Chill factor prolongs cutting tool life in sinter-hard working

They may not be exactly new, but as sinter-hardened alloys gain popularity because of their economic characteristics in a cash-strapped auto industry, new protocols on treatment and handling are being researched and written. Machining additives in the alloy mix teamed with low-temperature cutting seems to be a winning combination...

Sinter-hardened alloys are gaining in popularity and acceptance in the automotive world and replacing conventional heat-treated PM steels by virtue of their shorter cycle time, excellent mechanical properties and elimination of oil quenching.

However, the hardenability and mechanical properties of sinter-hardened steels also makes machining difficult. Tooling choices are extremely limited, with polycrystalline cubic boron nitride (PCBN) being the only viable option. Cutting speeds are generally slower compared with conventional heat-treated PM steels of similar bulk and particle hardness.

Cutting is usually done dry, since use of coolant has been shown to negatively impact tool life under certain conditions [1] and the coolant must be removed from the porosity within PM part after machining. However, dry cutting causes significant heat generation and retention at the tool's cutting edge, resulting in thermal deformation of the tool and accelerated diffusion wear. Previous research on machining of sinter-hardened steels is limited, partly because of the newness of these alloys as well as the perceived difficulty of using these alloys in parts that require machining. Researchers Ranajit Ghosh from Air Products and Chemicals Inc, of Allentown, Pennsylvania, and Bruce Lindsley from US metal powder giant Hoeganaes Corporation, have been looking at possible solutions to some of the perceptions and published their findings in *Role of machining additives and cryogenic cooling of sinter-hardened materials*, a paper given at the Washington World Congress in June.

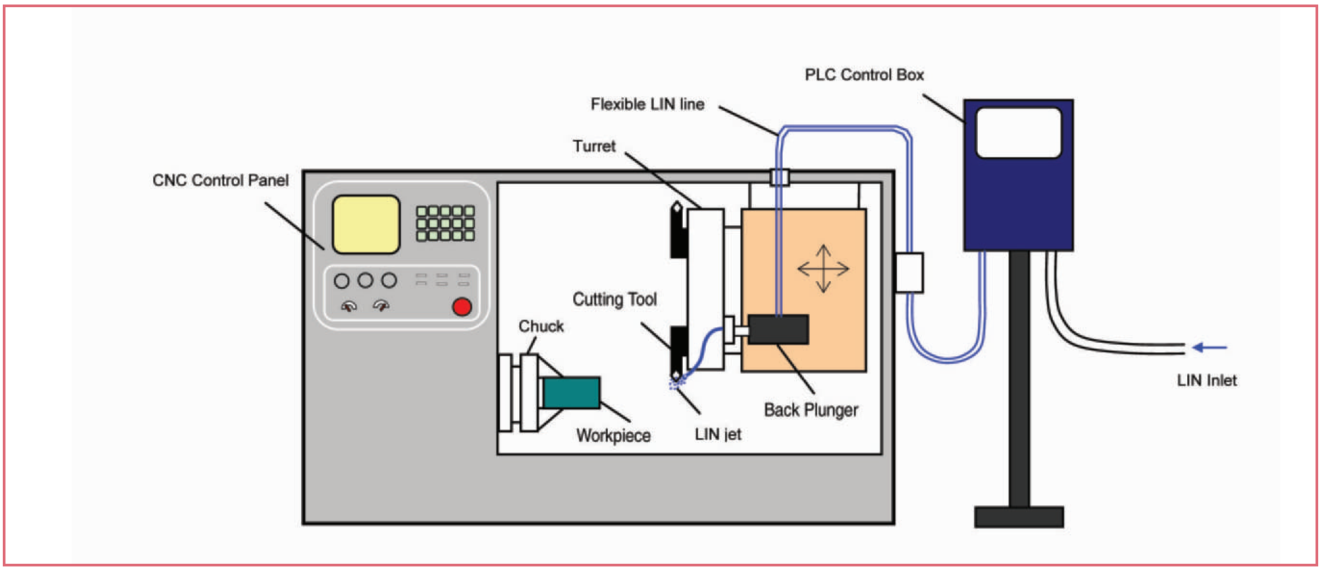

Figure 1. Schematic setup of the cryogenic machining process.

