# Improving Machinability of PM Components: Response of Novel Machining Additive and Predictability Analysis of Machining Behavior

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**ABSTRACT**

The advantage of PM processing is the achievement of near net shape components with minimal material waste – under 5%. Despite its close to die tolerances, secondary machining remains a necessary step for several high performance PM applications, such as automotive – which constitute over 70% of ferrous PM business-. The need for high throughput and tight tolerances translate into developing a machining additive able to provide long tool life, constant dimensions throughout the machining process and reliability. MnS, the most widespread machining aid in the industry, has shown to cause suboptimal dimensional consistency and accelerated rusting, due to its chemical reactivity with moisture and oxygen. A novel machining additive has been developed and an extensive analysis pursued. Tool life has been assessed for several machining conditions, dimensional and surface tolerances investigated, and an in-depth analysis of machining behavior carried out. Analytical considerations to determine predictability of machining behavior (time to tool failure) and of machining conditions (matching tool material, speeds, and work-piece material) for the novel machining additive have also been addressed.

## INTRODUCTION

Despite being considered a near-net-shape process, 40-50% of PM steels require secondary machining in applications for which wrought steels are usually selected [1]. The most common finishing operations are hard turning and drilling. Near-net-shape turning only requires shallow cuts and a minimum number of steps, but machining accuracy and a precise holding of the work piece are pivotal for dimensional tolerances and low surface roughness. In addition to this, the presence of porosity constitutes the very reason for reduced tool life in machining of PM components: the nature of a PM part is heterogeneous on a microscopic scale, which creates an interrupted cut condition as the tool tip continuously moves from solid to pore. Small thermal and mechanical fatigue cracks and chipped tool edges develop from such phenomenon as well as from the presence of single hard particles. Oxides and carbides resulting from sintering and heat treating can also contribute to enhance the abrasion of the machining tool [2]. Nevertheless, time-sensitive production schedules, favoring elevated tool feeds (i.e. high machining throughput), accentuates the wear connected to the "intermittent-cut" condition. Ad-mixed machining additives are meant to alleviate such effects, and the industry has converged in using MnS as the preferred and most effective additive. It has been proved [3] that manganese sulfide is stable at the sintering temperature and does not interact with the alloy matrix. In addition to this, MnS does not compromise the strength of compacts based on a water atomized iron powder. MnS acts to improve machinability by providing lubrication between cutting tool and work piece, and thus reducing wear at the cutting edge of the tool [4,5]. However, drawbacks deriving from the addition of MnS in PM components were observed, the main one being enhanced oxidization in humid atmosphere and consequent accelerated corrosion especially when ad-mixed with Fe-Cu-C mixes. MnS bears other processing disadvantages limited not only to Cu containing materials (FC-020X), such as high reactivity during storage and release of sulfur containing gas during sintering, which can lead to detrimental deposits in the furnace itself. There is the compelling need for an effective machining additive that can be manufactured in large quantities and characterized by chemical stability along the production chain.

A novel machining compound (AncorCut) has been designed and extensively tested in Fe-Cu-C mixes for both turning and drilling operations [6-8]. Turning studies have also been conducted [6,7] on diffusion-alloyed steel (FD-0405) and improvements in tool life have been observed (Fig.1).

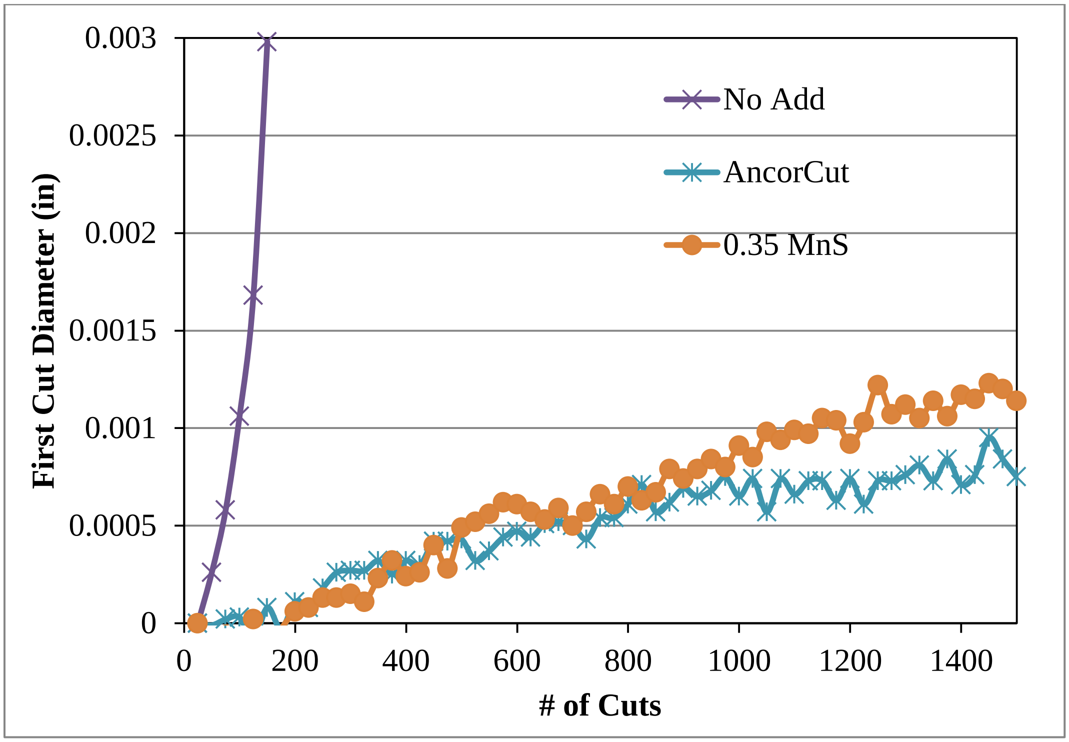



**Figure 1.** Diameter change vs. number of cuts for FD-0405 base material, with 0.5% MnS addition and 0.2% AncorCut. 750 sfm [6].

Tool wear, as shown by increasing part diameter change, is greatly reduced with the addition of machining additives. After 1500 cuts, AncorCut shows a reduced tool wear of about 30% compared to MnS. This is of great interest especially because the outcome is not disguised by possible rusting of MnS, as the comparison has been performed with fresh and unexposed MnS. No detrimental effects on the strength of the base alloy have been detected [6,7]. Due to the promising turning results in FD-0405, AncorCut behavior in drilling operations will be assessed. In this paper, machinability has been rated by measuring number of holes drilled and hole diameter variation per condition. In addition, the influence of machining additives and processing parameters (feed, drill bit materials and lubricant regime) will be assessed. Hole diameter variation and drill bit appearance will be used to identify and compare wear modes for FD-0405, MnS and AncorCut. Torque values have been analyzed to establish a correlation with wear dynamics.

