Improving Machinability of PM Components via New Additive Compound

Cecilia Borgonovo and Bruce Lindsley

Hoeganaes Corporations, Cinnaminson, NJ, 08077

ABSTRACT

Machinability is a challenging post-processing step for PM components. Although powder metallurgy has the advantage of creating near-net-shape products, machining is often necessary as parts require increasingly tight tolerances, specific surface finish and features such as grooves and holes. The presence of porosity and non-homogeneous microstructures trigger enhanced tool wear, resulting in higher processing costs. Manganese sulfides are widely used in the industry to improve machinability response, but they have limitations such as reacting to humidity and oxygen. A new machining additive, AncorCut, has been developed with the goal to complement the role of MnS. In this paper, the response of additives to drilling operations has been studied and compared with the commercially available machining additive MnS. Specifically, the investigation focused on the effects of the new additive in relation to drill material, drilling speed and presence of coolant.

INTRODUCTION

PM steels are very attractive materials for automotive and aerospace applications. The ability to attain near-net-shapes through PM processing meets the progressively increasing demand for complex and intricate geometries from both industries [1]. Secondary operations, such as machining, are expensive and time consuming. Sustainability and recyclability of industrial waste are also stringent issues that drive the need for PM components, given the low scrap rate which results from using approximately 97 percent of the material that goes into compaction [2]. Despite this, some high precision applications still require some machining in order to achieve tight dimensional and geometrical tolerances and low surface roughness. It is estimated that 40-50% of PM steels require additional machining in applications where wrought steels are normally employed [3]. Because of their discontinuous microstructure, PM materials are challenging to machine. The alternating presence of material and voids (porosity) creates an “intermittent cut” condition that on one end, it bears the advantage of producing short -and therefore easy to remove- chips, and on the other end, it enhances thermal and mechanical fatigue on machining tools. The need for elevated tool feeds (leading to high machining rates) accentuates this latter drawback.

Several factors are involved in the response of PM materials to machining. They can be grouped into three main categories [4]:

- material properties, involving additives to improve machinability, pore filling strategies such as impregnation and infiltration, and the development of microstructurally cleaner materials.
- production processes such as alloying, heat treating, pre-sintering and green machining.
- optimized cutting conditions (tool materials, coatings, presence of coolant and cutting parameters such as speeds, feeds, and depth of cut).

There is an overall lack of understanding of the synergies between these elements. It has been determined that optimal machining conditions are entirely predicated on application, specifically on the interaction of material, drill bit and processing parameters. During drilling trials, Jandeska [5] observed that for iron-copper-carbon steels (FC-0208) resin impregnation in dry cutting conditions leads to longer drill bit life than the absence of impregnation and coolant-assisted drilling. Moreover, he noticed that at about 180 m/min (600 sfm), FLN2-4405 drill bit life was increased by around 30% compared to FC-0208 both pressed at 6.7 g/cm^3, while as the feed was increased to about 240 m/min (800 sfm) the behavior of the two materials converged. Danninger [6] confirmed that adding MnS to iron-copper-carbon materials enhances machinability both dry and with coolant, although MnS has the fundamental disadvantage of rusting, which makes the use of coolant not advisable. M'Saoubi et al [7] also witnessed an increase in tool life and decrease in cutting forces when MnS are added to the base material. Blais et al. [8] observed that FC-0208+0.5%%MnS machines better during drilling when the manganese sulfide particles are pre-alloyed rather than admixed. Machining is not always a post-processing step: Robert-Perron et al. [9] have shown that machinability of powder metals can be improved by machining in the 'green state' i.e., before sintering.

Tool materials range from HSS (high speed steels) to cobalt and carbides. HSS and cobalt are normally coated with oxide or nitride compounds (TiN), while carbides are available with more complex coating compounds (AlTiN, TiAlN, Polycristalline diamond coatings, etc) deposited on the carbide core in different ways (PVD, CVD, double layered, etc). According to Wada [10], cemented carbide (coated with TiVN PVD) is the most effective insert material for turning of sintered stainless steel, in terms of improved tool-life and surface finish. In addition to this, carbides have been proved to provide the best results on FC-0208 in drilling trials compared to TiN-coated HSS bits [5]. When MnS is added and carbide tools used, drill bit life is increased even more drastically. This is not the case for HSS drill bits, for which FC-0208 with and without MnS addition show the same behavior as the speed is increased from about 30 m/min (100 sfm) to 90 m/min (300 sfm) [5]. For what concerns sensitivity to process conditions, Rocha et al. [11] investigated the influence of speed, feed and depth-of-cut in machining of ferrous powder metal valve seats using PCBN tools. They determined that cutting speed has the predominant effect on tool-wear and they proved that attrition wear arises at lower cutting speeds, while diffusion wear is characteristic of medium cutting speeds. Lindsley et al. [12] tested the response of FC-0208 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.

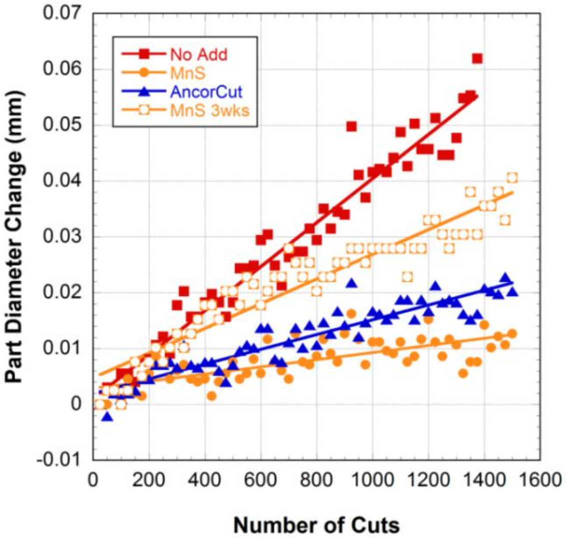


Figure 1. Diameter change vs. number of cuts for FC-0208 base metal, with 0.5% MnS addition and 0.2% AncorCut [12].

For drilling applications, machinability can be quantified by accounting of the following parameters: number of holes drilled per drill bit, spindle torque, axial thrust force, flank wear, hole diameter and surface finish. 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. Number of holes drilled, spindle torque, axial thrust force, and hole diameter will be measured to rate machinability in each condition and investigate wear mechanisms. Due to the promising results in turning, AncorCut behavior in drilling operations will be assessed.