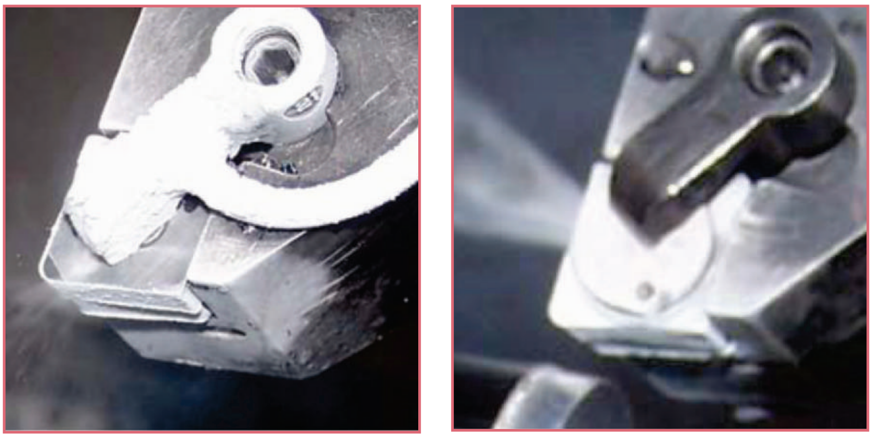

Figure 2. Cooling strategies with LIN (a) Top Cooling (TC) (b) Bottom Cooling (BC). Ancorsteel 737 SH, 2.0% copper, 0.9% graphite 2% Nital / 4% Picral.

With the advent of sinter-hardening alloys and furnaces, hardened steel microstructures can be obtained in the as-sintered condition. During the sinterhardening process, increased alloying (such as molybdenum (Mo), nickel (Ni), chromium (Cr), Manganese (Mn), copper (Cu) and carbon (C) and/or increased cooling rate cause the high temperature austenite to transform to martensite. Martensite is the hardest metallic phase in steel (microhardness) due to carbon remaining in solution and a distortion of the crystal structure to accommodate the carbon. Martensite hardness is greater than 60 HRC in fully dense materials for carbon contents greater than 0.4%. As with quenched alloys, sinter-hardened alloys should be tempered to relieve stresses and improve the overall mechanical properties.

The major benefits of sinterhardening include the elimination of oil quenching and issues related to retained quenchant in the pores of the PM component. Retained oil can be a problem during tempering, with vapour emissions, or during future secondary processing steps, such as resin impregnation, where the pores need to be free of contaminants.

Sinterhardening also results in improved dimensional tolerance compared with oil quenching. In large parts and parts with tight tolerances, the slower cooling rates in sintering furnaces greatly reduce distortions. These benefits must be balanced with the added alloy cost of sinter-hardening alloys.

Machining of sinter-hardened parts is challenging. While most features are formed during compaction, some machining must be performed in the sintered state in order to meet final tolerances.

Even after tempering, the high hardness of martensite results in accelerated tool wear under most cutting conditions and tool materials. It has been shown that increasing amounts of martensite can greatly increase the rate of tool wear [2]. In addition, as increasing carbon content drives up the hardness of martensite, it also increases abrasion wear in tools machining fully sinter-hardened components. Advanced tooling, cooling and machining techniques are required to provide adequate tool life and throughput.

