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Cryogenic Machining with Brittle Tools and Effects on Tool Life

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ABSTRACT

With the current popularity of finish hard turning, the need for improved productivity and tool life is of significant importance to manufacturers. The present work explores the effects of cryogenic coolants in machining hardened materials, from an industrial perspective, with emphasis on productivity and tool life improvement, environmental effects, as well as reliable performance characteristics for brittle tools. Both alumina ceramic (Al_2O_3) and polycrystalline cubic boron nitride (PCBN) tools show significant tool life improvement in cryomachining of hard ferrous materials, such as 52100 bearing steel and A2 tool steel. Significant productivity gains have also been observed in cryogenic machining of WC-Co rolls with polycrystalline diamond (PCD) tools. The enhanced performance of cryomachining is attributed to more efficient heat removal from the cutting insert, as well as reduction in thermal softening of the cutting tools at higher temperatures.

INTRODUCTION

Finish turning of hardened steel is becoming a viable alternative to grinding applications, but the choice of tooling and process conditions are still fraught with difficult issues. The most popular choice for tool material is polycrystalline cubic boron nitride (PCBN), which has necessary chemical and thermal stability for application across a wide range of hard steels and irons, and across a range of cutting conditions (continuous to interrupted cuts). PCBN tools are also the primary tool material for machining sintered and heat-treated powder metal (P/M) parts; however, the high cost of PCBN tools makes the process tooling costs prohibitively expensive. Oxide-based ceramic tools, which have also been used in hard turning operations, are less expensive (5 – 20 times less than comparable PCBN inserts), but their applicability is limited by their incompatibility with emulsion-based (flood) coolants [1]. Researchers Dewes and Aspinwall report a shortening of tool life by 95% or more, using Al2O3 ceramics in milling of hardened steel dies [2]. Also, the low fracture toughness of ceramics can result in unpredictable tool failures [3]. Use of polycrystalline diamond (PCD) tools is prevalent in machining of hard composites (WC/Ni-Co etc.), but their applicability is limited by rapid oxidation wear of diamond at high temperatures. In all cases of brittle tool applications, the main barrier to improving productivity is the ability to remove the heat from the cutting zone more quickly and efficiently, allowing the tool to retain its hardness at higher temperatures.

Several researchers have investigated the wear of PCBN and Al_2O_3 ceramic tools in hard turning of steels. Chou et al. [4] demonstrated that low content CBN tools generate better surface finish and exhibit lower flank wear rate than high content CBN tools. Aspinwall et al. [5] showed that PCBN tools were better than ceramics in terms of tool wear and surface finish in machining H13 hot work die steel and hardened 52100. Similar conclusions were obtained by Konig et al. [6] in machining 100Cr6 (62 HRc).

Investigations of tool wear, surface finish and cutting forces in cryogenic machining have been attempted by researchers several decades ago [7], but only recently, has the topic generated renewed interest. However, most of the research has been concentrated on machining low/medium carbon steels [8, 9], high carbon/high alloy steels [10], stainless steels [11, 12], titanium alloys [13,14] and ceramics [15]. All previous attempts at machining of ferrous materials involved annealed workpieces (hardness < 25 HRc) and carbide inserts. To the best of the authors' knowledge, no previous applications of liquid nitrogen (LIN) cooling in hard turning of ferrous materials have been published.

CRYOMACHINING PROCESS

The cryomachining process 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 Fig. 1. LIN is either transported from a bulk tank outside the building or from a pressurized 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. [16] 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 = -196ºC) to form a non-toxic, inert gas. Although successfully shown in academic laboratories as an effective, safe and cost-saving coolant, LIN requires industrial delivery and jetting systems capable of accommodating diverse tool geometries and integration with modern CNC units.

