM applications since 2010. It exhibits superior machining performance with regards to tool life and productivity compared to MnS in low-alloyed, sinter hardened and heat treated steels[10, 13]. For copper steels, another machining enhancer named SM4 was developed to provide an alternative for components requiring both drilling and turning operations. Both additives provide improvement without degredation in corrosion resistance or staining.

This paper reviews the basics of machining PM materials and describes the importance of developing an effective laboratory testing procedure based on specific machining operations in order to avoid failure when scaling up to production conditions. Commerical advanced additives were examined for their effectiveness in improving the machining of commonly used PM material systems. Application cases are presented to demonstrate the benefits of the advanced machining enhancers with regards to improved productivity and reduced total machining cost.

1.1 Machining: Complexity and Challenges

Machining is a complex process which consists of a tribological system involving friction and wear. For PM components, the machinability is not a material property, but a response of the material to a process, i.e. machining[5]. Many variables influence the machinability of PM components. Table 1 summarizes the factors which are considered to affect the machining of PM materials[15].

Table 1

Factors affecting the machining of PM components

PM Component	Manufacturing Route	Machining
Base iron	Sintering temperature	Type of cutting
Alloying Elements	Sintering atmosphere	Type of tooling
Carbon Content	Cooling Rate	Cutting speed
Additives	Heat Treatment	Cutting depth
Microstructure	Steam Treatment	Feed rate
Hardness	Impregnation	Coolant usage
Porosity	Infiltration	

The machinability of a PM component is dependent on its material composition and the

manufacturing route. The most common PM material system, copper steel, is composed of ferritic and pearlitic microstructures with copper strengthening after conventional sintering. The amount of diffused carbon determines the ratio of ferrite and pearlite and thus the hardness of the matrix. The copper is alloyed into iron to form a harder and stronger material. For low-alloyed steels, the additional alloying elements (Cr, Ni, Mo, etc) result in multiphase microstructures or homogenious structures depending on the alloying technique and processing conditions. With the additional alloying, phases such as bainite and martensite are formed resulting in an increased matrix hardness. The microstructure of these materials is strongly influenced by the cooling rate where slight changes have the potential to change the microstructure. The most difficult microstructure to machine is martensite which is formed through sinter hardening, inducting hardening or through hardening. In general, the chemistry of the base iron is considered to play a major role in machinability since the majority of the matrix is the base powder[16].

Typical machining operations performed on PM components include turning, drilling, tapping, boring, and facing in which multiple operations are often involved to manufacture one component. In most cases, interrupted cutting is found. These features increase the complexity and difficulty in machining PM components. The amount of porosity (density level) is often claimed as the root cause of the poor machining performance of PM due to micro-interuppted cutting. Studies have shown the porosity has no detrimental effect on the machining of PM materials when an effective machining enhancer and/or the thermal energy can be effectively removed by coolant[15]. A comparison of interrupted cutting and porosity are shown in Figure 1.

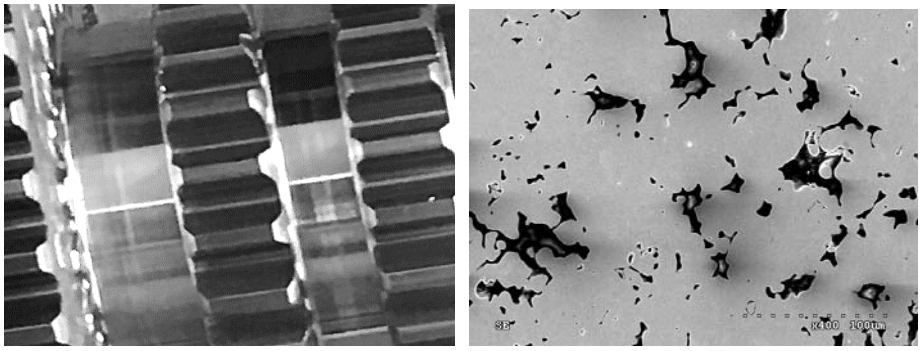


Fig. 1. Left: Example of interrupted cutting, Right: PM porosity (6.8 g/cm^3)

For a given PM component, selecting a suitable tool based on the machining operation is important. The machining parameters also require optimization in order to find the “sweet spot” allowing for maximum tool life and productivity. The “sweet spot” can change depending on the type of machining, type of tooling used, or other limitations on feed rate and cutting speed. With the addition of a machining enhancer, the “sweet spot” may also shift as different machining additives have different optimization areas.

