Sensitivity Analysis of Machining Parameters in Fe-Cu-C Mixes Containing Machining Enhancers

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Abstract

The paper addresses the need of improving machining behavior of PM components. Parts manufactured by means of powder metallurgy are characterized by a very heterogeneous microstructure, not only as far as phases in the material itself, but most of all for the presence of voids. As a result, the machining tool is subjected to very high thermal and mechanical stresses due to these diverse structures that the tool comes into contact at every pass. The addition of MnS to premixes has traditionally given enhanced machinability and lowered tool wear; despite this, MnS is a sub-optimal solution in that it tends to accelerate rusting under atmospheric conditions. This makes machining operations time-sensitive and difficult to control. In the present work, we investigate the response to drilling of the Fe-Cu-C system with addition of novel machining additives. Specifically, the dependency to feeds, speeds, coolant and drill bit material will be analyzed. The variables that will be accounted for in the study are number of holes drilled, torque, and variation in hole size. The wear mechanism for different test conditions will also be explored and ultimately the optimum machining variables per condition will be selected.

Introduction

PM components are widely used in the automotive and off highway industries. Often, PM is preferred for parts that are characterized by intricate shapes, attainable directly after sintering, which allows for minimization of post processing operations such as machining, that are expensive and time consuming [1]. Despite this, some high precision applications still require machining in order to achieve tight dimensional and geometrical tolerances. It is estimated that 40-50% of PM steels require additional machining in applications where wrought steels are normally employed [2]. The presence of voids makes PM materials challenging to machine. Porosity creates an “intermittent cut” condition that leads to severe thermal and mechanical fatigue of the machining tool. The need for high productivity, directly correlated to high machining speeds and feeds, accentuates this latter drawback. Many factors contribute to machinability, such as material properties, production processing and cutting conditions, and the synergy among them has not been fully understood yet. Danninger [3] found that adding MnS to iron-copper-carbon materials improves drilling behavior both dry and with coolant, despite the tendency of MnS to rusting, which renders dry conditions preferable to coolant use. M’Saoubi et al [4] also witnessed an increase in tool life and decrease in cutting forces when MnS is added to the base material. Blais et al. [5] saw that FC-0208+0.5%%MnS machines better during drilling when the manganese sulfide particles are pre-alloyed rather than admixed. Drilling life is further increased when MnS is added to the base material and carbide drill bits are used. This does not apply to HSS (high speed steel) drill bits, for which the same machining response has been observed in FC-0208 with and without MnS addition [6]. Process conditions greatly influence drilling behavior. Rocha et al. [7] studied the influence of speed, feed and depth-of-cut in machining of ferrous powder metal valve seats using PCBN tools. They concluded that cutting speed has a dramatic effect on tool-wear and proved that attrition wear arises at lower cutting speeds, while diffusion wear is characteristic of medium cutting speeds. Lindsley et al. [8-9] tested the response of Distaloy material with addition of a novel machining compound (AncorCut) in linear turning conditions and compared it to MnS (Fig.1). AncorCut appeared to provide less change in part diameter compared to MnS when machining is conducted three weeks after sintering. The tendency of MnS to interact with moisture makes it a time-sensitive additive and response to machining is dependent on environmental exposure after sintering. On the other hand, AncorCut has proved to be a stable additive as well as provide insert life comparable to MnS. Due to the promising results in turning (Fig.1), AncorCut behavior in drilling operations will be assessed.

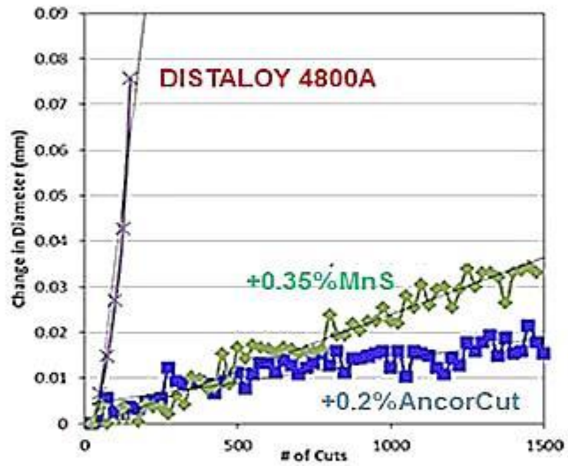
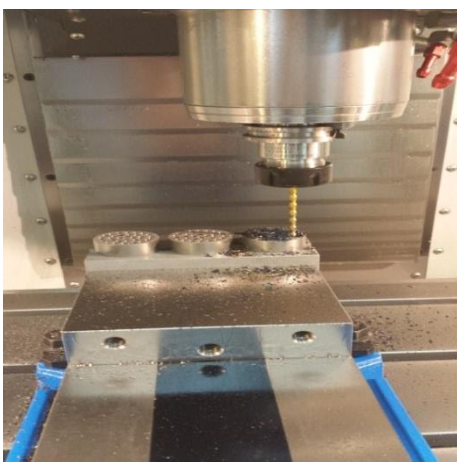


Figure 1. Change in diameters of ring samples. Distaloy base material, MnS addition and AncorCut addition [8-9].