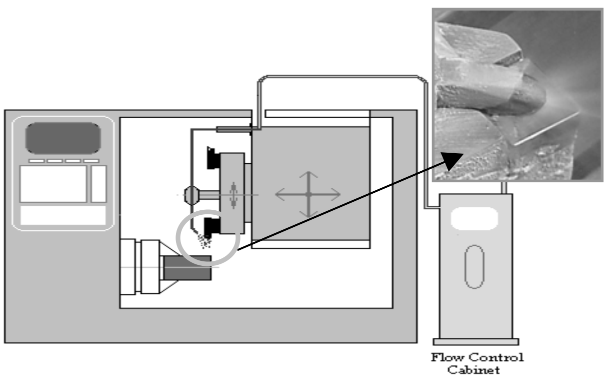


Fig. 1: Schematic setup of the cryomachining process

OXIDE CERAMICS

MACHINING TESTS WITH OXIDE CERAMICS

Several machining tests have been conducted to compare the effects of no coolant (dry), emulsion-based flood coolant (flood) and LIN on Al_2O_3 ceramics. Work material, cutting tools and tool life criteria are typical of those found in the hard turning industry. Testing was performed on a Mori SL-253B lathe (25 HP). In addition, dynamometry tests were conducted to analyze the effect of coolants on cutting forces. Forces were recorded using a Kistler 9121 dynamometer and charge amplifier, with a NI-DAQ data acquisition board and DASYLAB software data acquisition system. Wear measurements were done on a 3-axis Dynascope measuring system with a resolution of 0.001 mm and an accuracy of ± 0.003 mm.

A2 Tool Steel

Continuous turning tests were conducted on a through-hardened A2 steel (62 HRc). Cutting tests were run at constant surface speed; the feed and depth of cut were selected to be representative of finish turning conditions. The cutting tool selected, was a commercially available TiN-coated Al_2O_3 ceramic with 0.004 in. (0.1 mm) land and a 20 deg. chamfer angle. The wear patterns under flood, dry and LIN cooling are plotted in Fig. 2.

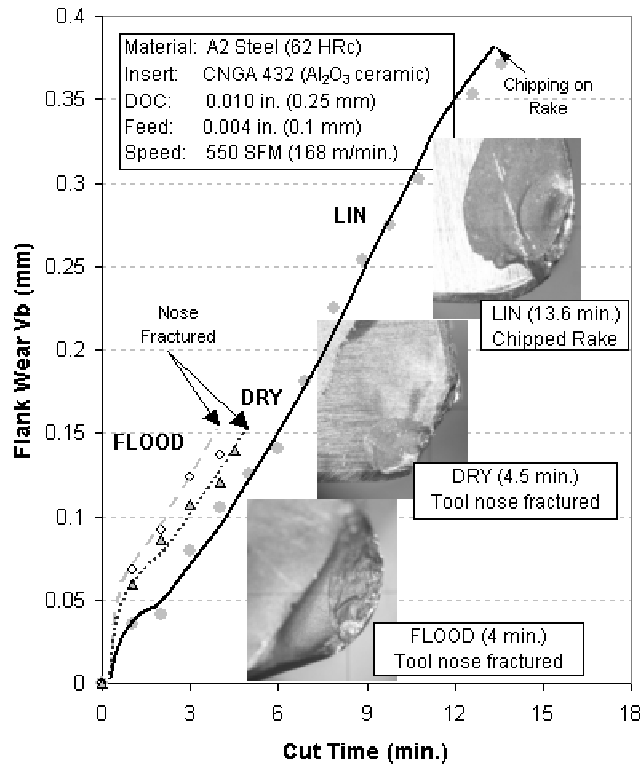


Fig. 2 Tool life comparison in machining A2 steel (Dry, Flood and LIN)

Tool life with LIN is extended by over 200%, compared to flood and dry cutting conditions. The major reason for better performance of cryo-cooled inserts at high cutting speeds is due to significant reduction in thermal softening of the tool at higher temperatures. Also, due to extremely low temperatures of the LIN coolant, a steep temperature gradient is established between the chip/tool interface and the body of the insert; thereby, facilitating efficient heat removal from the cutting zone. The more interesting aspect of this result is the unpredictable catastrophic failure of inserts under flood and dry conditions, whereas for LIN, the flank wear progressed gradually and predictably, as is typically observed with carbide inserts. The unpredictability of oxide ceramics under dry and flood conditions is well known in the industry, which precludes their use in critical operations and/or fine finishing situations. With LIN, ceramic tools wear more predictably, and as such, they could be used as a replacement for PCBN tools in such applications.