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. The motor can deliver up to 30 hp and 8100 rpm. Travel along the three axes is allowed in the range of 50x40x50 cm (10”x16”x20”). The resolution of the center is 0.0025 mm. 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 used to probe the machined part and measure hole diameter. Specimen geometry and processing features can be seen in Table 1. The chemistry for FC-0208 is reported in Table 2. The setup (Fig.2) is constituted of three specimens (pucks) clamped by an aluminum fixture (Fig.3). 33 holes are programmed to be drilled in every puck which leads to a total of 99 holes drilled per cycle. Infinite life has been defined at 990 holes (10 cycles). Drill bit diameter was chosen to be 4.763 mm (0.1875”) and the depth of drilling has been set at about 25 mm (1”). Screw machine length drill bits have been selected over jobbers (which are longer) to minimize bending and wobbling of the bit. In addition to the baseline (FC-0208), the effects of adding MnS and AncorCut have been explored –Table 3-. Table 4 lists details of the drill bits employed in the investigation, speeds, feeds, and coolant conditions. LUBRICUT 4265 diluted with water in a 5:100 ratio has been chosen for coolant. Various machining additives and processing conditions (feeds and dry/wet conditions) have been tested. A control sample of base material was sectioned, mounted and examined. Good degree of sintering, scattered copper precipitates, lamellar perlite and ferrite were observed during microstructural analysis, which agrees well with FC-0208. Torque and axial thrust force have been recorded for every hole. Hole diameter has been measured every 5 holes for HSS and HSS+TiN bits, while for PVD-diamond coated carbide, whose life is expected to be drastically longer, the diameter was probed every 10 holes.

Table 1. Specimen Features for Machining Trials.

Geometry	**Dimensions**	**Material**	**Density**	**Sintering Conditions**	**Hardness (HRA)**
Puck	Diameter = 45 mm (1.75”) Height = 32 mm (1.25”)	FC-0208	6.9 g/cm^3	T=1120 °C (2050 F) Atm:N_2/H_2 = 90/10	45

Table 2. Chemical Composition of FC-0208.

Cu	**Graphite**	**Wax**	**Fe**
2%	0.85%	0.75%	Ancorsteel 1000B = remr

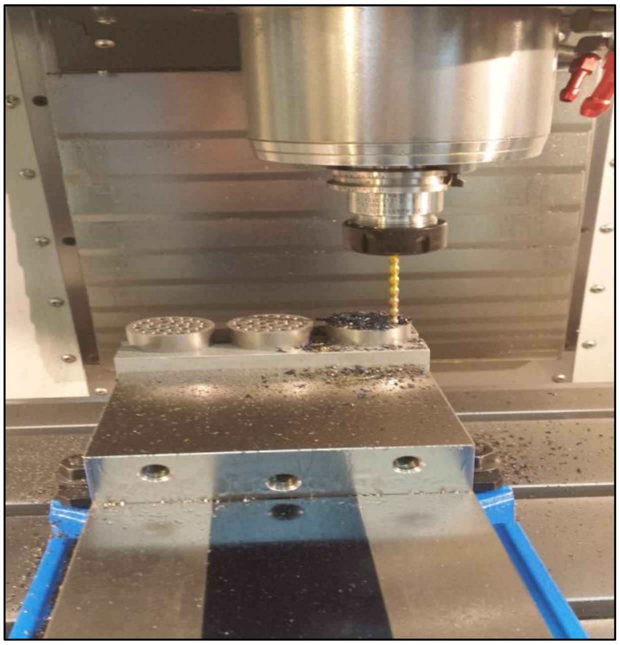


Figure 2. Drilling setup on HAAS VF-1.

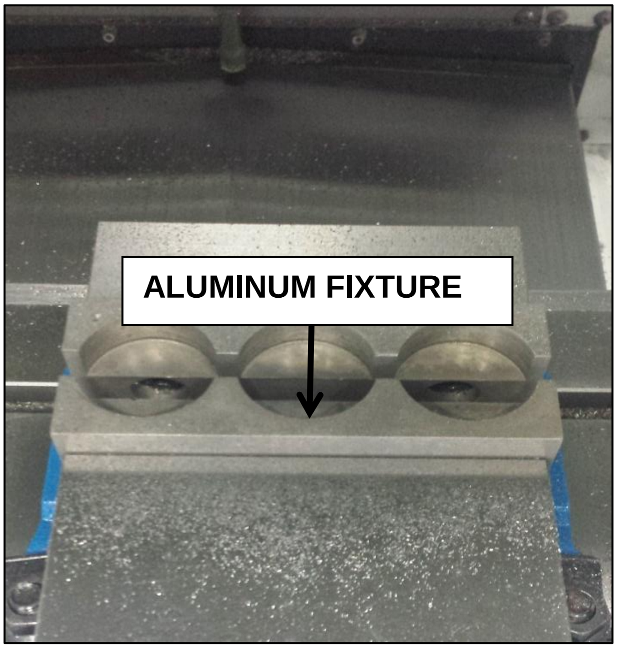


Figure 3. Aluminum fixture.

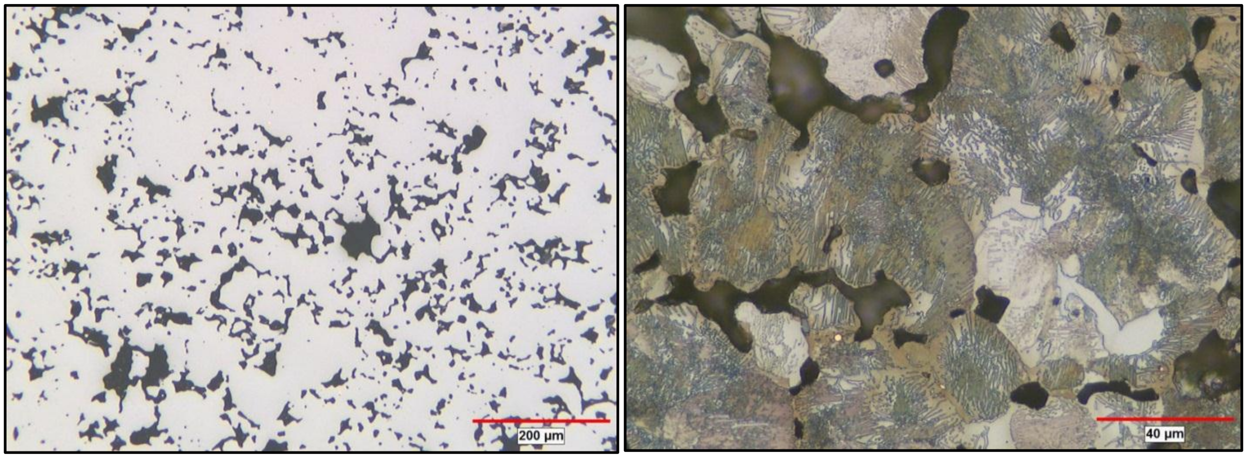


Figure 4. Microstructure of FC-0208. Left) As-polished; 100X. Right) 2% Nital / 4% Picral; 500X.

Table 3. Materials Tested.

Material Code	**Base Material**	**Machining Additive**	**Density (g/cm^3)**
1	FC-0208	None	6.9
2	FC-0208	+0.35% MnS	6.9
3	FC-0208	+0.2% AncorCut	6.9

Table 4. Matrix of Experiments.