The present work focuses on the machining response to drilling of iron-copper-carbon steel FC-0208. Specifically, the effect of machining additives, feeds, drill bit materials, coatings and lubricant regime will be evaluated in sintered and green conditions. Number of holes drilled, diameter variation and spindle torque will be measured to rate machinability in each condition and investigate wear mechanisms.

Experimental Procedure

Drilling trials were performed in the Machining Laboratory within the Innovation Center at Hoeganaes Corporation in Cinnaminson, NJ on a HAAS VF-1 vertical milling center. Maximum torque at 2000 rpm is 12.5 kg-m (90 ft-lbs). A 2 mm (0.078") tungsten carbide ball stylus 50 mm (2") long from Renishaw has been employed to measure variation in diameter. The setup (Fig.2a) involves three specimens (pucks) clamped by an aluminum fixture. Every puck can contain 33 holes which leads to a total of 99 holes drilled per cycle. Infinite life has been set at 990 holes (10 cycles).



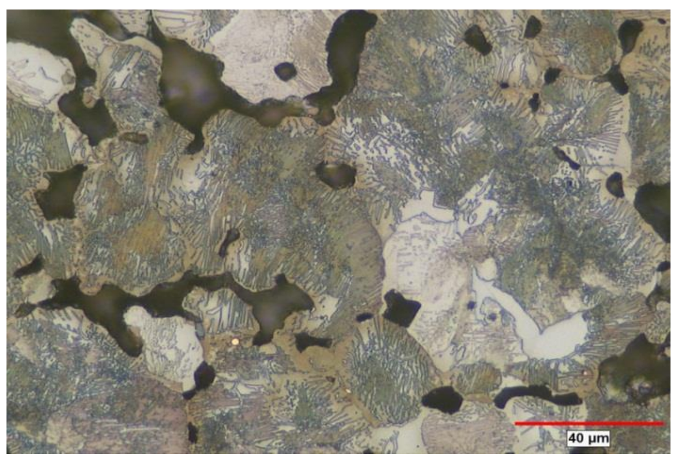


Figure 2: a) Drilling set up with aluminum fixture; **b)** Nital etched microstructure. FC-0208.

Drill bit diameter was is 4.763 mm (0.1875") and depth of drilling about 25 mm (1"). Screw machine length drill bits have been chosen over jobbers to minimize bending and wobbling of the bit. Diameter was probed every 5 – 10 holes depending on tool material. In addition to the baseline (FC-0208, Fig.2b), additions of MnS and AncorCut have been investigated (Table 1). Pucks were pressed at 6.9 g/cm^3 and sintered at 1020 °C (2050 °F) in a hydrogen/nitrogen atmosphere. Table 1 also reports speeds, feeds, and coolant conditions (LUBRICUT 4265 diluted with water in a 5:100 ratio has been selected for coolant) used for the investigation.

Table 1. Summary of Drilling Trials (sintered).

Material Code Machining Additive	Test Code	Drill Bit Material	Coating	Speed (rpm)	Feed (mm/min)	Coolant
1 None (FC-0208)	**HS1** **HS2**	HSS, Screw Machine Length	None	2000	159 318	YES/NO
2 +0.35% MnS	**HT1** **HT2**	HSS, Screw Machine Length	TiN	2000	159 318	YES/NO
3 +0.2% AncorCut	**CD1** **CD2**	Carbide, Short Length Jobber	PVD polycrystalline diamond	3500	318 508	YES

Results and Discussion

Rusting of FC-0208+0.35%MnS

It is pivotal to mention that addition of MnS causes rusting, particularly in hot and humid environments. Figure 3 shows severe rusting in MnS-containing pucks 2 weeks after machining with coolant, while the no additive and AncorCut samples appear to bear any accelerated rusting. Rusting affects tool life dramatically. Pucks of Material 1, Material 2 (MnS) and Material 3 (AncorCut) were kept in a humidity chamber at 92% humidity and room temperature for three days. After that, test HT1 (HSS +TiN coating, low feed) dry has been pursued on pucks right after sintering and exposed to humidity. Figure 4 reveals a decrease in tool life of about 30% for FC-0208, while drill life for FC-0208+0.35%MnS dropped of about 85%. Number of holes drilled for FC-0208+0.2%AncorCut only dropped only about 5%.