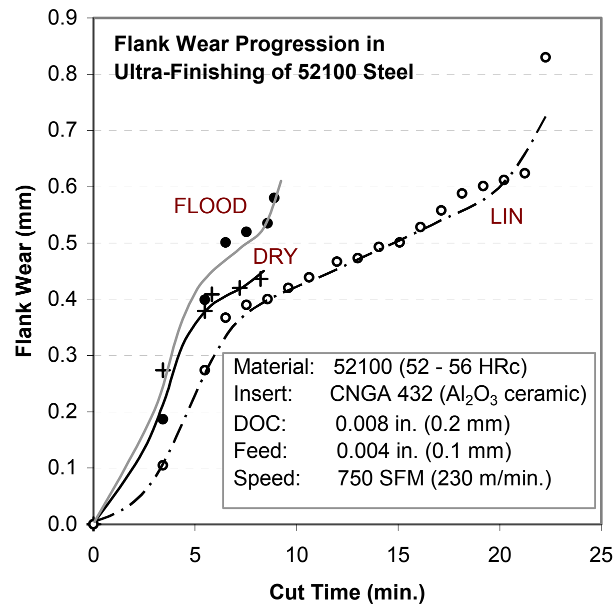
52100 Bearing Steel

Two sets of hard turning tests were conducted on 52100 steel, involving ultra-finishing and light-roughing conditions. Low hardenability of 52100 made it especially challenging to develop test specimens, with a consistent hardness profile. The specimens were 5 in. (127 mm) diameter bars, with a 3 in. (76 mm) ID machined out. This ensured uniformity of the hardness on the OD and ID of the "pipe". The specimens were heat-treated to 56 HRc.

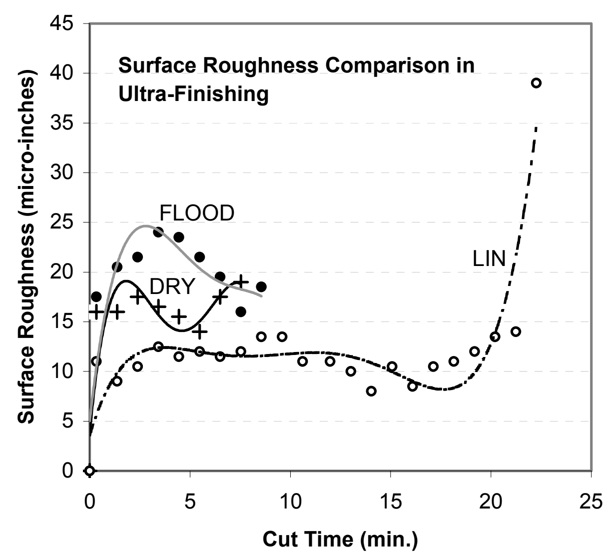
Machining tests on the bar included facing cuts across the 1 in. (25 mm) wall thickness. Initially, a bar was machined and the hardness checked periodically to develop a hardness profile. The hardness variation was between 56 – 40 HRc, varying both along the length of the pipe and the cross-section. To ensure uniformity in testing, machining was limited to a minimum hardness of 52 HRc, at both ends of the pipe. Two sets of tests were conducted, with consistent results both in terms of surface roughness and flank wear.

The substantial benefits of LIN cooling, both in terms of tool life and surface roughness, are illustrated in Fig. 3. Flood and dry performance were similar; with flood being slightly worse in terms of both flank wear and surface roughness. Surface roughness with LIN was significantly better than both flood or dry. The authors believe that this is due to two factors (**a**) better edge integrity for the LIN-cooled tool and (**b**) less smearing of the hot metal in the compressed finished surface layer. Consequently, in ultra-finishing, a tool life criterion of 0.6 mm flank wear is acceptable with LIN, since the surface roughness was never more than 15 micro-inches (0.38 μm). This aspect has an important commercial significance in the machining industry. For parts with a maximum surface roughness criterion of ~ 15 - 18 micro-inches (0.38 – 0.46 μm), ceramic inserts cannot be used under flood or dry conditions, necessitating the use of more expensive PCBN tools for finishing these parts. LIN makes the use of less expensive ceramics possible in these situations, with acceptable tool life.