One approach to thermal deformation and associated diffusion wear is to keep the temperature of the cutting tool down. Cryogenic machining involves jetting a small quantity of liquid nitrogen (LIN) onto the rakeface of the cutting tool insert during the cutting process. A typical schematic setup is shown in Figure 1. LIN is either transported from a bulk tank outside the building or from a pressurised cylinder close to the machine through vacuum jacketed lines. The control box, integrated with the machine controller, would signal the LIN flow on demand, through flexible lines, to specifically designed nozzles either integrated into the clamp or mounted close to the insert. The nozzle discharges a stable, precise LIN jet towards the chip/tool interface. Care is taken not to impinge the cryogenic jet directly onto the workpiece to prevent workpiece freezing. Zurecki et al [3] provides a more comprehensive description of the cryogenic delivery system and machine interface.

Liquefied nitrogen readily boils on contact with warmer surfaces (normal boiling point = -196°C) to form a non-toxic, inert gas phase. Although successfully demonstrated in academic laboratories as an effective, safe and cost-saving coolant, LIN requires industrial delivery and jetting systems for instant startup, shutdown and stabilised flow of liquid cryogen, as well as integration with modern CNC lathes and controllers.

The conventional cooling process in cryogenic machining is shown in Figure 2(a), wherein the liquid nitrogen is jetted from the nozzle built inside the top clamp, onto the rakeface of the insert.

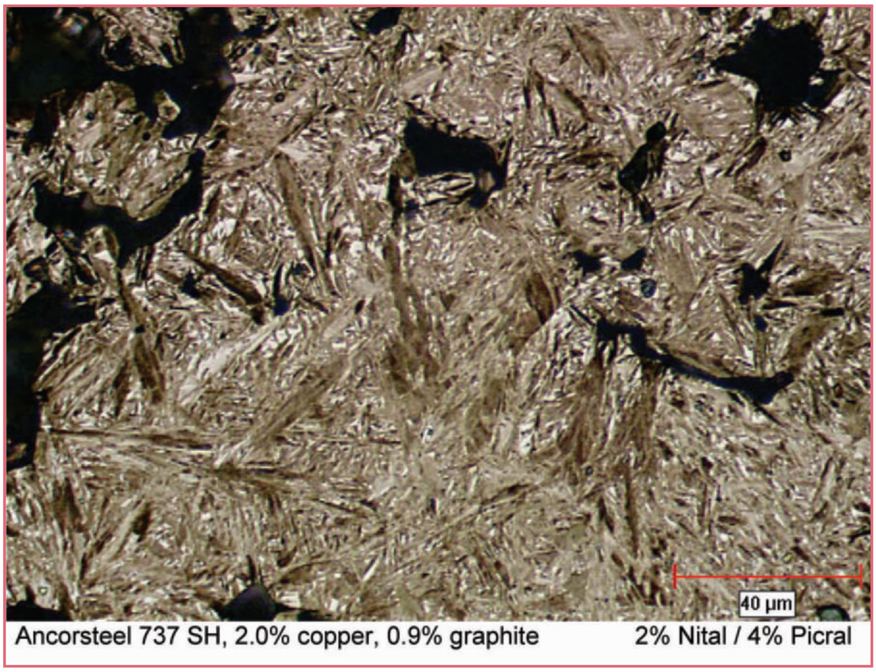

Figure 3. Microstructure of the sinter-hardened machining samples (MPIF FLC-4608).

LIN removes heat from the cutting process convectively by impinging onto the cutting area and conductively through the cutting tool insert. This process is also known as top cooling, as LIN is sprayed from the top of the insert.

For certain materials and workpiece geometries, the conventional LIN jetting process has been found to be unsuitable and potentially detrimental to tool life. Materials that quench-harden (eg materials containing retained austenite), as well as severely interrupted cutting operations, fall into this category.

For quench-hardening materials, the secondary cooling effect from the LIN jetting causes the uncut material to harden, resulting in more abrasive wear on the tool. For severely interrupted cutting operations, the LIN jetting cools the free edges of the interruptions, resulting in higher impact forces and shorter tool life.