Test Code	Drill Bit Material	Coating	Tip Angle	Manufacturer	Speed (rpm)	Feed	Coolant
HS1	HSS, Screw Machine Length	None	135	Chicago-Latrobe	2000	159 mm/min (6.25 ipm)	YES/NO
HS2						318 mm/min (12.5 ipm)	YES/NO
HT1	HSS, Screw Machine Length	TiN	135	Chicago-Latrobe	2000	159 mm/min (6.25 ipm)	YES/NO
HT2						318 mm/min (12.5 ipm)	YES/NO
CD1	Carbide, Short Length Jobber	PVD polycrystalline diamond	118, split point	Ultra-Tool International	3500	318 mm/min (12.5 ipm)	YES
CD2						508 mm/min (20 ipm)	YES

RESULTS AND DISCUSSIONS

Machining operations in industrial settings have two fundamental requirements:

- *Fast machining rates and long tool life:* this translates into the ability of processing a large number of parts in a small amount of time with the least number of tools. As a result, conditions leading to longer tool life at high feeds are to be preferred.

- *Finishing of the part:* dimensional tolerances as well as surface roughness have to conform to print specifications throughout machining operations as the tool (drill bit or turning insert) wears out.

In drilling, the critical parameter to assess machining rate and tool life is number of holes drilled, whereas dimensional and superficial tolerances can be evaluated by measuring hole diameter and surface roughness vs. number of holes drilled. In this section, number of holes drilled and hole diameter per test condition will be discussed.

Number of holes

Table 5 summarizes the number of holes drilled for each material and process condition. End of life of the drill bit has been set to bit breakage and infinite life when the number of holes drilled reached 990 (10 cycles, 30 pucks drilled).

Table 3. Number of Holes Drilled.

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

Material 1 (FC-0208) provided better tool life compared to the others solely for HSS+TiN bits when drilling under coolant. Material 2 (FC-0208+0.35% MnS) showed the best performance for test HS1 and HT1 (low feed, 6.25 ipm) in dry conditions. At high feeds (12.5 ipm) for both HSS and HSS +TiN bits under coolant, Material 2 drilled the least amount of holes. Material 2 provided the longest tool life in drilling with carbide bits for both feeds, 12.5 ipm and 20 ipm. Material 3 (FC-0208+0.2%AncorCut) exhibited excellent behavior at high speeds (12.5 ipm) both in the presence of coolant (HS1 and HS2) for uncoated HSS and dry drilling for HSS+TiN (HT2). 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.

Hole diameter vs. number of holes drilled

For the purpose of assessing machining quality, variation in hole diameter has been investigated. The analysis is not aimed to determine how the diameter changes throughout the life of the tool but how much variation it encounters. The interval of variation will be higher for those combinations of materials and machining parameters leading to poor dimensional stability. Figure 5 represents the diameter variation at 159 mm/min (6.25 ipm). Material 2 varied the least for HS1 in dry and wet conditions. On the contrary, hole diameter of Material 2 varied considerably for test HT1 dry. When coolant is added in test HT1, diameter variation is minimal for Material 3 (AncorCut). This data point is also the lowest across all test conditions at 159 mm/min (6.25 ipm). Figure 6 summarizes diameter variation at 12.5 ipm. Results for test HS2 dry have not been included since every material with the exception of Material 2 resulted in very few holes drilled. It can be noted that Material 2 resulted in the lowest variation for test HS2 in the presence of coolant and for test HT2 in dry conditions. Both materials 2 (MnS) and 3 (AncorCut) provided the lowest variation for test HT2 with coolant. Figure 7 represents diameter variation when PVD diamond-coated carbide bits are used. It can be noted that conversely to HSS and TiN coated HSS bits, Material 2 displays the largest diameter variation both at 318 mm/min (12.5 ipm) and 508 mm/min (20 ipm). Diameter for Material 1 and 3 fluctuate in a range between 0 and 0.023 whereas for Material 2 the range of change is more than three times wider.

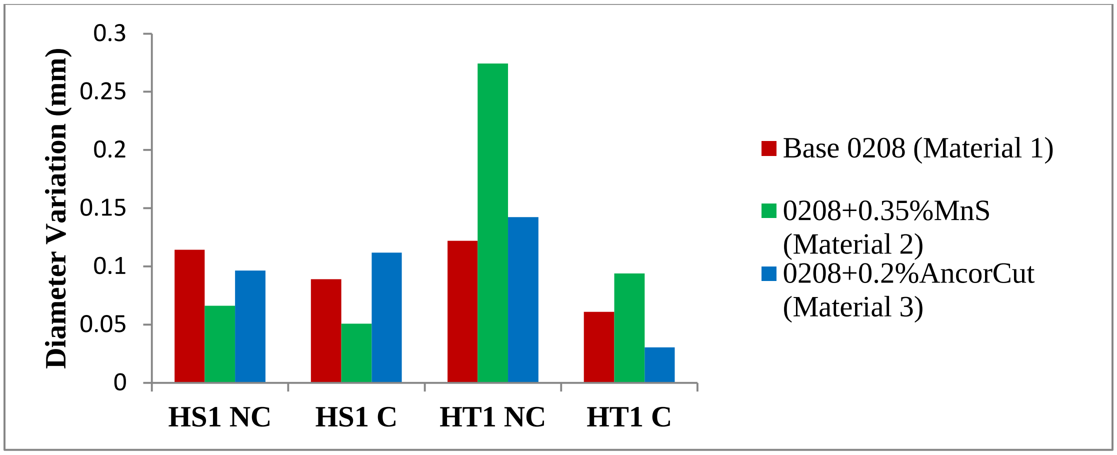


Figure 5. Diameter variation throughout tool life vs. material. Feed= 159 mm/min (6.25 ipm).

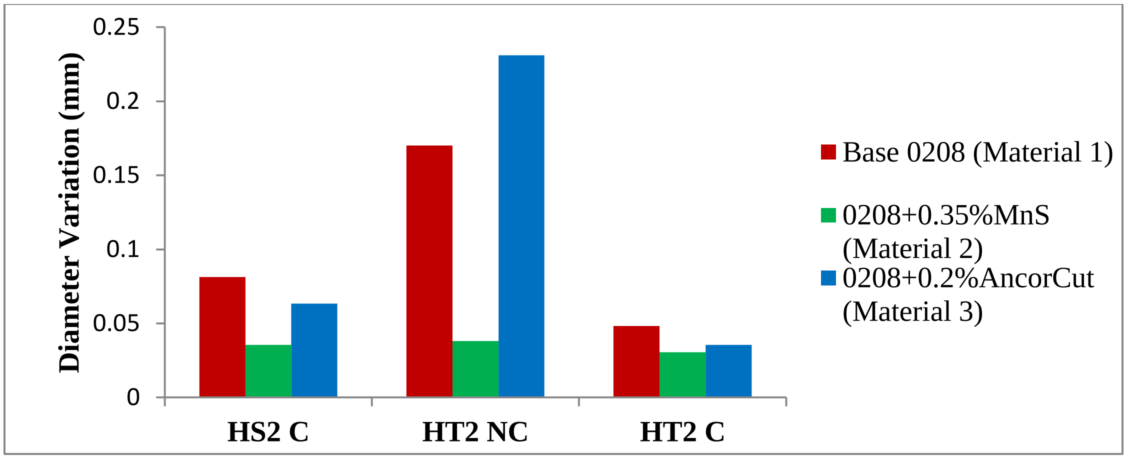


Figure 6. Diameter variation throughout tool life vs. material. Feed= 318 mm/min (12.5 ipm).