Cutting tests under light roughing conditions show a similar performance for LIN, but the flood-cooled inserts fractured prematurely. This was consistent over both sets of tests. The authors presume that with higher tool pressure in light roughing, propagation of micro-cracks is facilitated, with thermal shock and moisture as promoters.



(a)



(b)

Fig. 3: Ultra-finishing of 52100 steel
(a) Flank wear (b) Surface roughness

An interesting comparison can be drawn between the behaviors of the flood/ceramic combination in ultra-finishing and light roughing. With lower heat generation in ultra-finishing, environmental corrosion and thermal shock are reduced. In addition, development of micro-cracks and moisture penetration is delayed with lighter tool pressure. The role of cutting speed is considered secondary, since the ultra-finishing test was run at higher cutting speeds.

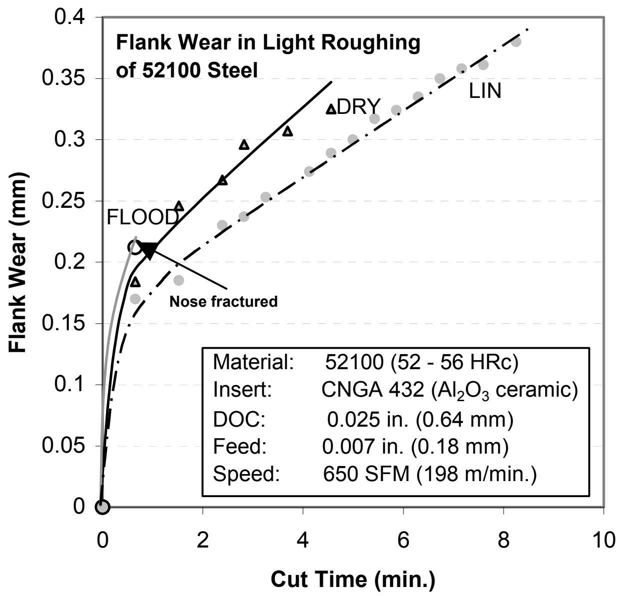


Fig. 4: Flank wear in light roughing of 52100 steel with a ceramic tool

DYNAMOMETRY TESTS

Dynamometry tests done under accelerated cutting conditions show that cutting forces for different cooling media are similar at the beginning of the cut, but start to diverge, as the tool starts to wear. A comparison of the feed forces under four cooling situations (high-pressure flood at 400 psi (2.76 MPa), low-pressure flood at 20 psi (0.14 MPa), dry and LIN) is shown in Fig. 5.

Although the tests were conducted under accelerated conditions (700 SFM/213 m/min.), the tool life patterns clearly follow similar patterns as obtained under "LIN-enhanced" cutting conditions for A2 (550 SFM/168 m/min.). Flood is clearly the worst performer, with catastrophic failure of the cutting edge under both conditions. High-pressure flood (HPF) performed marginally worse than regular low-pressure flood (LPF). Dry was the second-best performer, but generated more surface smearing and heat damage on the workpiece. Tool life with LIN was twice that of dry. More importantly, the LIN curve shows a gradual increase in feed force midway through the cut, signifying gradually increasing flank wear and consequently, a more predictable failure.