To counter these disadvantages, the authors have used a patented process of conductive cooling of the tool using a cryogenic coolant and eliminating the convective heat transfer process [4]. The LIN is sprayed from the bottom of the insert through pre-machined channels in the shim and is jetted out without contacting the work surface or the cutting area. The main advantage of this process is significant cooling of the insert which hardens and toughens the tool without adversely affecting the workpiece properties.

The sinter-hardened steel selected for this investigation is MPIF alloy FLC2-4808 (Ancorsteel® 737 + 2% Cu + 0.9% graphite + 0.75% EBS lubricant). The microstructure is shown in Figure 3. Machining additives (MA) were admixed into this alloy to test their effectiveness with the cryogenic cooling technique. The four compositions developed, were with no additive, 0.35% manganese sulphide (MnS), 0.15% MA and 0.3% MA. Hollow cylinders measuring 44.5 mm OD by 25.4 mm ID by 32 mm long were compacted using a 140-ton press to a green density of 7.0 g/cm^3. The samples were sintered in a continuous belt furnace at temperature of 1120°C. Accelerated convective cooling was used to ensure a fully martensitic microstructure, as shown in Figure 3. All parts were tempered at 205°C for one hour after sintering. The apparent hardness of the test samples was 30 – 38 HRC, while particle hardness was 58 – 60 HRC.

A set of machining tests with varying levels of different machining additives were carried out under dry and cryogenic cooling conditions. The objectives of the tests were twofold:

1. To estimate the tool life improvement using the various levels of different additives compared to additive-free samples; and
2. To investigate the effects of LIN cooling on tool life in various samples.

Depth of cut at 0.25 mm (0.010”) and feed rate of 0.30 mm/rev. (0.012”) were held constant for the entire test matrix, while cutting speeds were varied between 290 and 412 m/min. (950 - 1350 SFM). The sinter-hardened sample without additives was set as the benchmark. Uncoated polycrystalline cubic boron nitride (PCBN) and TiN-coated Al_2O_3 tools were used for the tests. Four different cooling conditions were used: dry, flood coolant, liquid nitrogen top cooling (LIN TC) and liquid nitrogen bottom cooling (LIN BC). Machining was continued till end of tool life, characterized by deep cratering and eventual chipping of the cutting edge. Hardness uniformity of the samples during machining was ensured by monitoring the

Table I: Comparison of tool life under various cooling conditions (additive-free samples)

Operation:	**Rough turning of a sinterhardened sample**				
Material:	LC2 4808 (Ancorsteel 737+2%Cu+0.9%Graphite)				
Hardness:	30 - 38 HRc (apparent)				
Work Condition:	Sinterhardened (no additives)				
Cutting Condition	Depth of Cut: 0.010 in. Feed: 0.012 in./rev. Speed: 950 SFM				
Cutting Data	PCBN / DRY	PCBN/FLOOD	PCBN / LIN (TC)	PCBN / LIN (BC)	Al_2O_3 / LIN (BC)
Insert:	CNGA 433	CNGA 433	CNGA 433	CNGA 433	CNGA 433
grade	BN700 (Sumitomo)	BN700 (Sumitomo)	BN700 (Sumitomo)	BN700 (Sumitomo)	A66N (Toshiba)
Results					
edge life criteria	crater wear/chipping	crater wear/chipping	crater wear/chipping	crater wear/chipping	crater wear/chipping
Tool life (min.)	6.8	5.7	10.3	16	4.6
increase in tool life %		-16.2%	51.5%	135.3%	-19.3%

apparent hardness after every few passes. A first set of comparative tests was conducted on the additive-free sinter-hardened parts. A comparison of the tool life under various cooling conditions is given in Table I.

Comparison of the PCBN/Dry and PCBN/Flood conditions shows a 16% decrease in tool life with flood cooling. Similar behaviour has also been observed by other authors in a lower carbon martensitic alloy [1]. A possible explanation for the reduced tool life with coolant is related to a lower temperature in the workpiece. A higher temperature in the PM workpiece may lead to softening of the martensitic structure and locally cause a phase change to austenite at the interface, which could dramatically reduce cutting forces. With flood cooling, the workpiece is cooled, so no softening of the matrix occurs. The beneficial softening effect with dry cutting outweighs the detrimental effect of a hotter tool, where thermal softening of the cutting tool accelerates the rate of diffusion wear.