## EXPERIMENTAL PROCEDURE

Drilling tests were carried out on a HAAS VF-1 vertical milling center at the Hoeganaes Innovation center. The motor can deliver up to 30 hp and 8100 rpm, with resolution of 0.0025 mm. A 2 mm (0.078") tungsten carbide ball stylus 50 mm (2") long from Renishaw has been employed for measuring machined parts and hole diameter. Specimen features and processing details can be seen in Table 1. The chemistry for FD-0405 is reported in Table 2. The machining setup (Fig.2) comprises of three samples (pucks) held by an aluminum fixture (Fig.3). 33 holes can be drilled per puck -a total of 99 holes drilled per cycle-. Infinite life has been set at 990 holes (10 cycles). Drill bit diameter was selected to be 4.763 mm (0.1875") and depth of drilling about 25 mm (1"). Screw machine length drill bits have been used to reduce bending of the bit. Drilling response of FD-0405 containing no additive, MnS and AncorCut have been investigated (Table 3). Table 4 summarizes drill bit types, speeds, feeds, and coolant conditions. The coolant used is LUBRICUT 4265 diluted with water (5:100 ratio). The control sample of base material shows good degree of sintering, and microstructure containing ferrite, pearlite, bainite, martensite and Ni-rich austenite areas can be seen which agrees well with FD-0405 (Fig.4). Torque and axial thrust force have been recorded for every hole. Hole diameter has been recorded every 5 holes for HSS and Cobalt bits, and every 10 holes for PVD-diamond coated carbide that demonstrated longer tool life in the past.

**Table 1.** Specimen Features for Machining Trials.

| Geometry | Dimensions | Material | Density | Sintering Conditions | Hardness (HRA) |
|---|---|---|---|---|---|
| Puck | Diameter = 45 mm (1.75")<br>Height = 32 mm (1.25") | FD-0405 | 6.9 g/cm$^3$ | T=1120 °C (2050 F)<br>Atm:$N_2/H_2$ = 90/10 | 57 |

**Table 2.** Chemical Composition of FD-0405 (wt%).

| Cu | Ni | Mo | Graphite | Wax | Fe |
|---|---|---|---|---|---|
| 1.5 | 3.9 | 0.5 | 0.6 | 0.75 | Rem. |

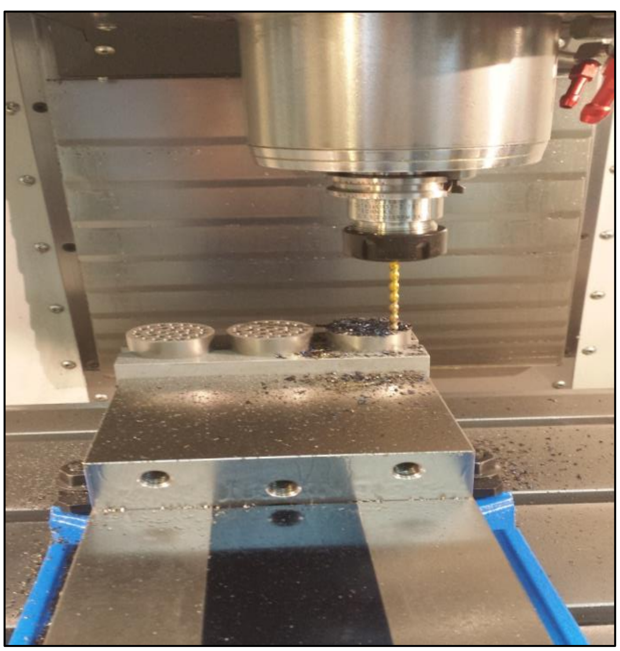


**Figure 2**. Drilling setup on HAAS VF-1.

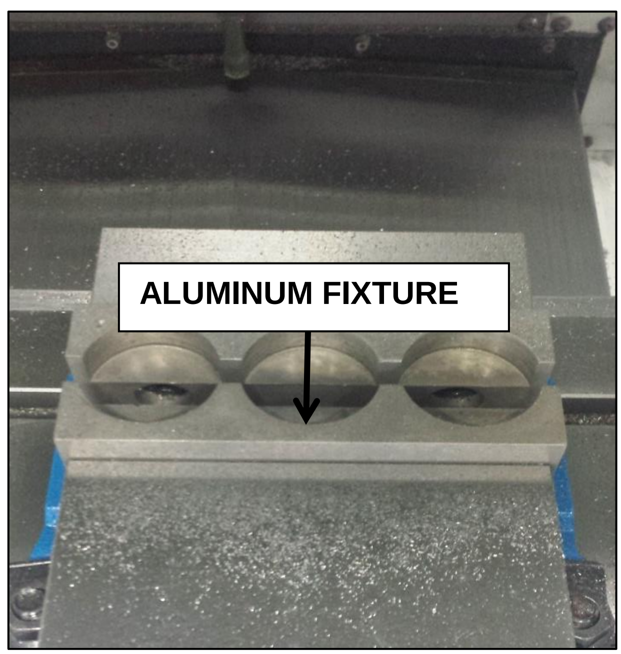



**Figure 3.** Aluminum fixture

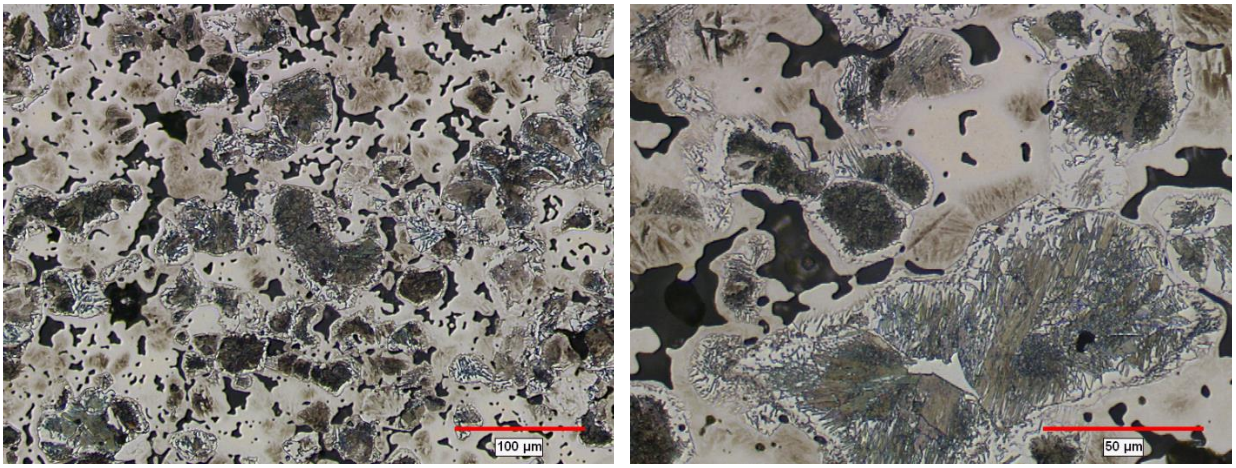



**Figure 4.** Microstructure of FD-0405. Etched 2% Nital / 4% Picral. Left) 200X. Right) 500X

**Table 3.** Materials Tested.

| **Materials Tested** | **Base Material** | **Machining Additive** |
|---|---|---|
| **1** | FD-0405 | None |
| **2** | FD-0405 | +0.35% MnS |
| **3** | FD-0405 | +0.2% AncorCut |

**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 |
| **CO1** | Cobalt, Screw Machine Length | None | 135 | Chicago-Latrobe | 2000 | 159 mm/min (6.25 ipm) | YES/NO |
| **CO2** | | | | | | 318 mm/min (12.5 ipm) | YES/NO |
| **CD** | Carbide, Short Length Jobber | PVD polycrystalline diamond | 118, split point | Ultra-Tool International | 3500 | 508 mm/min (20 ipm) | YES |

## RESULTS AND DISCUSSIONS

Two pivotal factors should be used to evaluate machinability in drilling operations:

- *Number of holes drilled:* this provides insights on the life that our tool is expected to have. Long tool life translates into substantial cost savings in production.