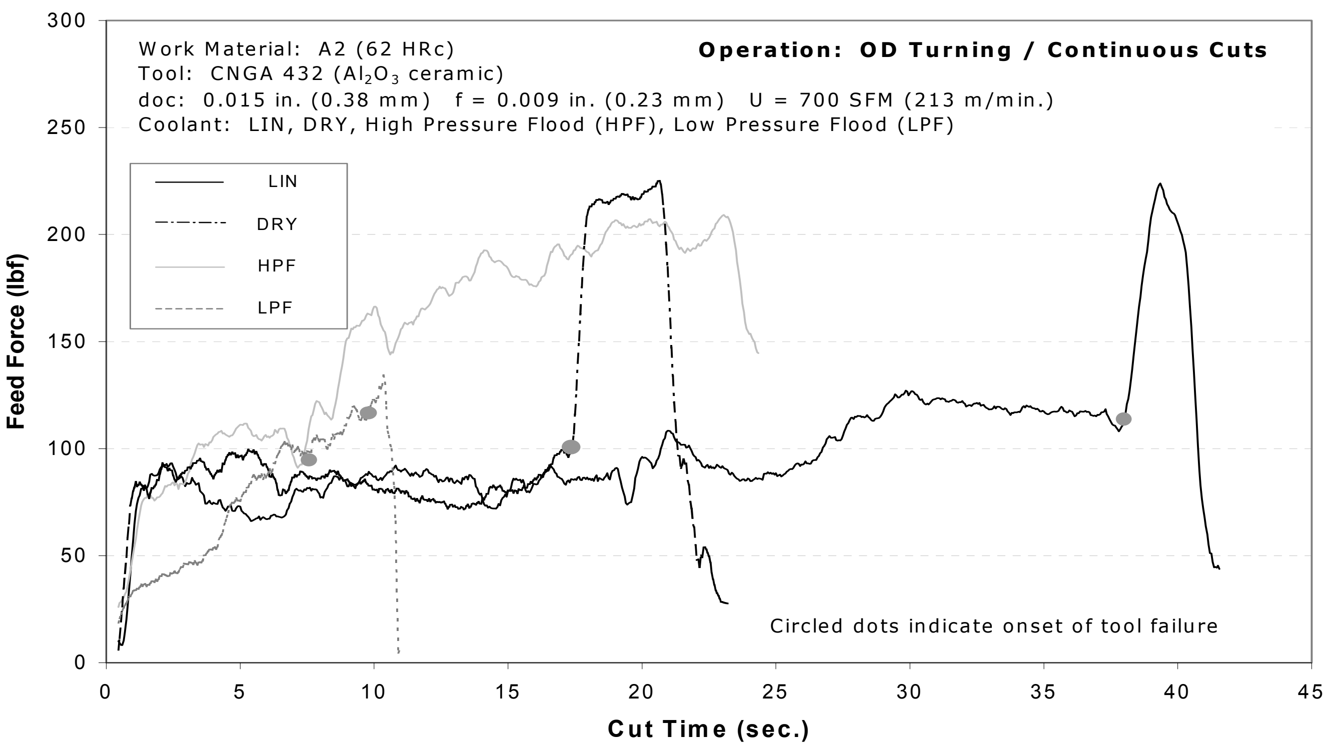
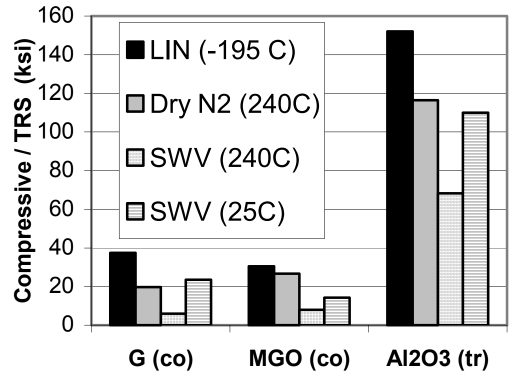


Fig. 5: Feed Force Comparison between LIN, DRY, and Flood Cooling

The incompatibility of conventional flood coolants with oxide-based ceramics has been detailed in several previous references and has also been observed during comparison tests for the present work. From available literature information, two factors are primarily responsible. Catastrophic failure of inserts has been attributed to low thermal shock resistance (Mehrotra [17], Edwards [18], D'errico et al. [19]). In addition, the interaction of moisture with oxide ceramics has been experimentally established as a primary cause for reduction in transverse rupture strength [20] (Fig. 6) and crack propagation [21]. Dry cutting is usually the operation of choice with oxide ceramics, but heat build-up at the cutting edge causes workpiece surface defects and tolerance problems in finishing. As such, oxide ceramics are typically run slower than comparable PCBN/flood combinations, and are limited to continuous roughing and semi-roughing operations.