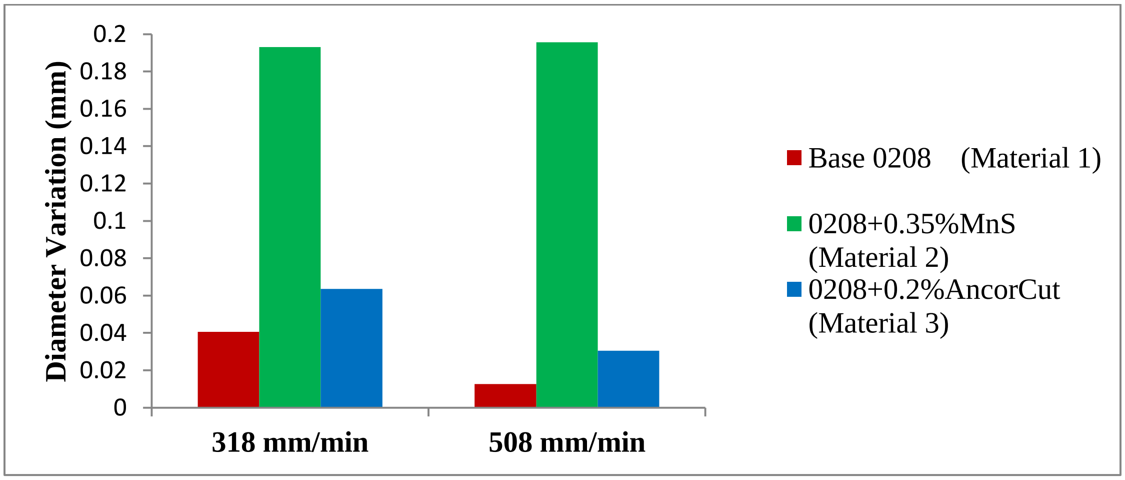


Figure 7. Diameter variation throughout tool life vs. material. Diamond coated carbide.

Discrete Diameter Variation (DDV)

Table 6 clearly indicates that for each test, the maximum number of holes and the minimum diameter variation is not given by the same material.

Table 4. Material Codes Leading to Highest Number of Holes and the Lowest Diameter Variation per Test Condition.

Test Code	Number of Holes	Diameter Variation
HS1-Dry	2	2
HS1-Coolant	3	2
HS2-Dry	2	NA
HS2-Coolant	3	2
HT1-Dry	2	1
HT1-Coolant	1	3
HT2-Dry	3	2
HT2-Coolant	1	2-3
CD1-Coolant	2	1
CD2-Coolant	2	1

Both parameters are equally important to define machinability in industrial settings. In order to consolidate such discrepancy and unify the data, the concept of Discrete Diameter Variation (DDV) has been introduced. The DDV can be expressed as the average change in diameter per hole drilled:

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

Figure 8 compares the DDVs at 159 mm/min (6.25 ipm). It is evident that Material 3 (AncorCut) exhibits not only very low DDV values for every test conditions, but also very similar data across all tests. The same trend can be observed at 318 mm/min (12.5 ipm) (Fig. 9) for both Material 1 and 3. Very low numbers were observed for Material 2 (MnS) in test HS1 dry. Overall, it can be concluded that Material 3 offered on average the lowest and more consistent DDV values. This tendency is even more conspicuous in drilling with coated carbide (Fig.10). The addition of AncorCut provides the lowest DDV at both feeds. Material 2 at 508 mm/min (20 ipm) showed DDV values in a range six times larger than Material 3, and over three times larger than Material 1 (FC-0208).

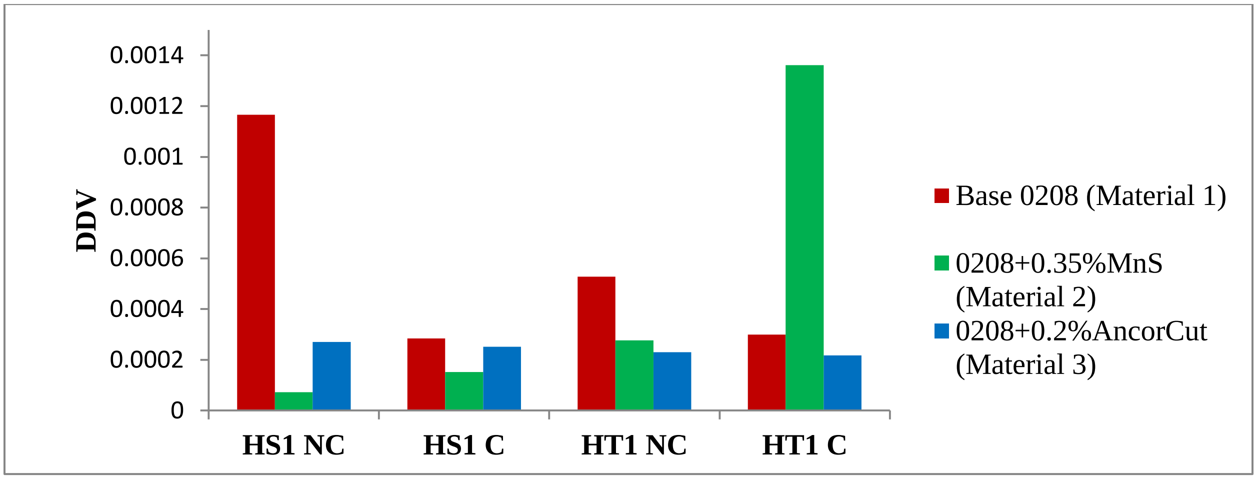
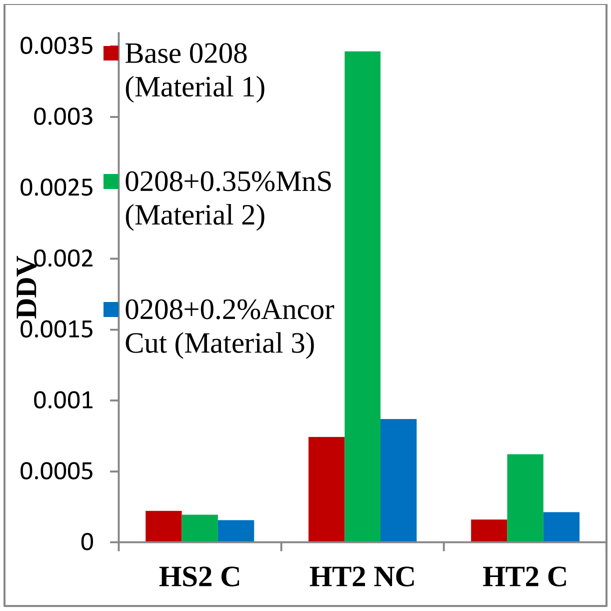


Figure 8. DDV vs. material. Feed= 159 mm/min (6.25 ipm).