1.2 Ways to Improve Machining

Machining is a process where momentum energy is converted to cutting forces to make elastic and plastic deformation on the workpiece removing an unwated portion of material. Friction and thermal effects created during the machining process play important roles in tool wear and the machined surface roughness as the temperature on the tool face greatly affects the size and stability of the built-up edge (BUE)[17]. It also causes chemical reactions at high temperature, such as diffusion and oxidation, which

make the machined surface harder. The balance of friction, wear and lubrication at the surfaces make machining a tribological process.

As shown in Figure 2, the friction between the cutting tool and workpiece generates heat and the resultant thermal effects will heavily influence tool wear. Therefore, tool life, chip formation and surface finish are three major aspects of concern during machining.

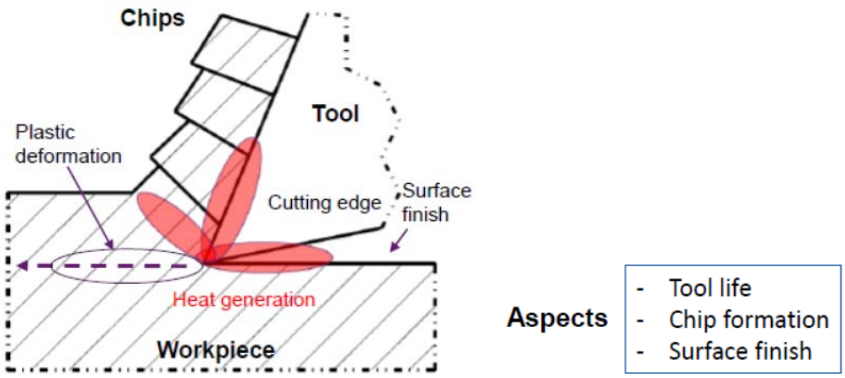


Fig 2. Schematic diagram of interactions between cutting tool and workpiece (friction and wear)

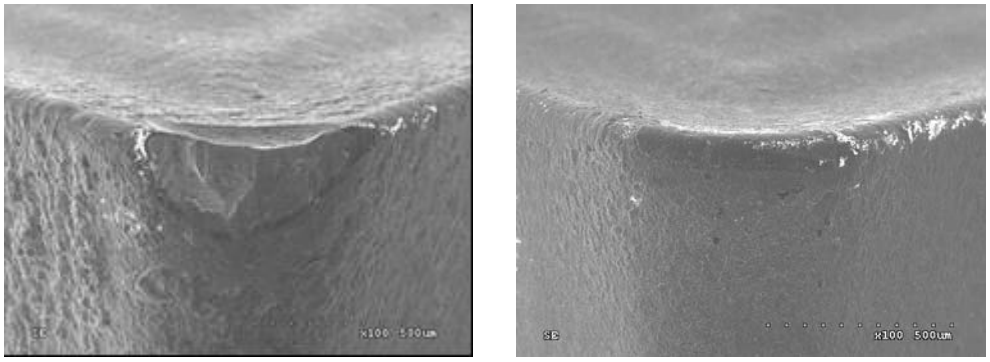
For a given cutting tool and workpiece, the life of the tool is directly related to the cutting conditions. High cutting speeds, fast feed rates and increase cutting depths will reduce the tool lifespan. In the mass production of machining PM components, a balance between productivity and tool life is required and is optized using these paramenters. Machining chips form ahead of the tool tip through plastic deformation of the workpiece during cutting. Heat and stress are generated in the cutting zone and the level generated depends on the cutting conditions discussed above. Removing the chips produced from the cutting area can reduce the stress and heat resulting in decreased tool wear. Many of the components machined require a specific surface finish of the machined area. A good surface finish can generally be achieved through the use of high cutting speeds. As the tool wears, the surface finish will degrade until replacement is required.

If the heat generated from friction between the cutting tool and workpiece can be quickly transferred from the cutting area, the thermal degredation of the tool piece is reduced and tool wear reduced. In dry machining (no coolant used), the heat transfer relies on the thermal conductivity of the workpiece material. If a coolant is used, the heat will be removed through the coolant.