Contrary to prior machining research and teachings on fluid coolants, a cryogenic fluid jet impinged at the rake surface does not induce fractures, chipping, or cleavage of oxide-based ceramic tool materials. While the exact reason for the obtained improvement is not clear, it is believed to be due to a combination of factors such as (1) cryogenic hardening of the entire tool material, (2) reduction in thermal expansion-driven stresses within the entire tool, and most unexpectedly, (3) reduction in thermal gradients at tool surfaces due to the boundary film effect and the *Leidenfrost* phenomenon [22]. The boundary film is a jetting-condition-controlled, semi-stagnant, transient film, which reduces the cryogenic chilling shock and prevents drastic changes in the thermal gradient at the impinged surface [23]. The Leidenfrost phenomenon occurs to a larger or smaller degree with all liquids sprayed at a target surface that is hotter than the boiling point of the liquid. In the case of cryogenic liquids, all tool surfaces are at a higher temperature than the liquid boiling point. Therefore, a typical cryo-liquid jet "slides" on a boundary film of its vapor without directly wetting the tool. This makes the thermal profile of the impinged tool surface more uniform and may explain why the free-expanding cryo-fluid jet is effective in enhancing the life of brittle tools. In the case of an oil or water-based cutting fluid, with its boiling point significantly higher than room temperature, boiling occurs only at a very close distance from the perimeter of the chip/tool contact zone, and not over the entire rake surface. When the chip changes direction during cutting, or the tool encounters a sudden cutting interruption, a conventional fluid spreads over a suddenly exposed, hot tool surface area where it boils explosively releasing vapor, micro-droplets, and pressure waves. The water vapor results in a drastic reduction in transverse rupture strength (TRS) and aids in crack propagation in the ceramic, leading to catastrophic failure.



G:Granite   MgO: MgO crystal Al_2O_3: Al_2O_3 crystal

Fig. 6: Compressive/TRS values of crystals in dry N2, LIN and saturated water vapor (SWV) [20]

With cryogenic cooling of the insert, the increase in bulk hardness is clearly evident, as it is a function of temperature. An interesting and not well-understood phenomenon is an increase in toughness of the insert. To illustrate this phenomenon, dynamometry tests were conducted, in which the load on the insert was progressively increased by increasing feed, until the insert fractured. The idea was to induce severe loading on the insert to increase tensile stress, leading to crack propagation and ultimate failure.

A constant depth of cut of 0.015 in. (0.38 mm) and cutting speed of 600 SFM (183 m/min.) were selected for the test. The starting feed was 0.004 in. (0.1 mm/rev.) and that was increased by 0.001 in. (0.025 mm) after every second in cut (Fig. 7). The insert under HPF conditions was the first to fail at a feed of about 0.011 in./rev. (feed / land = 2.75). Inserts under both dry and LPF conditions were the next to fail, both around the 0.012 in./rev. feed point (feed / land = 3.0).

An interesting aspect of the graph is the comparison of the HPF, LPF and DRY forces. Inserts under both high and low pressure flood conditions catastrophically failed with sudden, instantaneous and complete loss of the nose, and as such, failure is not preceded by a sharp increase in forces. Under dry conditions, the catastrophic failure is preceded by a large flank wear on the insert, as is evident from the rise in feed forces, before fracture. The insert under LIN cooling conditions lasted until 0.017 in./rev. (feed / land = 4.25), with gradual increase in feed forces until failure. The 42% increase in tool life over dry or flood conditions is indicative of a rise in fracture toughness of the insert. It is the authors' understanding that, thermally induced increase in compressive stresses in the body of the insert delays crack propagation through the bulk. Ordinarily, because of the low fracture toughness of ceramics, a small chipping would be sufficient to cause catastrophic failure. This is also aided by moisture, as shown from the results.