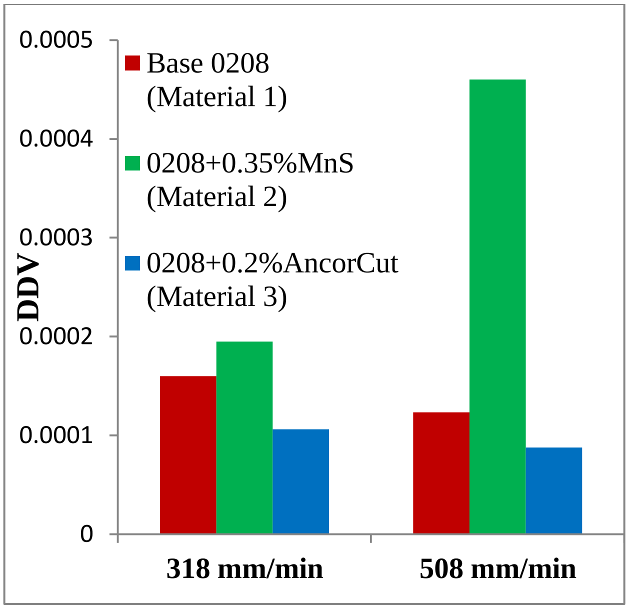


Figure 9. DDV vs. material. Feed= 318 mm/min. (12.5 ipm).

Figure 10. DDV vs. material. Diamond coated Carbide.

Rusting of FC-0208+0.35%MnS

It is pivotal to mention that the addition of MnS causes rusting, especially when parts are exposed to hot and humid environment. Lindsley et al. [12] noticed a dramatic decrease in tool life in turning applications when Material 2 (FC-0208+0.35%MnS) is machined after 3 weeks of sintering (Fig.1). Figure 11 shows severe rusting in MnS-containing specimens (pucks in the center) 2 weeks after machining with coolant, despite pucks being kept in a cool and dry environment afterward.

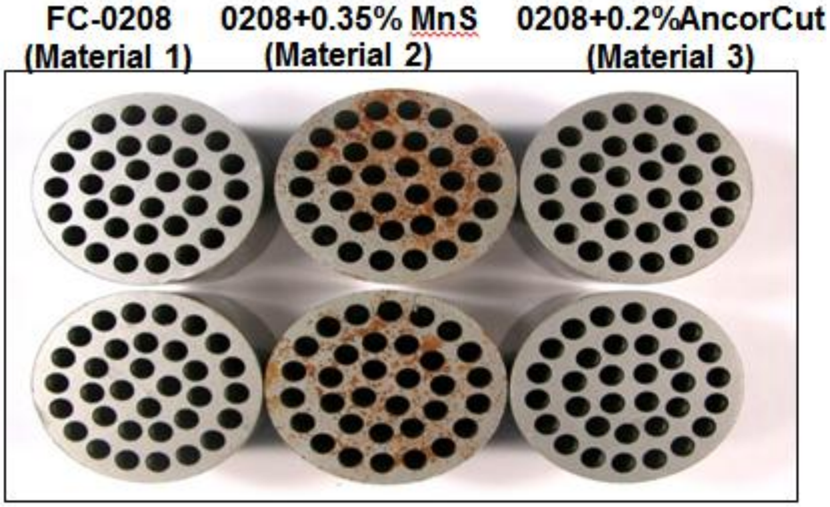


Figure 11. Rusting after 2 weeks of drilling with coolant.

Rusting can be explained through a chain reaction (Equation 1).

$$\mathrm{MnS} \rightarrow \mathrm{MnSO_4} \rightarrow \mathrm{MnO} + \mathrm{H_2SO_4} \quad (1)$$

MnS oxidize in the base material when heated during sintering. Evidence of such reaction (at lower rates) can also been observed when MnS powder alone comes in contact with air at room temperature. Once $MnSO_4$ is formed, water (humidity) triggers the reaction of the peroxysulfide phase with hydrogen to form sulfuric acid. This results in accelerated rusting of MnS-containing parts [13]. Rusting affects drilling both for what concerns drill bit life and hole quality. Pucks of Material 1 (FC-0208) and Material 2 (FC-0208 +0.35%MnS) were placed in a humidity chamber at 92% humidity and room temperature for three days. After that, test HT1 dry has been repeated on the exposed pucks. Note that we have chosen test HT1 dry because Material 2 showed tool life close to infinite in such instance (990 holes). Figure 12 reveals a decrease in tool life of about 30% for Material 1, while drill life for Material 2 dropped of about 85%.

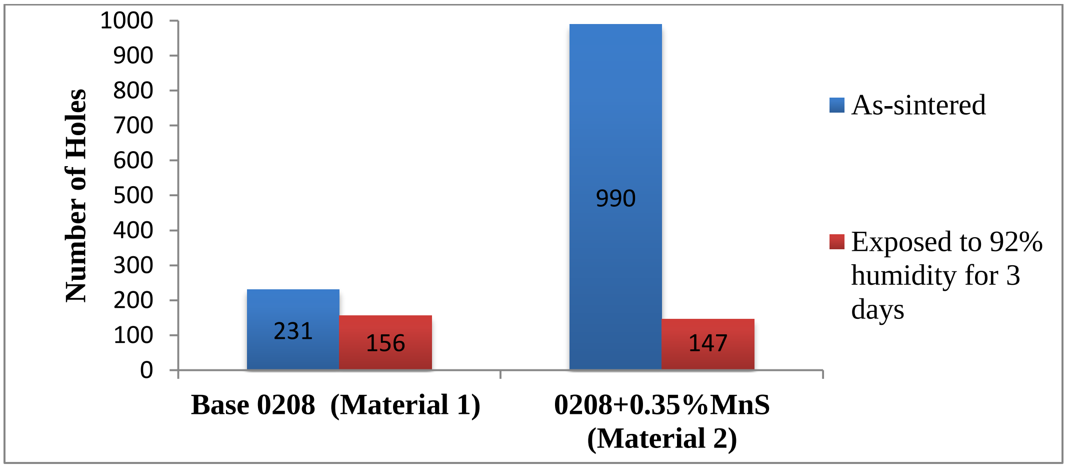
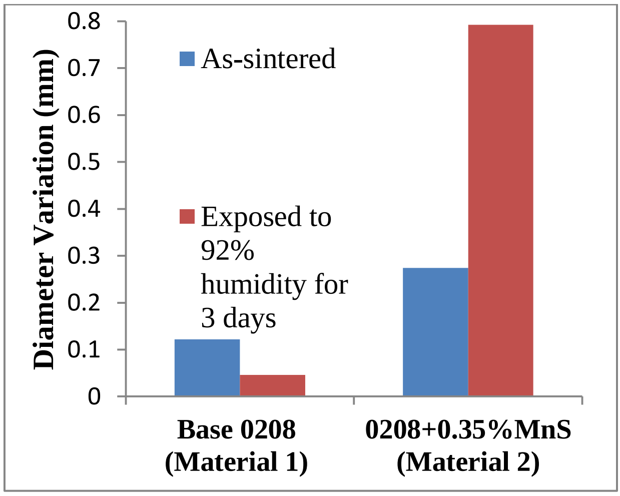


Figure 12. Effect of humidity on drill bit life. Material 1 vs. Material 2. Test: HT1 dry.