The increase in tool life with LIN (TC) over dry cutting is somewhat unexpected,

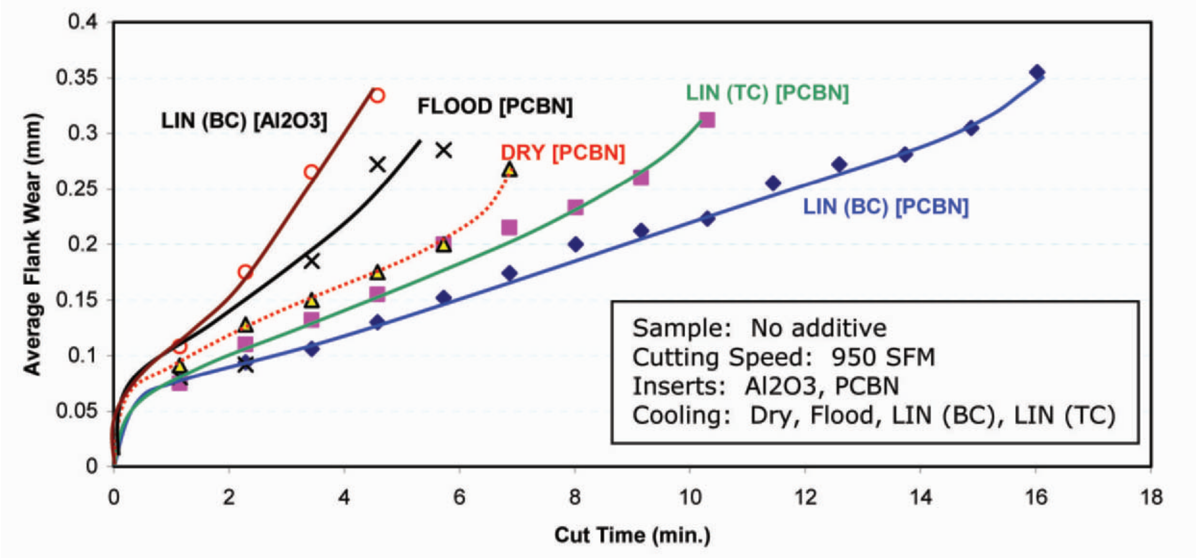

Figure 4. Tool flank wear progression for various cooling conditions.

in light of the reduction in tool life with flood coolant. However, LIN jetting on the rakeface results in significant hardening of the cutting tool, which leads to higher abrasion resistance and lower flank wear, offsetting the effects of a harder work material. Higher tool toughness also allows LIN (TC) to outperform dry cutting, by preventing chipping failure until a higher level of flank wear was reached. Figure 4 compares the average flank wear progression for all cooling conditions.

With LIN (BC), the primary mode of heat transfer is conduction through the tool. Since the bulk of the insert is at cryogenic temperature, this creates a very steep thermal gradient across from the cutting edge. With the tool acting as an efficient heat sink, rate of diffusion wear (cratering) is slowed significantly. The combination of a softer work material and a harder and tougher cutting tool also results in a slower rate of flank wear growth as well. The net result is a 135% improvement in tool life over dry cutting. It can be seen in Figure 4 that the tool wear rate is considerably slower for the