- *Dimensional tolerances:* prints spell out the tolerance that the machining operation is required to maintain. Larger dimensional variation can result in scrapping of the component during quality inspection. In drilling, hole diameter measurements as the tool wears out can be used to calculate dimensional tolerance.

This section will assess both these elements per each process condition.

### *Number of holes*

Table 5 recapitulates tool life for each processing condition and additive used.

**Table 5.** Number of Holes Drilled with Coolant

| **Test Code** | **Feed** | **Material** | | |
|---|---|---|---|---|
| | | FD-0405 | 0.35%MnS | 0.2%AncorCut |
| **HS1** | 159 mm/min | 499 | 138 | 310 |
| **CO1** | 159 mm/min | 362 | 185 | 765 |
| **CD** | 508 mm/min | 56 | 496 | 933 |

In dry conditions, no drill bit machined more than a few holes before failure. This is to be expected given the hardness of the diffusion-alloyed material. With use of coolant, there was a wide variation in tool life. 159 mm/min (6.25 ipm) appears to be the optimal feed rate for non-carbide bits, as tool life exceeded 100 holes for multiple conditions. FD-0405 with no addition showed the longest tool life with HSS bits, while the addition of AncorCut led to a dramatic improvement in holes drilled for both Cobalt and Carbide Coated drill bits. MnS resulted in tool life of about 25% of AncorCut for Cobalt and 50% for Carbide Coated bits. The condition with highest productivity (speed) and longest tool life is the combination of carbide drill bit with AncorCut in the sintered compact. Previous work on AncorCut in FC-0208 resulted in very discrepant tool life behaviors: for a given combination of drill bit material, coating, feed and coolant regime, the optimal additive could have been MnS, AncorCut or the absence of either. In the present work with FD-0405, AncorCut appears to provide long tool life consistently across the conditions.

### *Hole diameter vs. number of holes drilled*

The range in hole diameter (maximum diameter minus minimum diameter) has been measured for processing conditions HS1, CO1, and CD. A large variation indicates a change in machining quality and could result in possible out of specification dimensional tolerances. Figure 5 clearly shows that for HSS drill bits, FD-0405 with no additive is characterized by the largest variation in diameter (three times compared to MnS and AncorCut), despite having drilled the highest number of holes. It is important to note that there is no direct correlation between tool life and machining quality, therefore it is fundamental to investigate both. For the remaining conditions (CO1 and CD), AncorCut exhibited the largest diameter variations: about 30% higher than MnS. Once again, the addition of AncorCut led to the longest tool life but dimensional tolerances are higher compared to other materials.

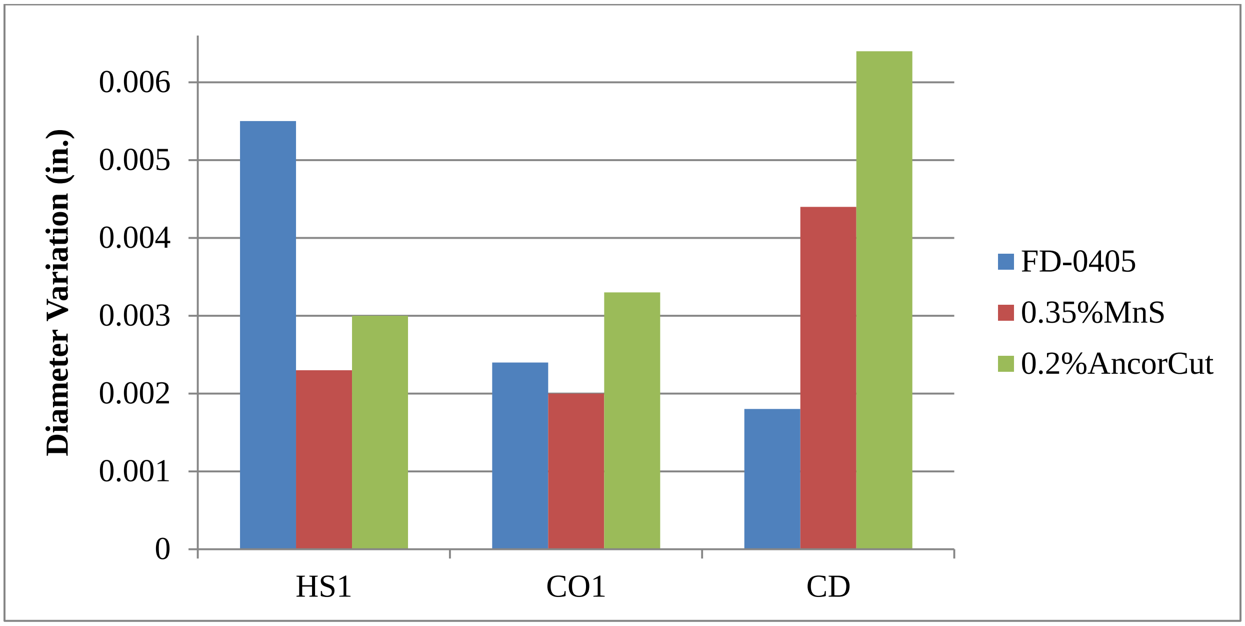



**Figure 5.** Diameter variation for HS1, CO1, CD.

### *Discrete Diameter Variation (DDV)*

It is evident that machinability is affected not only by machining additives but also from cutting conditions. In order to express tool life and machining quality in one measure and thus, compare various processing conditions and materials, the Discrete Diameter Variation (DDV) factor has been introduced. The goal is to select an additive able to deliver the overall best performance.

**Table 6.** Number of Holes and Diameter Variation. HS1, CO1, CD.

| Test Code | Number of Holes | Diameter Variation |
|---|---|---|
| **HS1** | FD-0405 | 0.2%AncorCut |
| **CO1** | 0.2%AncorCut | FD-0405 |
| **CD** | 0.2%AncorCut | FD-0405 |

The DDV indicates how much the diameter varies per each hole drilled on average throughout the entire machining process and can be defined as:

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

Figure 6 demonstrates that AncorCut is the optimal choice for every condition when both tool life and machining quality are accounted for. It can be observed that MnS, currently the most common machining additive in the PM industry, has a DDV 50% higher than AncorCut for HS1 and 120% for CO1. It can also be noticed that, when Carbide drill bits are used (CD), the presence of machining additive is imperative, considering FD-0405 exhibits a DDV around five times higher than AncorCut. The same outcome has been drawn for FC-0208 in previous works [8], where AncorCut led to overall low DDVs, validating its efficacy on enhancing machining of a wide range of base materials.