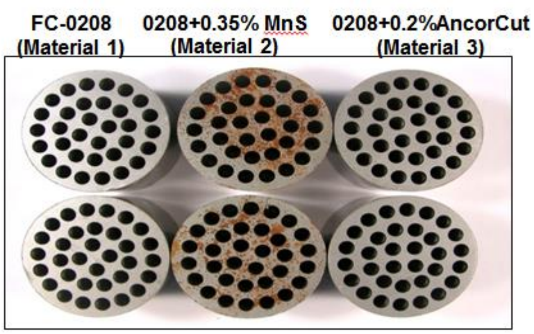


Figure 3: Rusting after 2 weeks of drilling with coolant.

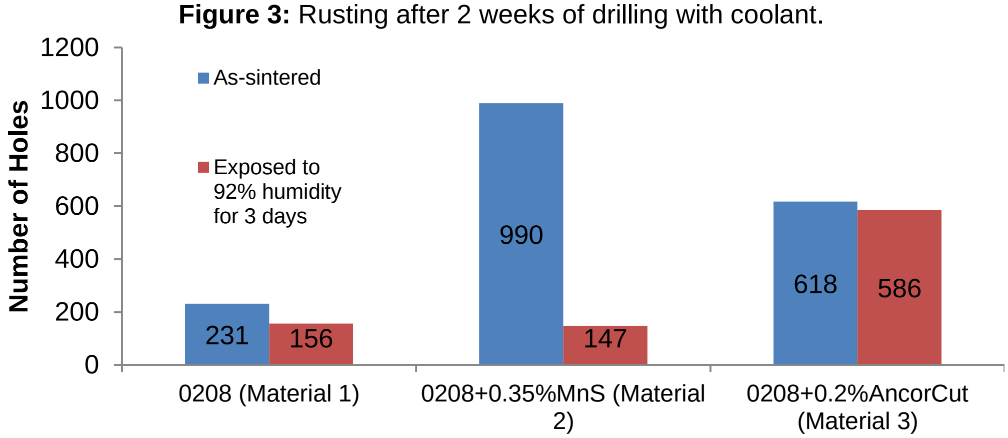


Figure 4: **Effect of humidity on drill bit life. Material 1, Material 2, Material 3. Test: HT1 dry.**

Number of holes, diameter variation and DDV

Table 2 displays number of holes drilled for each test condition. Material 2 (FC-0208+0.35% MnS) showed the best performance for high speed steel bits at low feeds and no coolant. Material 2 also provided the longest tool life in drilling with carbide bits for both feeds (CD1, CD2). Material 3 (FC-0208 + 0.2% AncorCut) exhibited excellent behavior for HSS uncoated with coolant and dry drilling for HSS+TiN (HT2) at high feeds. Although it did not drill all 990 holes, Material 3 appeared to be promising in drilling with carbide bits compared to the base material (Material 1). The results shown here demonstrate that tool life is highly dependent on the cutting conditions and drill bit materials, and that test results from one test can not necessarily be used as a guide to predict the response under different test conditions.

Table 2. Number of Holes.

Test Code	Coolant	Material Code		
		1	2	3
HS1	NO	98	921	357
	YES	313	334	445
HS2	NO	2	186	3
	YES	366	183	403
HT1	NO	231	990	618
	YES	204	69	140
HT2	NO	229	11	266
	YES	301	49	167
CD1	YES	254	990	598
CD2	YES	103	425	348

In order to assess dimensional accuracy throughout machining, variation in hole diameter has been measured. The interval of variation will be larger for materials and machining parameters that lead to poor dimensional consistency. Material 2 had the smallest interval of variation for high speed steel dry. Material 3 (AncorCut) provided low diameter variation for TiN coated high speed steel under coolant at low feeds. This data point is also the lowest across all test conditions. Figure 5a shows diameter variation for PVD diamond-coated carbide bits. It can be stated that Material 2 (MnS) is characterized by the largest diameter variation both at 318 mm/min and 508 mm/min. Material 3 (AncorCut) has a considerably smaller range, especially for high feeds, whereas the range for Material 2 is more than six times larger.