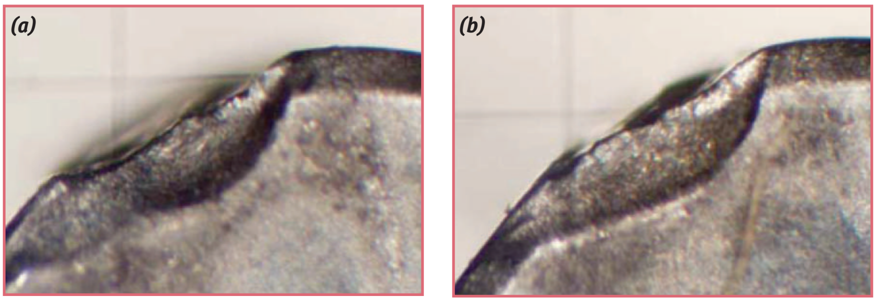

Figure 5. Tool failures in no-additive sinter-hardened PM with (a) Dry [1 minute] and (b) LIN (BC) [2 minutes].

Cryogenic cooling had the biggest impact with Hoeganaes machining additive, with tool life improvements of the order of 250%

bottom cooled PCBN. PCBN tools also significantly outperformed Al_2O_3 tools, with a 3X improvement in tool life under identical cutting conditions. Previous work has also shown that ceramic tools were inferior to PCBN under dry cutting conditions [5].

A comparison of tool failure modes in additive-free sinter-hardened material with dry cutting and LIN (BC) is highlighted using an accelerated test, by increasing the cutting speed to 350 m/min (1150 SFM).

Figure 5 compares the tool failure modes with dry cutting (1 minute) and LIN (BC) (2 minutes). Although chipping is the mode of failure in both cases, it is preceded by significant diffusion (crater) wear and subsequent thinning of the cutting edge.

With LIN (BC), bulk cooling of the tool slows the rate of diffusion wear, resulting in enhanced tool life.
The Hoeganaes machining additive MA was added to the sinter-hardened samples in two concentrations (0.15% and 0.3%). This was compared against a standard manganese sulphide (MnS)-added (0.35%) sample. [Manganese sulphide is well known in powder metallurgy as a machining-enhancing additive where residual porosity can limit tool life and restrict the use of liquid coolants.]

Dry cutting and LIN (BC) were selected as the only cooling options. Flood cooling was not included in the test matrix, since setup tests showed dry cutting to be the next best option to LIN cooling in terms of tool life. While depth of cut and feed were kept unaltered from the previous set of tests, the cutting speed was increased to 350 m/min (1150 SFM) on account of the improved tool life expectations, as demonstrated in our setup tests.

The flank wear comparison is shown in Figure 6. Addition of MnS improved tool life significantly over the no-additive scenario, as both dry cutting and LIN-cooled tests recorded 9X improvement in tool life.

However, LIN (BC) outperformed dry cutting by a 2:1 margin, as the efficient heat removal slowed the rate of crater wear significantly. The comparison of flank wear between dry cutting and LIN (BC) for the 0.15% MA sample is also shown in Figure 6. Again, LIN cooling through the bulk of the tool resulted in significant slowing of the diffusion wear compared to dry cutting.

Clearly, the MA additive was more effective, compared to the standard MnS additive, even in significantly lower concentrations. The lower percentage of machining additive is desirable in PM parts, as it leads to improved mechanical and fatigue properties in the finished part, as well as improved corrosion resistance. At higher concentrations of the MA additive (0.3%), end-of-life criterion was not reached with either dry or LIN-cooling after 34.5 min of cutting (Figure 7) at a higher cutting speed of 412 m/min. (1350 SFM). The tests were concluded at this stage due to insufficiency of sinter-hardened samples. Clearly, with dry cutting, the first stages of diffusion wear are visually evident at this stage, while the LIN-cooled tool shows negligible wear.

The interesting aspect of tool failure with sinter-hardened materials is that failure is always initiated by deep cratering of the tool, resulting in thinning of the cutting edge and eventual chipping. Addition of machining additives slows down the rate of diffusion wear. Higher amounts of additives were clearly beneficial in terms of tool life, although an optimal concentration balancing tool life with mechanical properties in the finished part needs to be established.