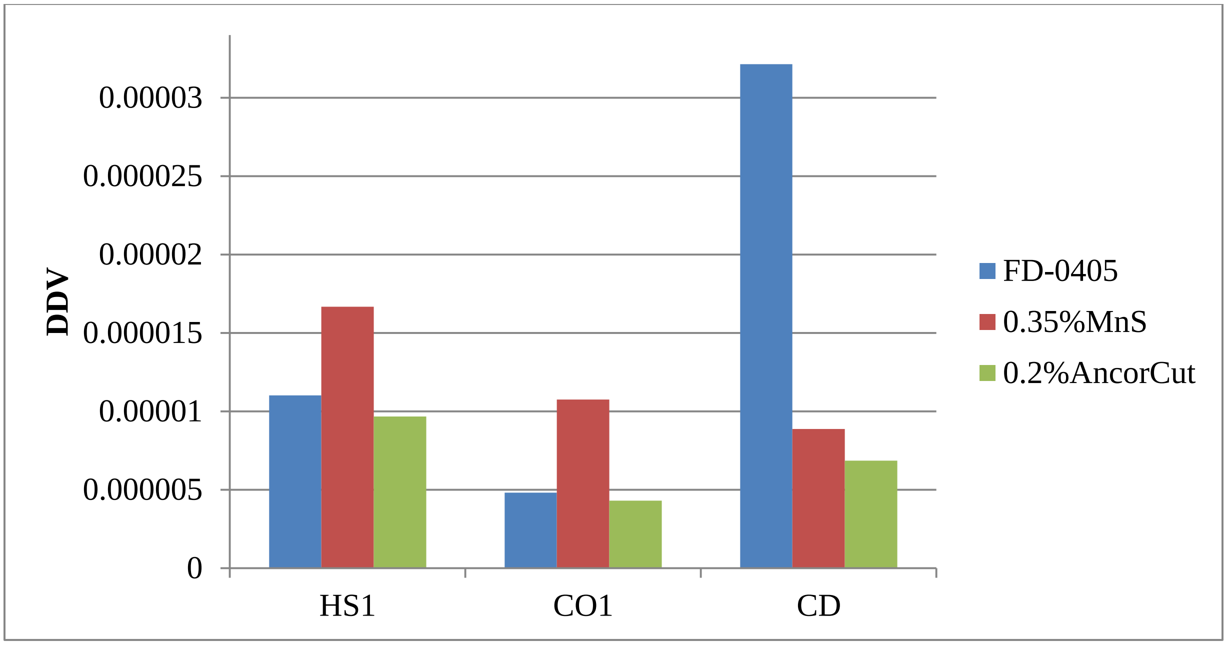



**Figure 6.** DDV (Discrete Diameter Variation) for HS1, CO1, CD.

### *Wear analysis*

Previous work by the authors [8] established a correlation between wear dynamics and trend of diameter variation curve for FC-0208 material. It was noted that downward polynomial modes reflect the presence of abrasive wear, while scattered diameter variations are the results of adhesive wear or mixed abrasive-adhesive wear. Abrasive wear translates into progressive thinning of the drill bit and thus, progressive reduction in hole diameter throughout the machining process. On the other hand, adhesive wear/chemical wear prompts hole enlargement as material welds on the drill bit, which would then chip away as machining continues together with some bit material, causing the hole variation to decrease and increase again from subsequent welding, resulting in a scattered curve. It has been noticed that the latter phenomenon generally correlates with a shorter tool life. For this reason, combinations of processing parameters and machining additive leading to abrasive wear are more desirable than those triggering adhesive wear. The presence of AncorCut was observed to generate abrasive wear for all processing conditions in FC-0208 for HSS and Cobalt drill bits, whereas carbide drill bits were associated with chemical/notch wear modes. The hole diameter enlargement in this case was mostly due to the higher rpm (3500 vs. 2000), which can be related to vibrations and wobbling of the drill bit.

The same analysis has been performed for FD-0405 with similar outcomes. Figure 7 shows the diameter variation for HSS drill bits (test HS1). Polynomial diameter decrease can be seen for all three materials although it is evident that the trend becomes progressively more linear from the material characterized by the shortest tool life (MnS) to the longest (FD-0405). Spindle torque curves for all materials and standard deviation of such curves have also been investigated. It can be observed (Fig.8) that after an initial drop, torque begins to rise as the drilling continues. *The slope of the rising curve* after reaching the minimum *appears to be directly linked to tool life.* Specifically, machining the no additive FD-0405 with HSS displays the lowest slope, followed by AncorCut and MnS. The lower the slope, the longer the tool life can be expected to be. Stability of spindle values have also been found to be correlated to tool life and therefore, wear. Figure 9 indicates that torque values remaining close to their mean (small standard deviation) during the increasing portion of the torque curve are associated with long tool life. This can be explained as follows. Intermittent cut conditions generate mechanical and thermal stresses on the tool that vary based on the presence of voids or solid. For material/processing combinations able to deliver low wear (because of improved heat flow or reduced chemical reactivity), the cutting edge of the drill bit will be more resistent to dulling. Cutting will require less force, resulting in torque values rising more slowly and steadily, as differences between void-induced stresses and solid-induced stresses will have a moderate effect on the drill bit.

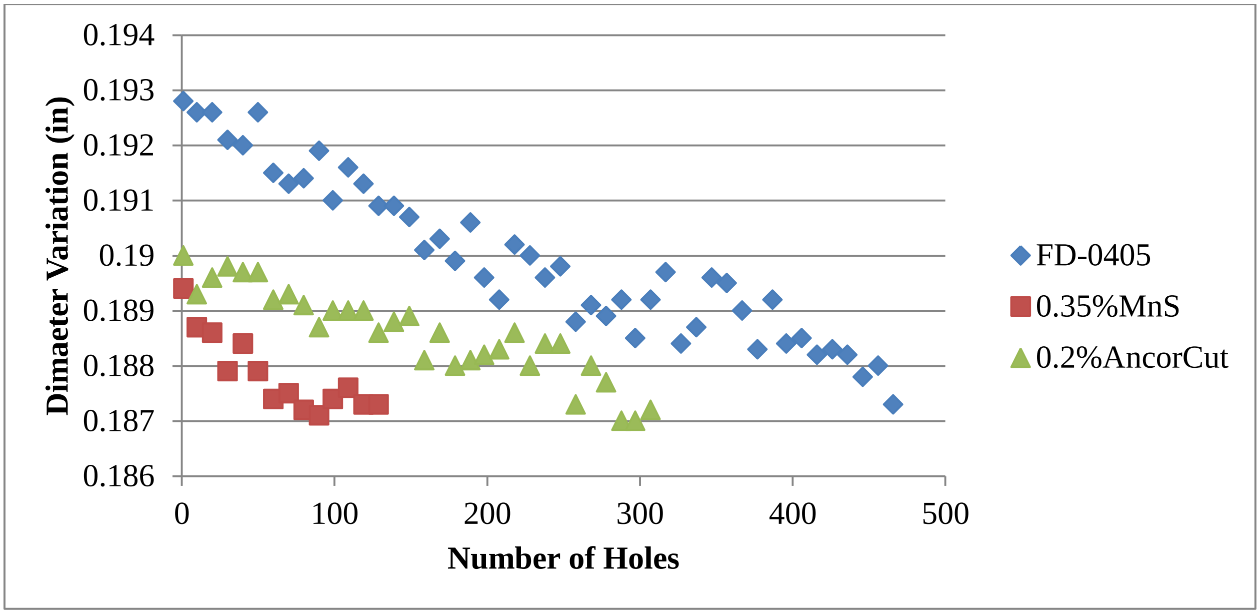
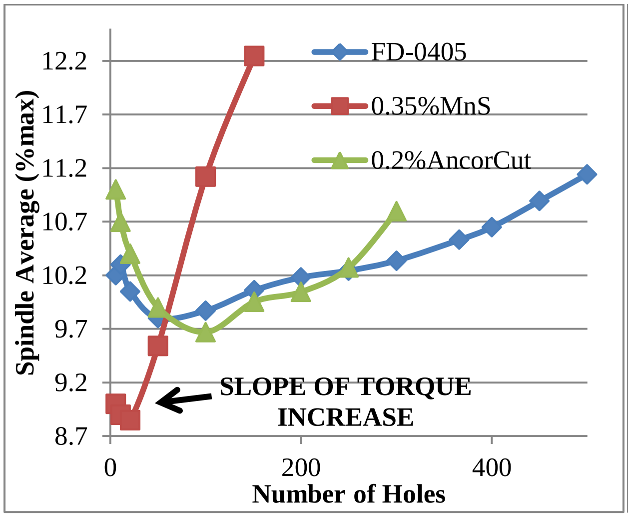