It has been concluded that the maximum number of holes and the minimum diameter variation are not given by the same material. Both parameters are pivotal in quantifying machinability in industrial settings. To unify both parameters into one variable, the concept of Discrete Diameter Variation (DDV) has been defined. The DDV can be expressed as average diameter variation per hole:

$$\text{Discrete Diameter Variation (DDV)} = \frac{\text{Diameter Variation}}{\text{Number of Holes}}$$

Material 3 (AncorCut) not only provides very low DDV values for every test conditions, but also very similar data across all tests. This tendency is even more noticeable in drilling with coated carbide (Fig.5b): the addition of AncorCut provides very low DDV at both feeds and Material 2 at 508 mm/ showed DDV values about six times larger than Material 3.

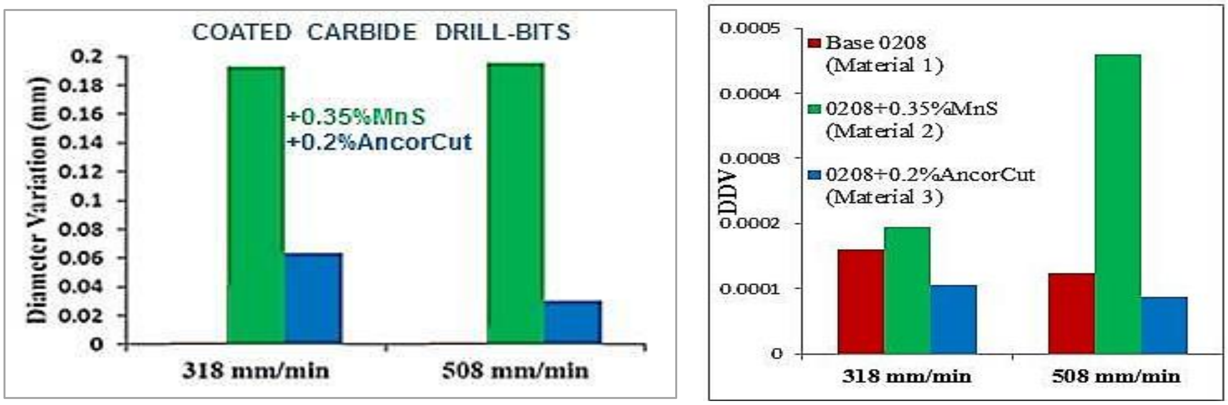


Figure 5: a) Diameter variation for coated carbide bits; **b)** DDV for coated carbide bits.

Wear Analysis

Important conclusions on wear mechanisms in drilling can be drawn when in lieu of measuring hole to hole variation, the analysis accounts for the overall trend of diameter change. It can be stated that, while *how much* the diameter changes is a measure of dimensional quality of the hole, *how* it changes is a measure of wear dynamics. Modes of diameter variation and wear meachanisms are closely correlated. Figure 6a exemplifies such trend for Material 1. Change in diameter when drilling with HSS bits under coolant follows a *downward polynomial-type* of trend whereas values for TiN-coated HSS in dry conditions are characterized by a *scattered moving average* fashion. Figure 6b shows spindle torque values as the drilling operation commence. Higher torque values can be correlated to tests showing a scattered diameter change (SC) whereas for downward polynomial (DP) trends the peak torque is lower. Generally, drilling under coolant or/and with TiN coated bits results in downward polynomial diameter variation. Gradual decrease in hole diameter (such as it happens for downward polynomial trends) indicates thinning of bit width, which takes places as a result of progressive *abrasive wear*. SC trends can be linked to *adhesive wear,* which onsets as the drill bit heats up, resulting in chips from the specimen to become welded on the bit, leading to in bigger holes. As the drilling process carries on, the welded chips are consumed and hole diameter once again decreases. The cycle will reiterate till breakage of the drill bit. Coolant lowers the temperature between drill bit and material, whereas TiN coating improves heat conduction because of its high thermal conductivity. For most test conditions, the presence of coolant is more effective in causing DP trends than TiN coating. This occurs since coolant locally decreases tool/piece temperature, avoiding the weldment of chips on the bit and therefore, adhesive wear. Confirmation of this hypothesis comes from the SEM analysis of the drill bit used for test HS1 dry and with coolant (Fig.7a). DP diameter variations can be linked to longer drill bit life compared to SC trends in most cases. Therefore, DP trends are to be preferred to scattered trends. In addition, DP trends tend to plateu towards end of life of the drill bit, allowing the operator to predict bit breakage. When AncorCut is added to FC-0208, the change in diameter is downward polynomic throughout all test conditions (Fig.7b).