Commerical machining enhancers are found to be effective in improving the machinability by imparting benefits such as lubrication, chip breaking and tool protection. Although not every machinability additive can provide all of these benefits, some may work for certain types of materials or operations within a range of cutting conditions. As machining is a material removal process, productivity is often a key measurement directly linked to the overall machining cost. An effective machining enhancer can use the functions listed above to enhance machinability through the extension of tool life or through an increase in productivity. Ideally, machining enhacners are preferred to achieve both longer tool life and increased productivity rates.

Figure 3 illustrates examples using an advanced machining additive for a copper steel that provides improved machining performance through improved chip breaking, tool protection and lubrication[15]. In this case, the enhancer extended the tool life more than three times the base line in a fast machining setting. In a dry drilling operation, most of the chips formed from the material without a machinability additive were dark blue in color indicating a high amount of heat generation during the operation. By

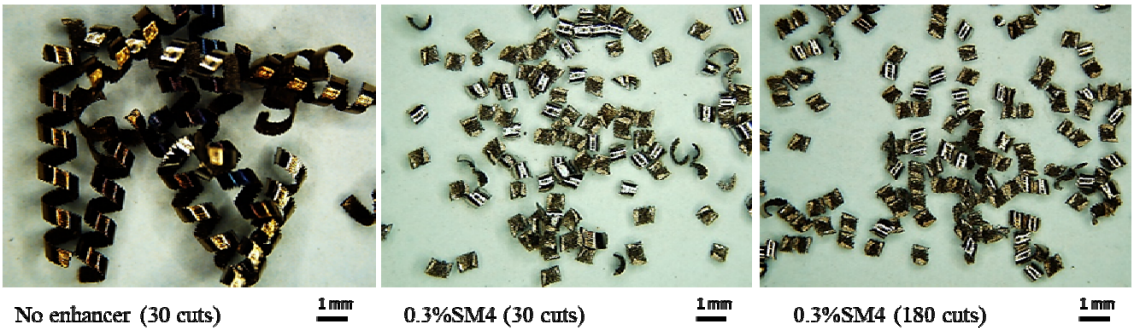
contrast, the advanced additive produced light colored machining chips comparable to material containing the MnS additive. The difference in color is a function of reduced heat generation and the additive's lubrication properties. Under the same machining conditions in a wet turning operation, the advanced additive exhibited good chip breaking performance and produced a shorter machining chip compared to the material containing no additive. The chips formed were dark blue and long, with no additive present, even in the presence of coolant. This indicated insufficient heat reduction and poor chip breaking.



No additive (78 cuts) 0.3% SM4 (300 cuts)



Chips generated from dry drilling of a FC-0208 material with various additives



Chips generated from wet turning of FC-0208 material with various additives

Fig. 3. Examples of features of advance machining additive SM4 providing tool protection, lubrication, chip breaking in a FC-0208 material system.

2. Effectiveness of machining enhancers in laboratory testing

When introducing a machining enhancer into a PM material, it is critical to develop an effective laboratory testing procedure based on specific machining operations in order to avoid failures when scaling up to production conditions. As machinability is the response of a material to machining, knowledge and experience in both material and machining operations is required to design laboratory testing conditions which will accurately assess the effectiveness of an additive. Simple laboratory drilling tests are often not able to predict real world machining performance due to the increased number of variables found on the manufacturing floor.

An example of this is found when evaluating a newly developed additive, SM4 with different testing procedures against MnS. In this example, a copper steel (FC-0208) was evaluated with both additives at their commonly used addition levels. The materials were tested using the machinability procedure listed in MPIF Standard 35[18]. The conditions of the testing are shown in Table 2. The material with SM4 quickly experiences tools failure after only 16 drilled holes while 600 holes were able to be successfully drilled using MnS. By modifying the test conditions, 100 holes could be drilled in the SM4 material with identical tool wear to the material containing MnS. Based on the information obtained from the modified tests, a production study was completed with a WC drill bit. In the production trial, 2800 holes were able to be drilled with the SM4 containing material without tool failure. This performance was similar to the performance of the parts containing MnS.

Table 2.