**Figure 7**. Diameter variation vs. number of holes. HS1.



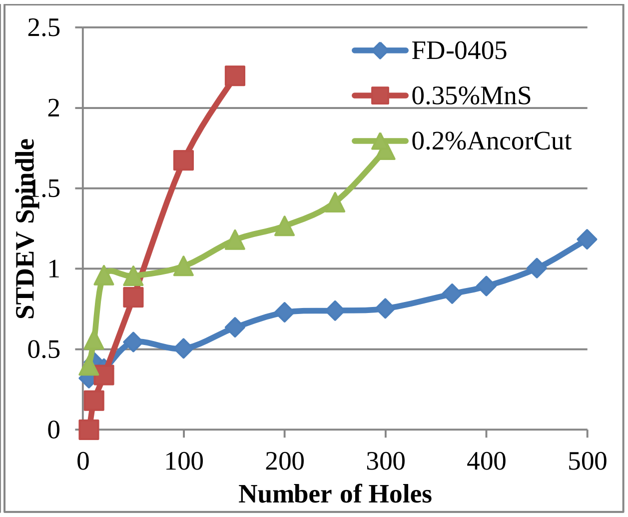




**Figure 8.** Spindle average vs. number of holes. HS1. **Figure 9.** Standard deviation spindle vs. number of holes. HS1.

Similar phenomena occur for Cobalt drill bits (Fig.10) with the difference that some adhesion is taking place. Hole diameter for MnS decreases in the first few holes and begins to demonstrate a scattered behavior as it gets closer to failure. This applies to the no additive FD-0405 as well. AncorCut not only provided the longest tool life, but diameter variation decreases linearly to reach a plateau close to failure. This has been noticed to occur for FC-0208 as well, and it can be beneficial to predicting drill bit end of life before getting to the failure event.

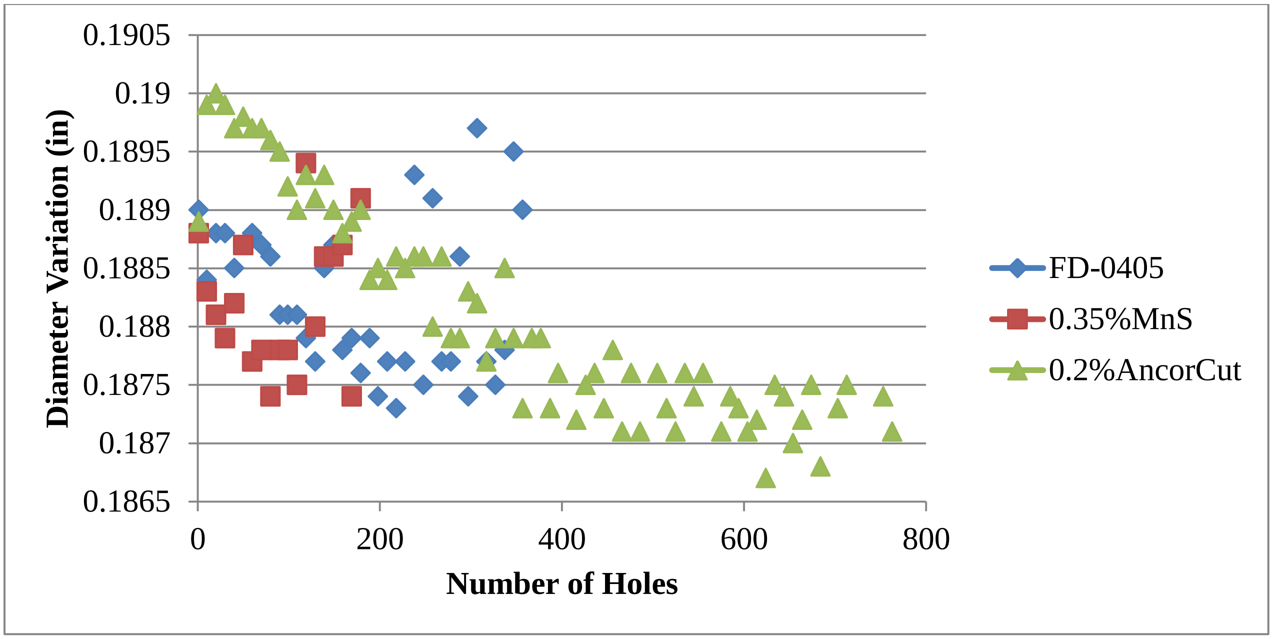



**Figure 10.** Diameter variation vs. number of holes. CO1.

The slope of spindle torque increase (Fig.11) and standard deviation of spindle values (Fig.12) shows the same correlation to wear and tool life for HSS drill bits (test HS1).

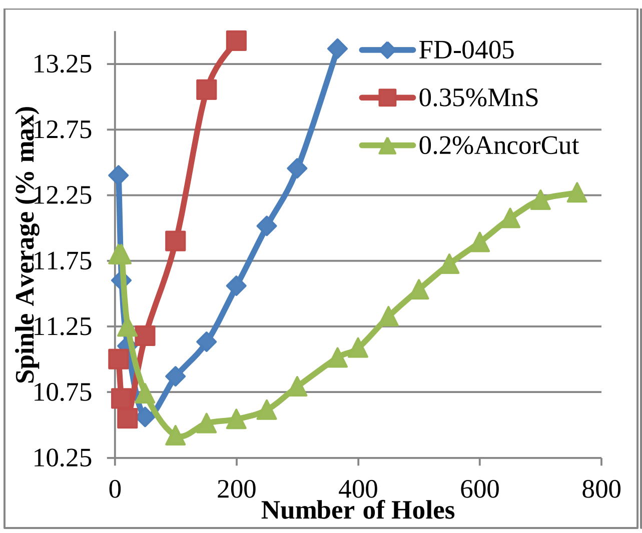



**Figure 11.** Spindle average vs. number of holes. CO1.

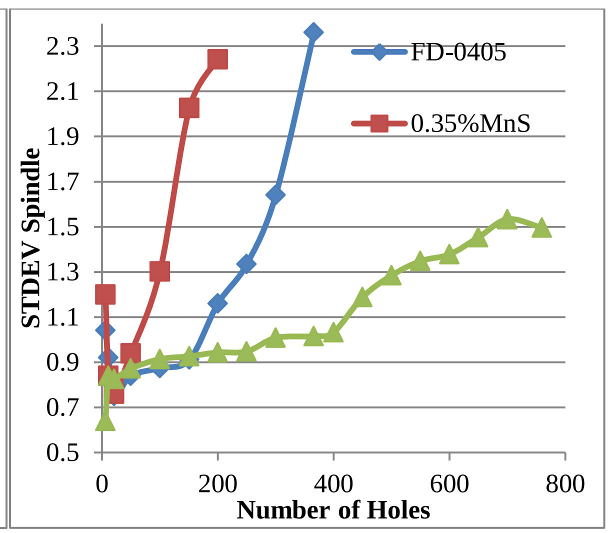



**Figure 12.** Standard deviation spindle torque vs. number of holes. CO1.

Similarly to FC-0208, diameter variation for Carbide drill bits displays diameter enlargement due to adhesive wear. It can be noticed that AncorCut follows a specific diameter increase, with a distinct plateau configuration.