In addition to this, diameter variation (Fig.13) was slightly smaller for Material 1 and increased by three times for Material 2, exhibiting a drastic decrease in machining quality. As a consequence of both instances, DDV values for Material 2 exposed to humidity were twenty times greater than DDV for as-sintered pucks (Fig.14).



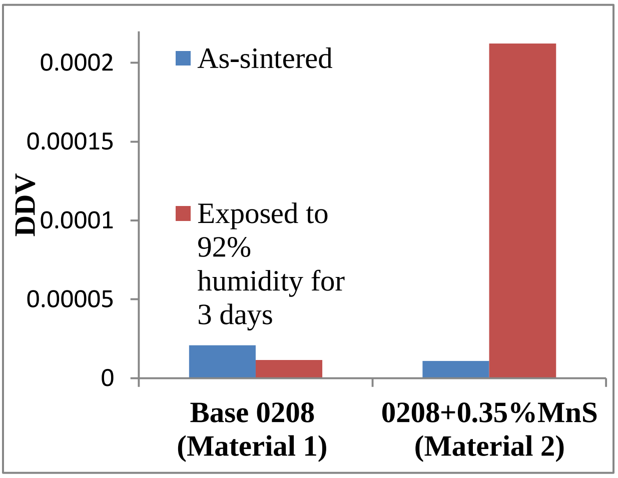


Figure 13. Effect of humidity on diameter variation. Material 1 vs. Material 2. Test: HT1 dry.

Figure 14. Effect of humidity on DDV. Material 1 vs. Material 2. Test: HT1 dry.

Wear analysis

In the previous section diameter variation has been discussed to assess dimensional stability of hole diameter throughout the drilling process. Critical information on wear mechanisms of the drill bits can be attained when in lieu of measuring hole to hole variation, the analysis accounts for the overall trend of diameter change itself. In synthesis, while *how much* the diameter changes is a measure of dimensional quality of the hole, *how* it changes is a measure of wear dynamics. A direct correlation has been detected between modes of diameter variation and wear meachanisms. Figure 15 is a clear example of this phenomenon for Material 1. It can be noted that change in diameter when drilling with HSS bits under coolant at 12.5 ipm follows a *downward polynomial-type* of trend whereas values for TiN-coated HSS in dry conditions at 318 mm/min (12.5 ipm) (HT2 dry) appear to be distributed in a *scattered moving average* fashion. The diameter progressively *decreases* in the downward trend whereas in scattered moving average conditions the diameter fluctuates between intervals of *decrease and increase*. Diameter change that follows a downward polynomial distribution coincides with longer drill bit life compared to conditions leading to a scattered moving average trend in most cases. Another evident case of such occurrence can be detected for Material 3 at feeds of 159 mm/min (6.25 ipm) (Fig.16). The test condition that led to the shorter drill bit life (HS1 NC) also shows scatter in diameter variation, whereas well-defined downwards trends can be identified for conditions that resulted in high number of holes drilled, HS1 with coolant and HT1 dry. Moreover, the behavior of Material 3 at 318 mm/min (12.5 ipm) follows a downward polynomial trend for all test conditions (Fig.17).

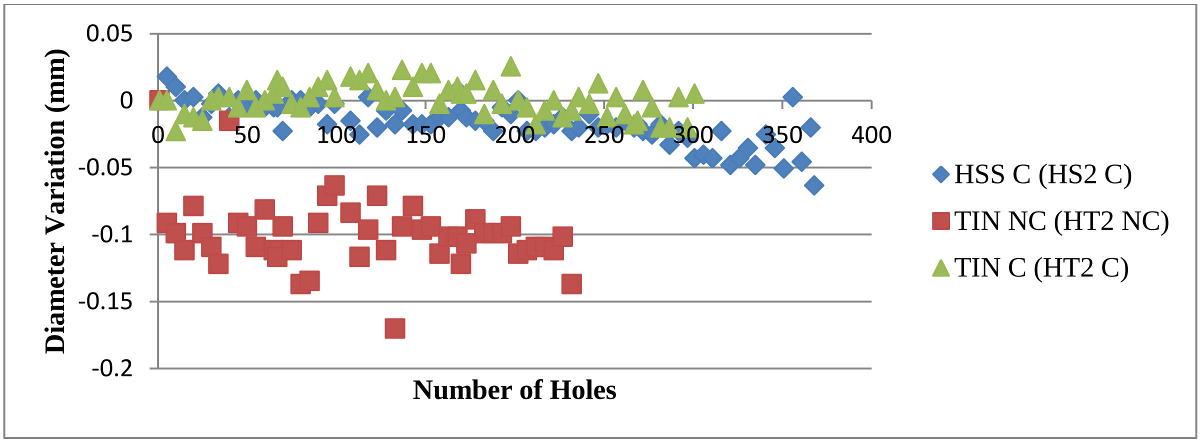


Figure 15. Diameter variation vs. number of holes. Material 1. Feed= 318 mm/min (12.5 ipm).

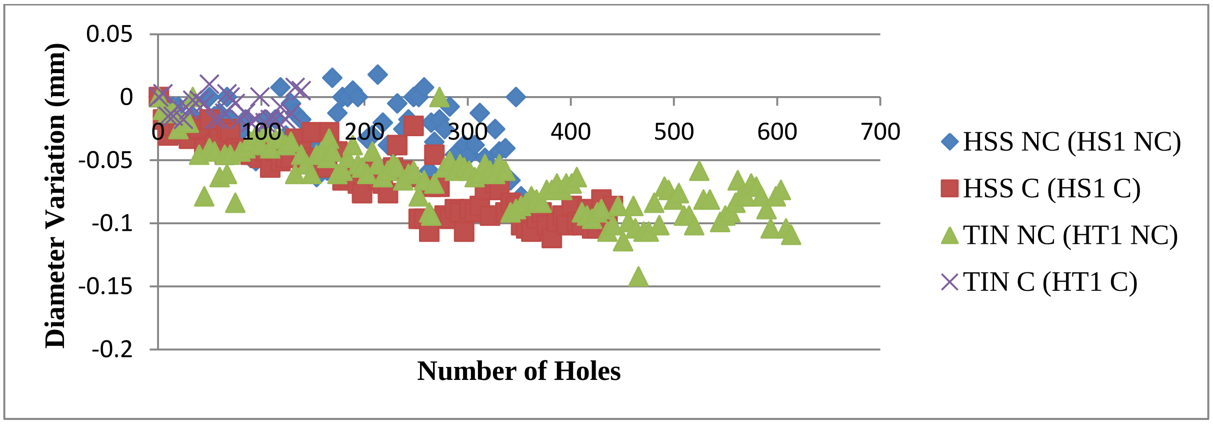


Figure 16. Diameter variation vs. number of holes. Material 3. Feed= 159 mm/min (6.25 ipm).