Number of holes drilled with a FC-0208 containing MnS and SM4

Testing Conditions	Conditions	0.5% MnS	0.3% SM4	SM4 vs. MnS
MPIF Std. 35 Test	HSS, dry	600	16	Tool failed at 16 holes
Modified Test A	HSS	50	50	Identical tool wear
Modified Test B	HSS	100	100	Identical tool wear
Production Test	WC	2800	2800	Identical performance

MPIF Std. 35 test conditions: 9.5 mm HSS drill, 1250 rpm, 0.23 mm/rev, 25.4 mm depth hole

Modified test A and B: modified cutting speeds, same feed and depth as MPIF Std. 35

Production Trial: WC drill bit, same test conditions as modified test B

As the example illustrates, the exisiting test procedure which was established for an additive such as MnS may not provide an accurate assessment of another type of additive which has different functions and attributes. An effective laboratory screening test on machinability additives should be designed based on the understanding of what behaviours the additives could exhibit and what benefits the additive could provide in the targeted machining operation. Several application cases have been selected to illustrate how advanced machining additives are effective machining solutions for PM components.

3. Production machining case studies

3.1. Grooving operation on carbon steel components

This component manufactured from a carbon steel (F-0005) required a groove machined into the outer diameter after sintering. The current machining solution utilized was MnS. However,

unpredictable corrosion issues were experienced and resulted in poor quality at the component manufacturer and end user. An advanced machining additive, SM3, was selected to replace the current solution in order to reduce the corrosion issue. The materials evaluated are shown in Table 3. An example of the machined components and typical microstructure are shown in Figure 4.

Table 3.

Materials and machining operations

Material	Carbon	Additive	Operation
Current	0.5%	0.5% MnS	OD grooving
Test	0.5%	0.15% SM3	OD grooving

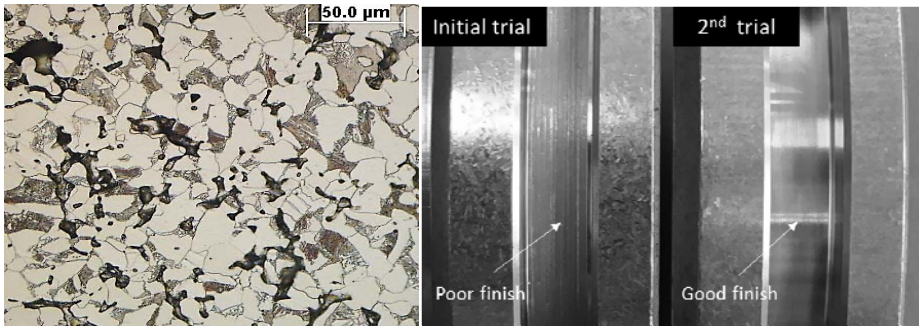


Fig. 4. Typical microstructure and machined components with SM3

The initial production trial which utilized the production conditions optimized for the current material showed poor surface finish when cutting the components containing the SM3 additive. Based on this result, laboratory tests were conducted and showed that the current production machining settings were not suitable for the advanced additive. Further testing was conducted to identify the "sweet spot" for cutting the SM3 material in order to achieve good surface finish and tool life. Parameters were optimized resulting in changes to the cutting speed and feed rate compared to the current production conditions. A second production trial was conducted using the new conditions. The results are shown in Table 4.

Table 4.

Production trials to evaluate replacing MnS with SM3 in a F-0005 grooving operation

Material	Additive	Tool Life	Productivity	Surface Finish
Current	0.5 % MnS	100 pcs/tool	100 pcs/hr	Good
First Test	0.15 % SM3	100 pcs/tool	80 pcs/hr	Poor
Second Test	0.15 % SM3	150 pcs/tool	120 pcs/hr	Good

With the recommended machining parameters, the production trials successfully cut the SM3 components without surface finish issues. The surface finish was maintained with an increase in tool life (50 %) and improved productivity (20 %) compared to the MnS containing material.

3.2. Drilling and reaming of components manufactured from copper steel

Variable valve timing components often require the drilling of small, deep holes from the outer diameter to inner diameter. Reaming of certain holes is required with a strict tolerance on surface finish.

Typically these operations result in poor tool life and low productivity due to the challenges and requirements of the final hole. Inconsistent machining with unpredictable tool failure results in scrap and downtime, further reducing productivity. Production trials were performed to evaluate an advanced additive, SM4, aiming to improve tool life and productivity. The materials evaluated in this production trial are shown in Table 5. An example of the VVT component and typical microstructure is shown in Figure 5.