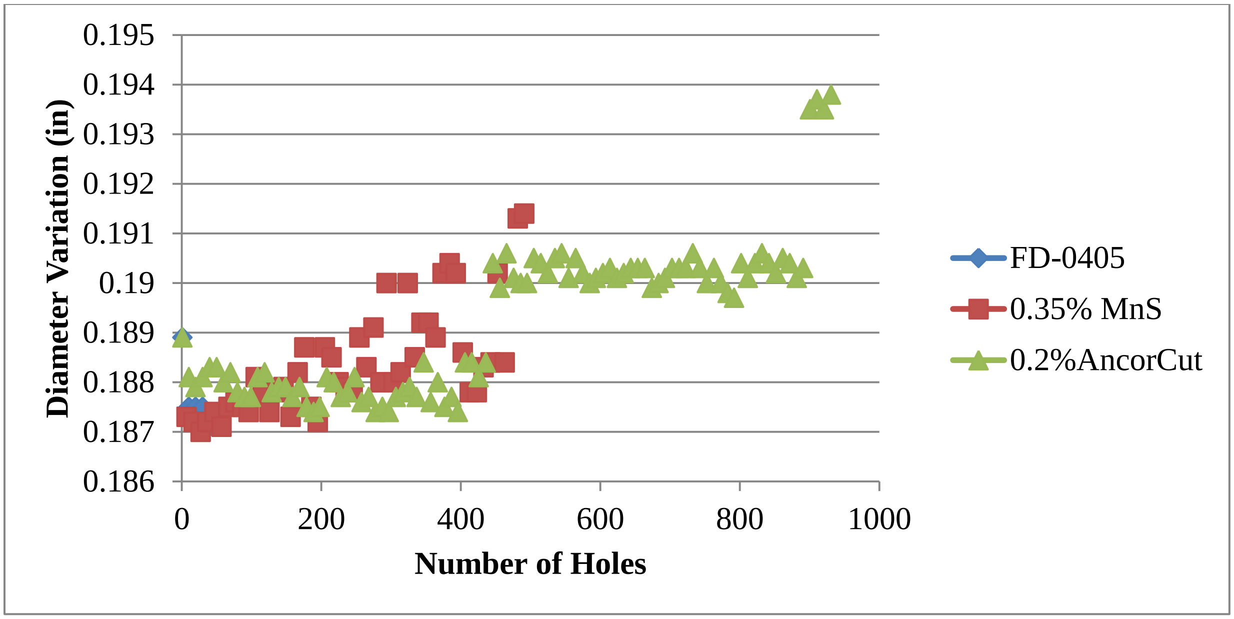



**Figure 13.** Diameter variation vs. number of holes. CD.

Moreover, high tool life appears to be related to the value of the initial drop in torque (Fig.14), with AncorCut reporting the lowest number. Torque standard deviation (Fig.15) reveals that torque progressively converges to a constant number for AncorCut, while FD-0405 and MnS standard deviations spike as the drill bit approaches end of life.

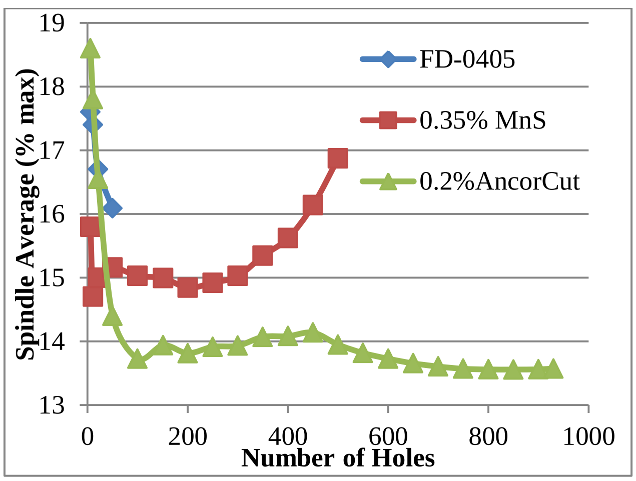



**Figure 14.** Spindle average vs. number of holes. CD.

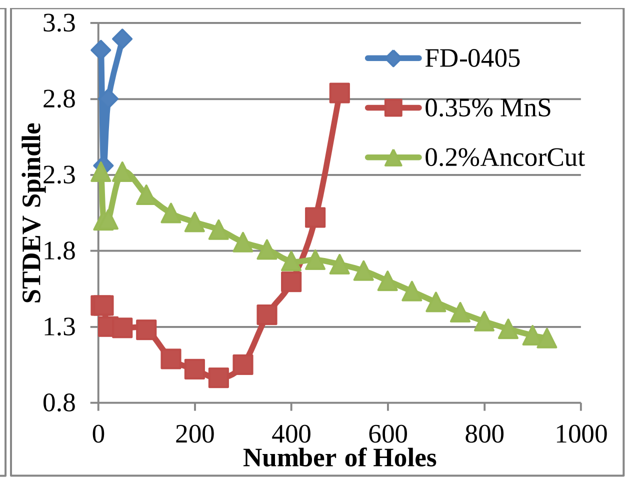



**Figure 15.** Standard deviation spindle vs. number of holes. CD.

Drilling tests for all three materials have been repeated and halted around 50% of what has been measured to be end of life during drill-to-failure tests. Fig.16 represents drill bits from test HS1. The presence of grooves by the cutting edge confirms the occurrence of abrasive flank wear. When MnS is added to FD-0405, plastic deformation is also present; this manifests when the cutting temperature is too high for a specific tool-work piece material combination. This plastic deformation dulls the cutting edge, leading to a rapid increase in spindle torque, as seen in Figure 8, thereby resulting in short tool life.