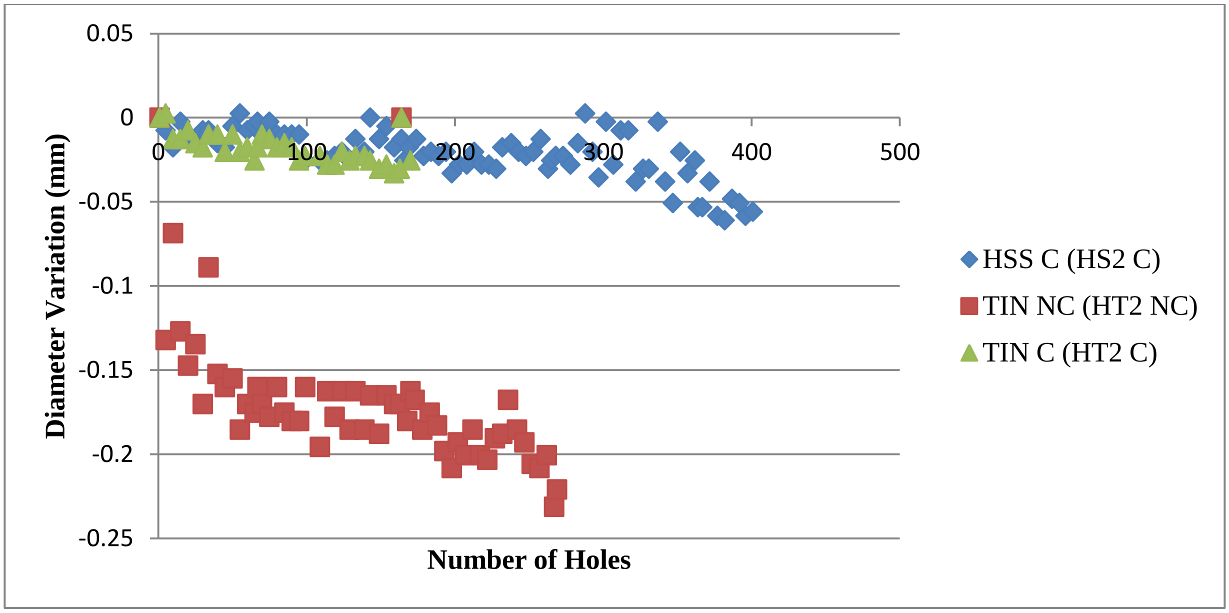


Figure 17. Diameter variation vs. number of holes. Material 3. Feed= 318 mm/min (12.5 ipm).

Table 7 reviews trends of change in diameter (polynomial or scattered) for each test conditions and materials. It is interesting to note that some mix modes are present (DP/SC or SC/DP depending on which one occurs first). A different trend has been spotted when carbide drill bit are used. Figure 18 indicates an initial decrease in hole diameter followed by diameter increase till end of life. Material 3 shows less scattered behavior than Material 2 as diameter becomes larger, which can be linked to superior machining quality exhibited by Material 3 (Fig.7).

Table 5. Trend of Diameter Change. SC= Scattered Moving Average; DP= Downward Polynomial.

Test Code	**Coolant**	**Material Code**		
		1	2	3
HS1	NO	SC	SC	SC
	YES	DP	DP/SC	DP
HS2	NO	-	SC	-
	YES	DP/SC	SC/DP	DP
HT1	NO	DP/SC	SC	DP
	YES	DP	DP	SC
HT2	NO	SC	DP/SC	DP
	YES	DP/SC	DP/SC	DP

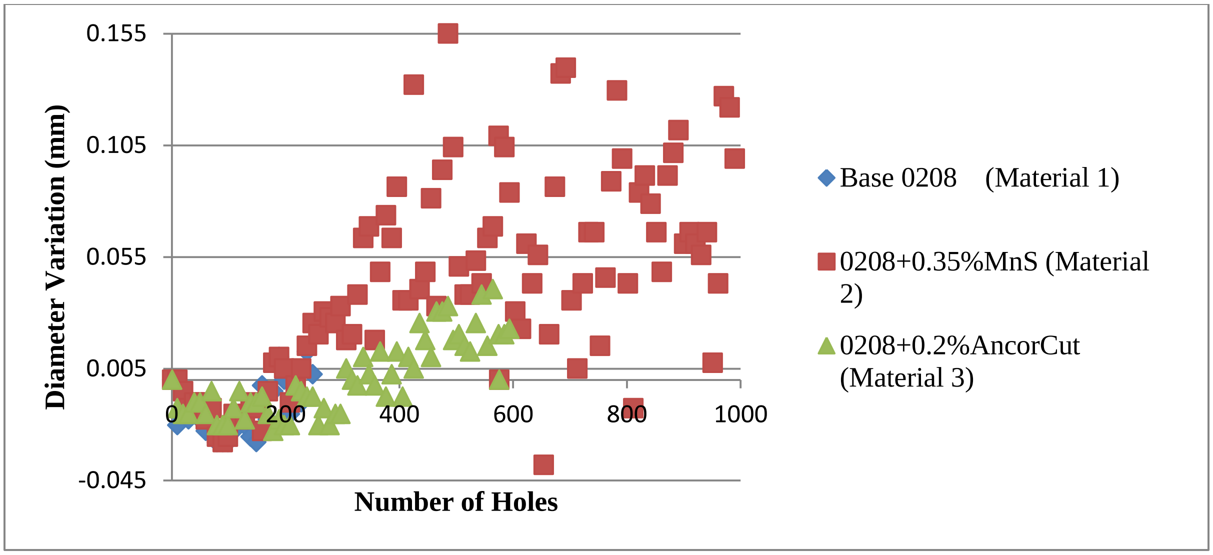


Figure 18. Diameter variation vs. number of holes. Diamond coated carbide. Feed= 318 mm/min (12.5 ipm).

Spindle torque and axial thrust force data have been analyzed to find a correlation between trends of diameter change and wear dynamics. For ease of representation, graphs will be reported in what follows for Material 3. Figure 19 shows spindle torque values for the first 20 holes for Material 3 at 159 mm/min (6.25 ipm). The peak torque is reached during the drilling of these first few holes and it is clear the correlation between diameter change and torque. Specifically, higher torque values correspond to scattered diameter change (SC) whereas for downward polynomial (DP) trends the peak torque is lower. At higher feeds, the correlation between torque and diameter variation is no longer valid and thrust force data substitute torque in such correlation. Higher peak values of thrust force are associated with scattered diameter variation and lower values are once again to be linked to downward polynomial diameter changes. A scattered trend in hole diameter variation is characterized by consecutive increase and decrease in hole size. It can be hypothesized that such phenomenon is caused by the onset of *adhesive wear*. As the drill bit heats up, chips from the machined specimen become welded on the bit, resulting in bigger holes. As the drilling process continues, the welded chips will be consumed and hole diameter will again decrease. The cycle will repeat till the end of life of the drill bit. Confirmation of this hypothesis comes from the fact that drilling under coolant conditions or/and with TiN coated bits generally leads to downward polynomial diameter variation. Coolant decreases the local temperature at the interface between drill bit and machined material, whereas TiN coating favors heat conduction because of its high thermal conductivity. It has been observed that for most test conditions coolant has a predominant effect on avoiding adhesive wear. Gradual decrease in hole diameter (downward polynomial trend) indicates thinning of drill bit size, which takes places as a result of progressive *abrasive wear*. SEM analysis of the drill bit used for test HS1 dry (Fig.20a) shows welded chip by the cutting flank, while the same test performed with coolant reveals no transfer of sample material and normal flank wear for abrasion (Fig.20b). Indeed, the first test corresponds to a scattered diameter variation whereas the latter to a downward polynomial trend (see Table 7, Material 1).