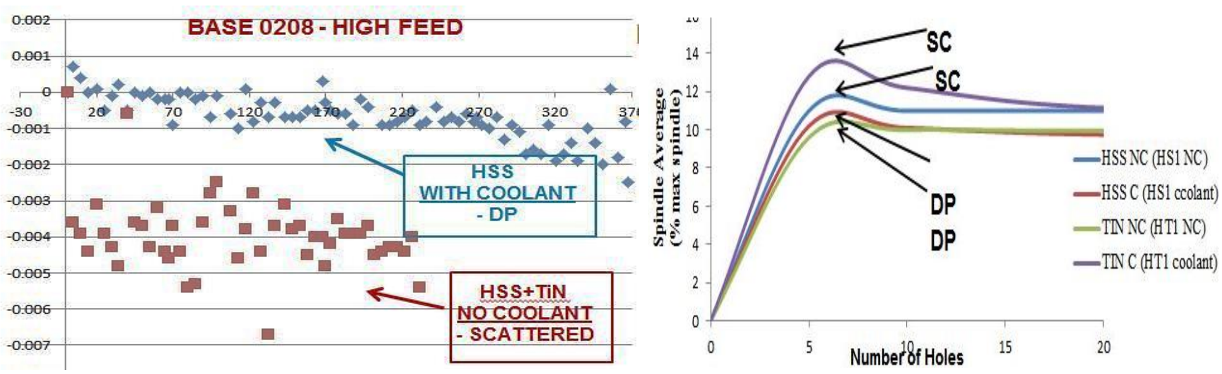


Figure 6: a) Diameter change vs. number of holes. Material 1; **b)** Spindle average vs. number of holes.

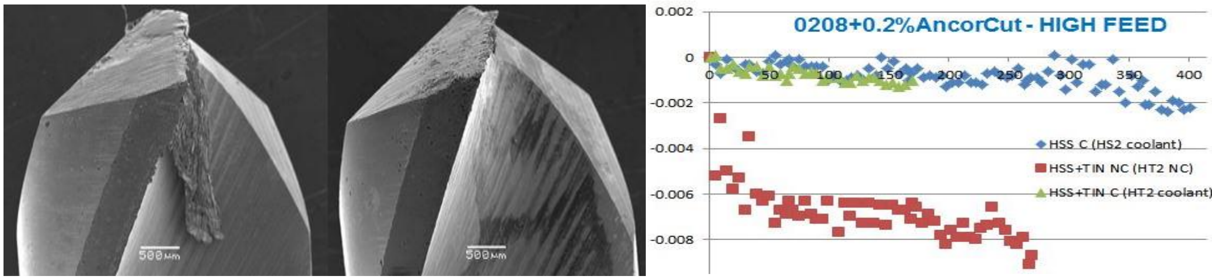


Figure 7: a) SEM images of adhesive wear. Test HS1. Left: dry (adhesive wear). Right: coolant (abrasive wear). Material 1. **b)** DP trends of diameter variation for Material 3 (AncorCut).

Conclusions

The present work aimed to assessing the drilling response of FC-0208 in the presence of two machinability additives: the commercially available MnS and AncorCut from Hoeganaes Corporation. Outcomes can be summarized as follows:

- The addition of MnS produces accelerated rusting of the part which can affect machinability, both for what concerns drill bit life and machining quality. AncorCut does not cause enhanced rusting.
- Tool life is highly dependent on test conditions and drill bit materials. Drill bit life for MnS-containing steels has been found to be excellent at low feed rate, no coolant conditions for HSS and HSS+TiN bits and low feed with coolant for carbide bits. Longest drill bit life was exhibited by the AncorCut-containing steel for HSS bits with coolant and TiN coated HSS bits at high feeds. This is pivotal for the achievement of high machining rates, which are critical in industrial environments. It also provided satisfactory drill bit life of carbide coated bits.
- A discrete diameter variation (DDV) parameter has been introduced to consolidate interval of diameter variation and number of holes drilled. DDV values close to zero signifies good machinability. AncorCut (Material 3) has exhibited DDV numbers both very low and constant for all test conditions, particularly for all tests with carbide coated drills (CD1 and CD2).
- A correspondence between diameter variation and wear dynamics has been formulated. In the majority of cases, downward polynomial (DP) variations lead to longer drill bit life and characterize *abrasive wear.* DP trends are characterized by low maximum spindle torque. Scattered diameter (SC) variations indicate the onset of *adhesive wear* and have shown high spindle values and low drill bit life. DP trends can be a measure of drill bit life as they plateau close to drill breakage. When AncorCut is added to the base material, diameter varies according to DP trends in all cases.

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