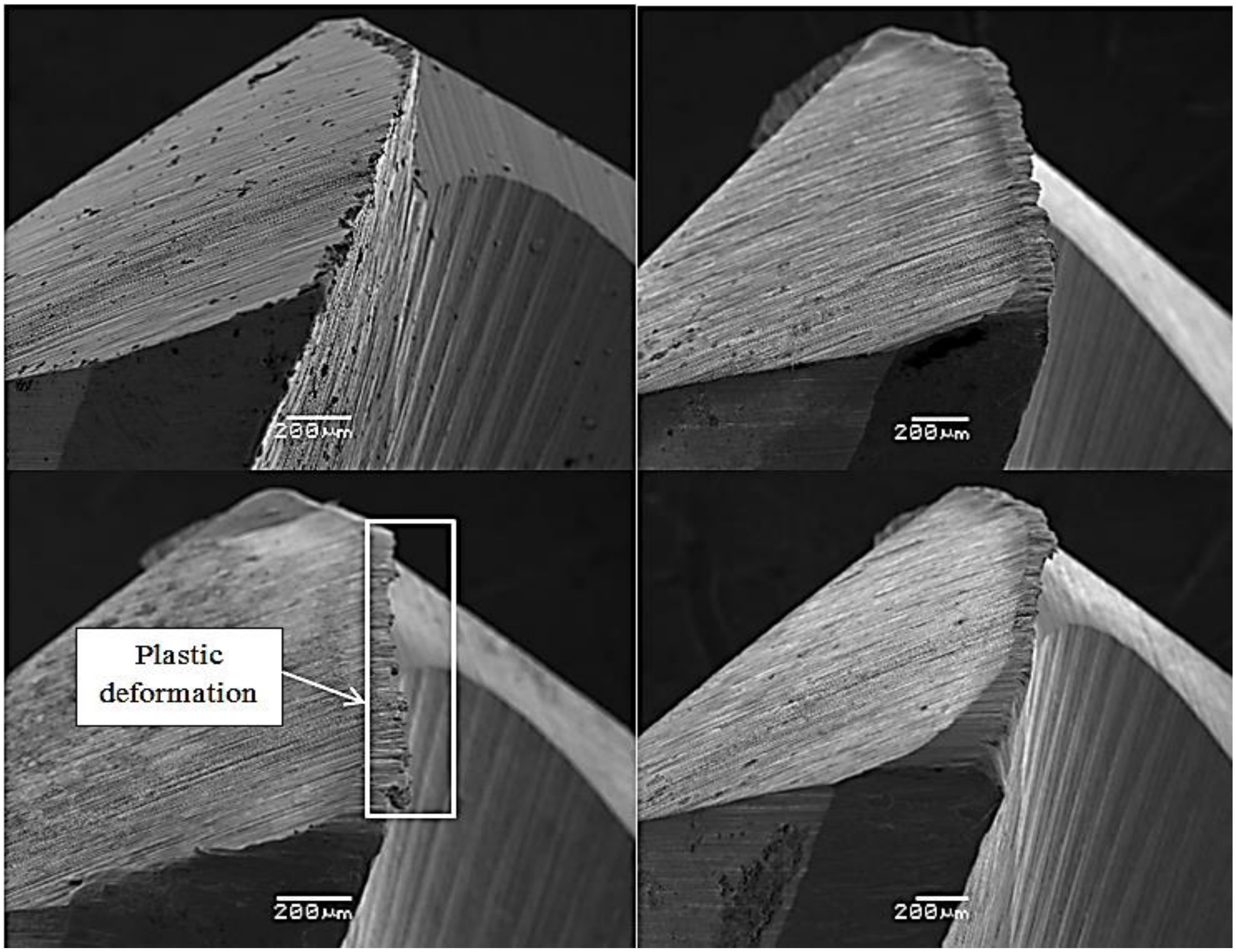


**Figure 16.** Top left: New HSS bit, Top right: FD-0405, Bottom left: +0.35%MnS, Bottom right: +0.2%AncorCut. Test. HS1.

Fig.17 represents drill bits from test CO1. Although the built-up edge (BOE) for the material containing MnS is masking the grooves, we can see deeper and more extensive abrasive wear characteristics for this material compared to both FD-0405 and AncorCut. In addition to this, the prominent BOE can lead to poor dimensional tolerances as well as early drill bit failure due to exportation of drill bit material together with the BOE. Some BOE can be notice for AncorCut also, but it is worth mentioning that the status depicted in Fig.17 represents wear at around 80 holes for MnS, whereas for AncorCut the picture has been taken after 300 holes. It is therefore clear that wear is accelerated for the MnS material in this test.

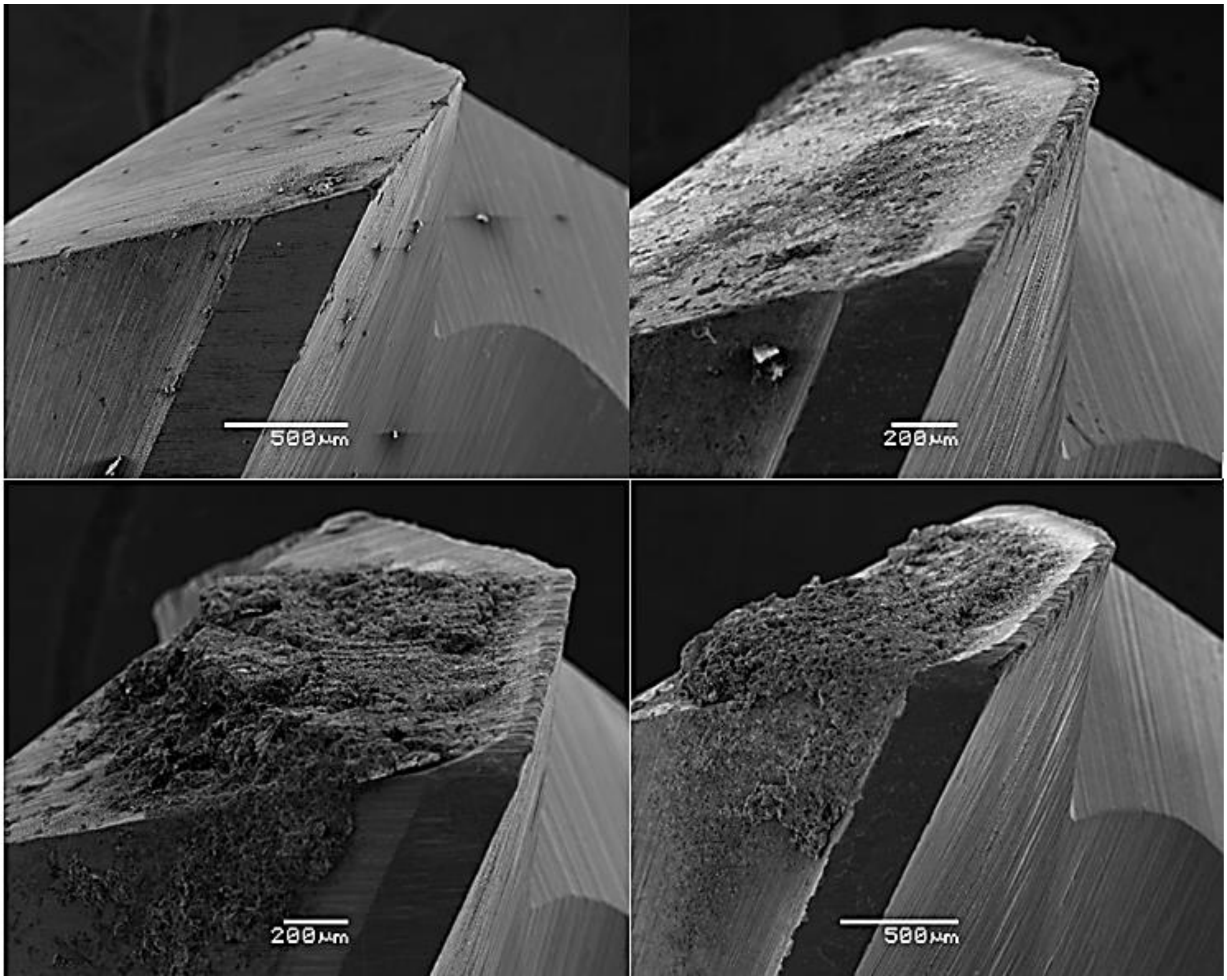


**Figure 17.** Top left: New Cobalt bit, Top right: FD-0405, Bottom left: +0.35%MnS, Bottom right: +0.2%AncorCut. Test. CO1.