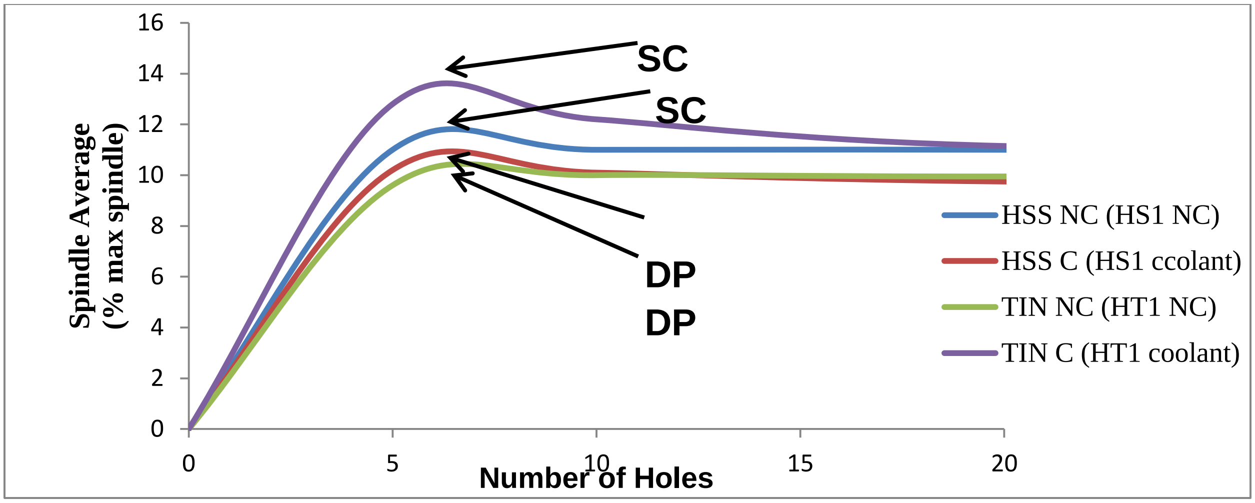


Figure 19. Spindle average vs. number of holes. SC/DP. Material 3. Feed= 159 mm/min (6.25 ipm).

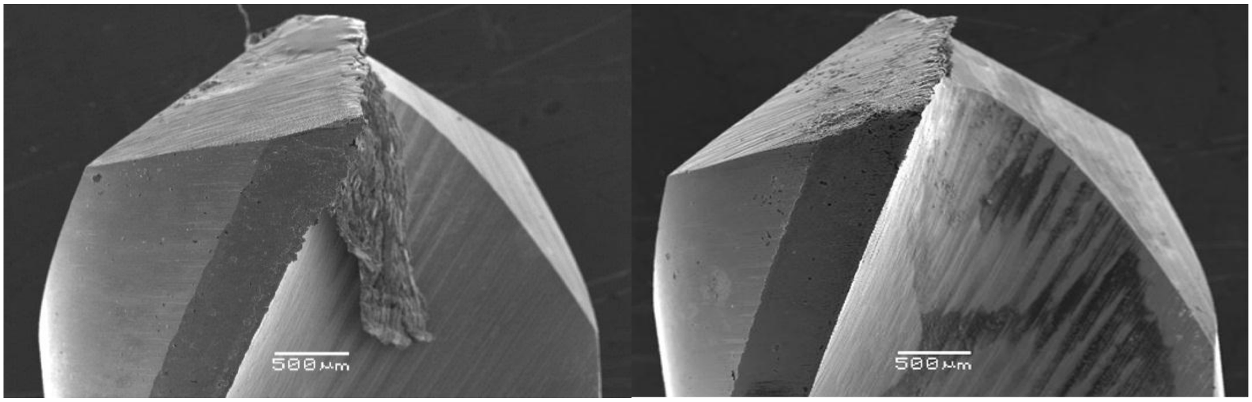


Figure 20. SEM images of adhesive wear. Test HS1: **a)** dry; **b)** coolant. Material 1 (FC-0208).

CONCLUSIONS

The investigation focused on assessing the drilling response of FC-0208 in the presence of two machinability additives: the commercially available MnS and AncorCut from Hoeganaes Corporation. Tests have been performed using three drill bit types: HSS uncoated, HSS- TiN coated, and diamond coated carbide bits. Experiments have been conducted both dry and in the presence of water based coolant. Two different feeds have been explored. Results can be summarized as follows:

- Tool life is highly dependent on test conditions and drill bit materials. Material 1 showed good drill life when HSS TiN coated drill bits are used in wet conditions (HT1 and HT2). Material 2 drill bit life has been found to be excellent both for all bit materials at low feed and absence of coolant (for HSS and HSS+TiN). Longest drill bit life was detected being given by Material 3 for HSS bits with coolant at any feed and TiN coated HSS bits at high feed drilling dry. 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.
- The quality of holes drilled is not captured by simply measuring number of holes drilled. A discrete diameter variation (DDV) parameter has been introduced in order to consolidate hole quality (as measured by diameter variation) and number of holes drilled. DDV values close to zero indicate good machinability. AncorCut (Material 3) has demonstrated DDV numbers both very low and constant for all test conditions, particularly for test HS1 with coolant and both tests with carbide coated drills (CD1 and CD2).

- While MnS (Material 2) exhibits good response to drilling (especially in dry condition), the addition of MnS causes accelerated rusting of the part which can affect machinability, not only for what concerns drill bit duration but also machining quality (hole diameter variation). AncorCut does not have such a drawback.
- A correlation between diameter variation and wear dynamics has been formulated. In the majority of cases, downward polynomial (DP) variations lead to longer drill bit life. DP trends are characterized by low maximum spindle torque at low feeds -159 mm/min (6.25 ipm)- and low maximum axial thrust force at higher feeds – 318 mm/min (12.5 ipm)-. Scattered diameter (SC) variations have shown high values for both variables. DP trends are typical of abrasive wear whereas SC trends indicate the presence of adhesive wear. Abrasive wear usually lead to longer drill bit life and smaller variation in diameter compared to adhesive wear. DP trends tend can help to predict drill life as they plateau close to drill breakage. Addition of AncorCut can be generally linked to DP trends.

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