Table 5.

Materials and machining operations for VVT production trial (FC-0208)

Material	Copper	Carbon	Additive	Operation
Current	2%	0.8%	0.15% MnS	Drilling, reaming
Test	2%	0.8%	0.2% SM4	Drilling, reaming

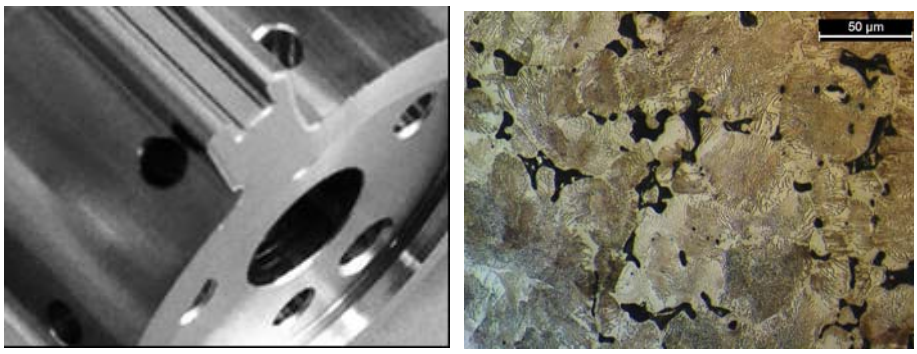
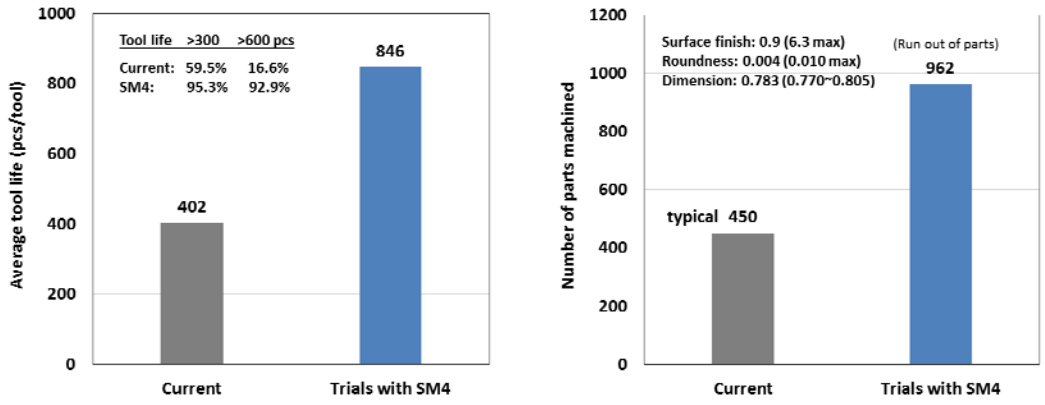


Fig. 5. Machined component and typical microstructure (FC-0208)

In the drilling operation, to evaluate consistency with regards to predictable tool life, 42 production machining trials were conduted. The tool life was extended on average by 110% compared to the current material by using the SM4 additive. With a consistent number of pieces machined by the SM4 additive, reduced downtime and scrap were able to be achieved. A summary of the drilling trials is shown in Figure 6 (left graph).



Drilling Reaming

Fig. 6. Machining results on FC-0208. Left: Average tool life from 42 production trials; Right: Tool life of reaming

Results of the reaming are shown in Figure 6 (right graph). In the reaming operation, a similar increase was found with the SM4 additive providing a 113 % improvement in tool life while maintaining the surface finish, roundness and dimensional requirements. The trial was terminated due to lack of available components with the advanced additive. This trial provided evidence that SM4 could provide improved tool life and increased productivity for these types of components.

3.3. Inner diameter turning of components manufactured from diffusion alloyed steel

A component manufactured from a diffusion alloyed steel was initially launched without a machinability additive. Over time, challenges with low productivity due to high tolerance requirements were encountered. The inner diameter requires machining after sintering. The component and typical terogenous microstructure are shown in Figure 7.



Fig. 7. Machined component manufactured from diffusion alloyed steel & typical microstructure

After review of the machining parameters and requirements for surface finish and dimensions, the machining enhancer SM3 was recommended as a solution. Production trials were completed with the current material without an additive compared to the material with a 0.15 % SM3 addition. Results from the production trials are shown in Table 6.