Fig.18 represents drill bits from test CD. Both notch wear and severe crater wear can be detected for FD-0405. Crater wear is due to a chemical reaction between the work piece material and the cutting tool and is enhanced by cutting speed. Notch wear is caused by pressure welding of chips and a deformation hardened surface. A common adhesive wear type that takes place especially at high cutting speeds. When MnS are added to FD-0405, crater wear is considerably diminished but notch wear can still be identified. Conversely, for AncorCut crater appear to be almost absent and notch wear cannot be detected.

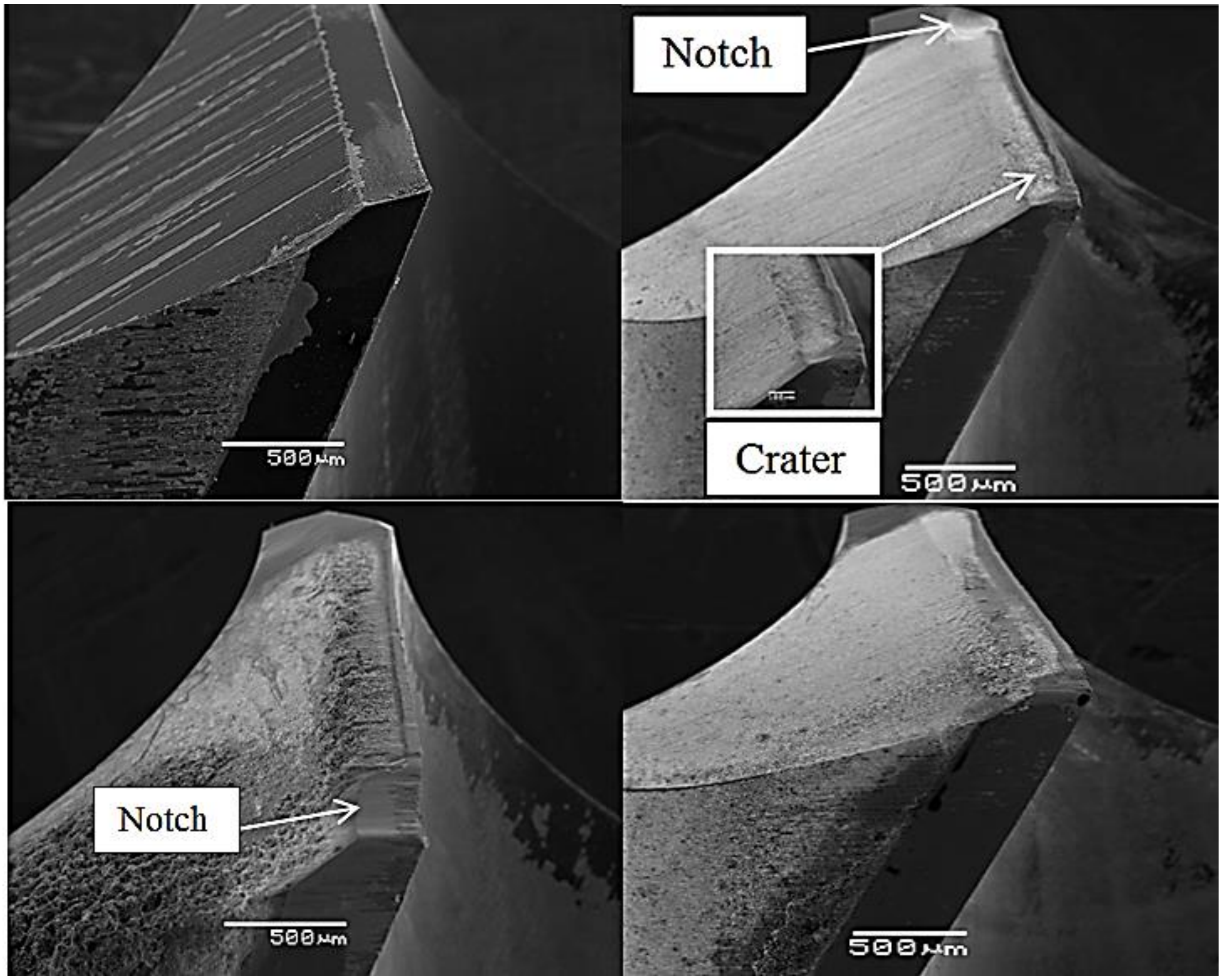


Figure 18. **Top left: New Carbide bit, Top right: FD-0405, Bottom left: +0.35%MnS, Bottom right: +0.2%AncorCut. Test. CD.**

## CONCLUSIONS

The current analysis followed promising results from the addition of AncorCut to FC-0208 material [8]. Drilling trials have been extended to FD-0405 and the effect of the commonly used MnS additive and AncorCut on tool life and hole diameter have been assessed. Wear patterns related to additives and processing conditions have also been identified. Results can be summarized as follows:

- Absence of coolant and high feeds resulted in drill bit failure within a few holes. HSS and Cobalt bits, used with low feed rates and coolant, as well as Carbide drill bits resulted in an order of magnitude increase in tool life.

- Tool life is highly dependent on test conditions and drill bit materials. FD-0405 with no additive displayed long tool life for HSS drill bit, while AncorCut outperformed the other two materials for both Cobalt and Carbide drill bits, approaching infinite life (990 holes) for Carbide bits. Variation of hole diameter was the lowest for MnS with the exception of Carbide (CD).

- Discrete diameter variation (DDV), previously introduced in [8], is a factor that allows the comparison of different materials and test conditions, consolidating tool life (number of holes drilled) and machining quality (variation of hole diameter). AncorCut exhibited the lowest DDV across all conditions, proving its attractiveness as an overall effective machining additive.

- The link between diameter variation and wear dynamics, previously observed for FC-0208, applies also for diffusion-alloyed materials. For HSS and Cobalt, decreasing polynomial trends typical of abrasive wear have been observed to become more evident for materials characterized by long tool life, while scattered trends typical of adhesive wears can be detected for materials associated with faster tool failures. Adhesive/chemical wear modes appear to not affect tool life in Carbide tests, where AncorCut showed a "plateau" like diameter variation trend.

- For HSS and Cobalt drill bits, the slope of spindle torque increase after the initial drop has been correlated to wear and tool life, as well as standard deviation of the same during drilling. Low slope values have been linked to long tool life. For Carbide drill bits, wear has been connected with the initial plunge of the spindle torque, with AncorCut showing a minimum compared to the other materials. Standard deviation of spindle torque for AncorCut has also been seen to progressively reduce during machining, as opposed to FD-0405 and MnS, for which exponential increase of standard deviation close to drill bit failure can be detected.

- Wear analysis has been performed for all test conditions. When HSS is used, lower tool life is associated with plastic deformation, while for Cobalt bits MnS shows prominent built-up edge (adhesive wear) and some abrasive wear. For Carbide drill bits, tool breakage is connected to crater wear and notch wear. The presence of AncorCut eliminates both wear modes.

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