Among the cooling options, cryogenic cooling using the indirect cooling approach (LIN(BC)) had the biggest, positive impact on tool life for both samples

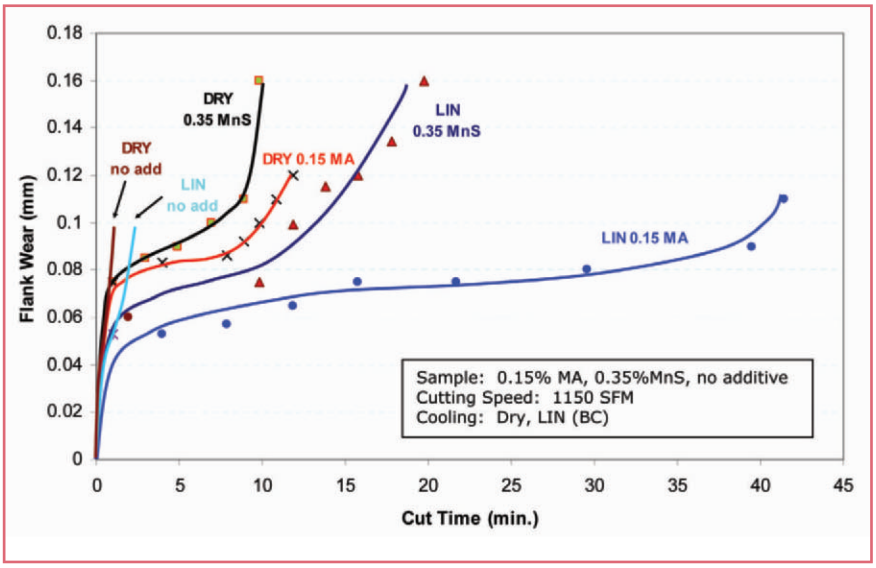

Figure 6: Tool flank wear progression for various cooling conditions
Sample: 0.15% MA, 0.35% MnS, no additive
Cutting Speed: 1150 SFM
Cooling: Dry, LIN (BC)

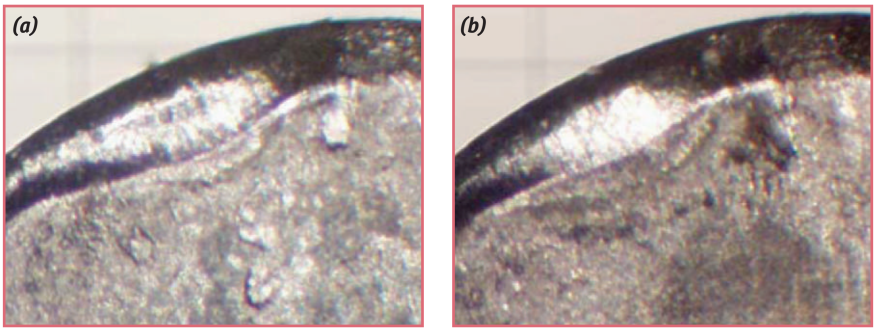

Figure 7: Crater wear comparison after 34.5 minutes of cutting 0.3% MA-added PM (a) Dry (b) LIN (BC)

without any additives and also for parts with varying levels of MA and MnS additives. In additive-free samples, the tool life improvements were ~ 135% over the next best option (dry cutting), while the extent of improvement in samples with additives was much higher.

The Hoeganaes machining additive MA has also been shown to be a more effective additive, compared to standard MnS additives, under all cooling conditions.

An addition of 0.15% MA additive increased tool life by 20X, over the no-additive sample. Samples with 0.15% MA also produced better tool life results compared to 0.35% MnS, under identical cutting conditions. With MA, cryogenic cooling had the biggest impact, with tool life improvement of the order of 250%, compared to dry cutting. Increasing the percentage of MA additive to 0.3% reduced tool wear to a point where it could not be easily measured under these test conditions.

The synergistic effect of both the LIN-cooled tool and the MA additive should allow high productivity machining of sinter-hardened PM components with reduced tooling and machining cost.

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