Table 6.

Diffusion alloyed steel production machining results

Material	Additive	Tool Life	Productivity
Current	None	150 pcs/tool	75 pcs/hr
Test	0.15% SM3	300 pcs/tool	110 pcs/hr

When using the advanced additive, the tool life was doubled compared to the current production material. As tool life was extended, the amount of scrap and downtime was reduced by an improvement in the consistency of the machined components for both dimesions and surface finish. This resulted in a 50 % increase in productivity.

3.4. Facing of heat treated prealloyed steel

The components manufactured in this case experienced a very short tool life due to a difficult facing operation completed after heat treatment. The tooling utilized to complete the facing operation was cBN and this added to the high cost of this machining operation. As the current production practice

was to not use MnS due to corrosion concerns and the fact that MnS is less effective in alloyed materials, an advanced additive was suggested to improve the machining. An overview of the materials compared in this case is shown in Table 7. Prior to the production trials, laboratory testing was completed with samples processed in the same sintering furnace and heat treatment conditions as the production component. The results of the laboratory testing indicated that the SM3 additive would be able to improve the machinability by more than 2 times. This anticipated improvement was determined at a higher cutting speed than currently used in production giving confidence that an improvement would be observed in the production trial.

Table 7.

Materials and machining operations for facing

Material	MPIF	Additive	Operation
Current	FL-4405	None	Hard Interuppted Facing
Test	FL-4405	0.1 % SM3	Hard Interuppted Facing

With the laboratory testing being used as the baseline, a production trial was completed on components in the production machining line. An example of the component and typical machined microstructure is shown in Figure 8.

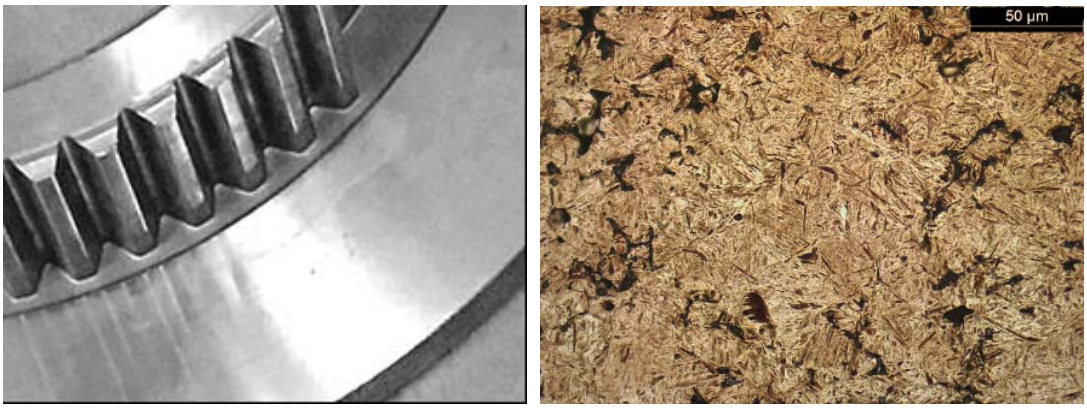


Fig. 8. Machined component and typical machined microstructure

The results of the testing are summarized in Table 8.

Table 8.

Production machining trials on FL-4405HT components

	Additive	Tool Life
Current Production	None	50 pcs/tool
Test with SM3	0.1 % SM3	150 pcs/tool

The components containing the advanced additive were easier to machine resulting in a tripling of the tool life. In addition, the advanced additive enabled the machining to be completed at faster cutting speeds and higher feed rates. The improved tool life and improved productivity resulted in immediate cost savings for the component manufacturer.

4. Summary

Machining of PM components is a complex process especially when multiple step machining operations are involved. Depending on the component, different limitations may exist for machining parameters, tooling options and quality requirements. It is important for the material engineer and machinist to collaborate in order to select a productive and cost-effective solution to maximize the machinability of the workpiece.

Commerical machining additives are proven to effectively improve the machinability of PM components. However, it is important to understand their advantages and limitations for different machining operations and conditions. The application cases presented in the paper clearly demonstrate the benefits which the advanced additives provide through improved tool life and higher productivity which ultimately reduces costs through a reduction in downtime.

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