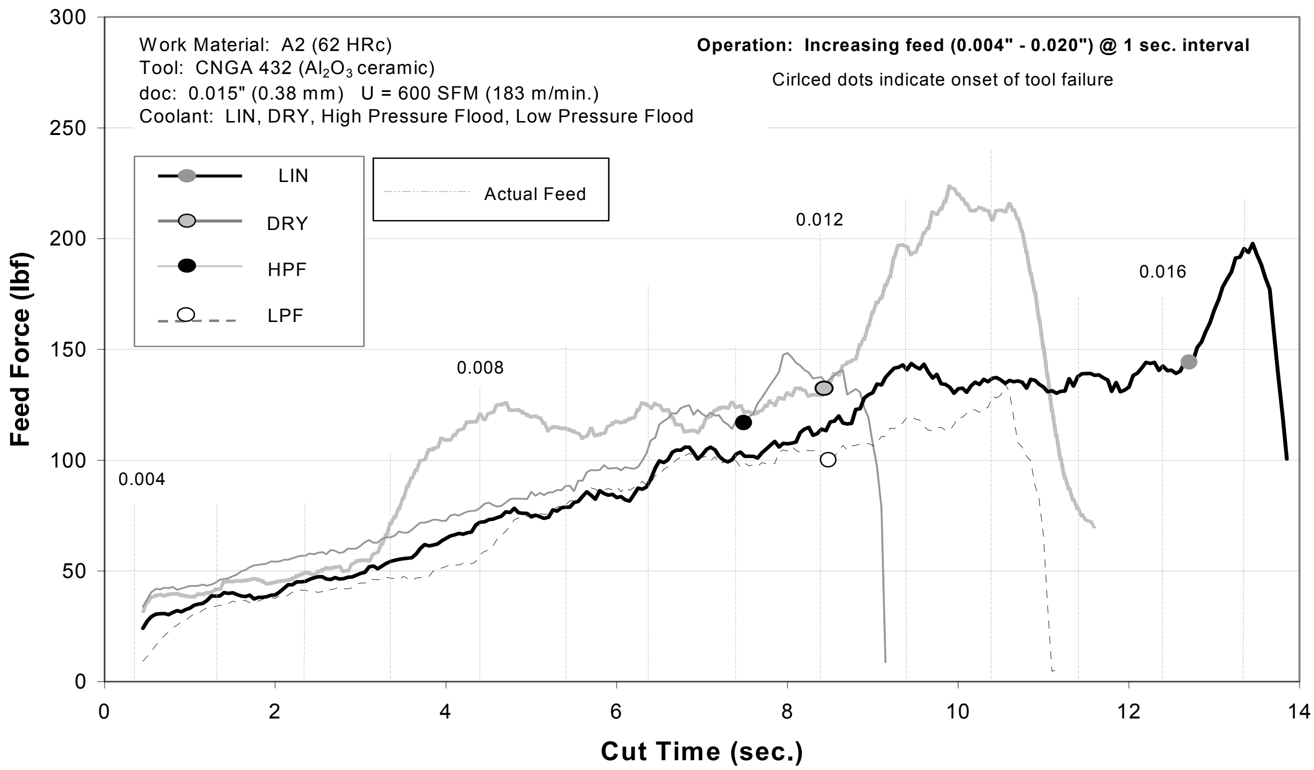


Fig. 7: Feed force comparison under variable feed between LIN, DRY, and Flood Cooling

POLYCRYSTALLINE CUBIC BORON NITRIDE (PCBN)

MACHINING TESTS WITH PCBN TOOLS

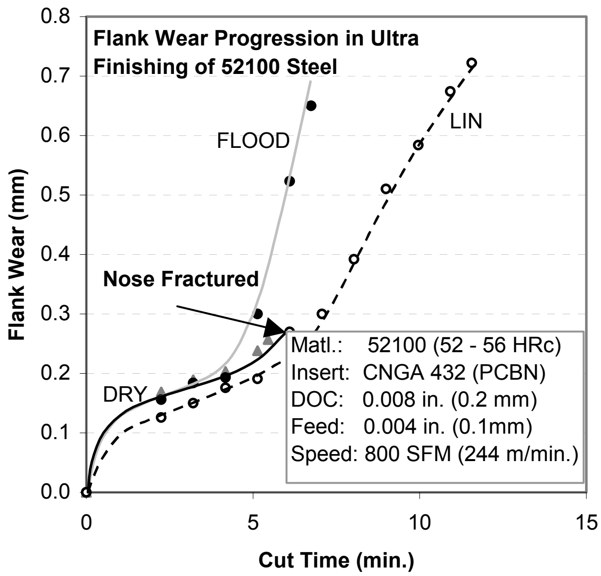
Machining tests were conducted with brazed-tip PCBN tools to compare tool life under dry, flood and LIN conditions. The test conditions were similar to oxide ceramic testing. The initial idea was to use the same cutting conditions as oxide ceramics. However, due to lack of availability of PCBN inserts with similar edge-geometry, the test conditions were slightly altered to reflect a reasonable feed/land ratio.

52100 Bearing Steel

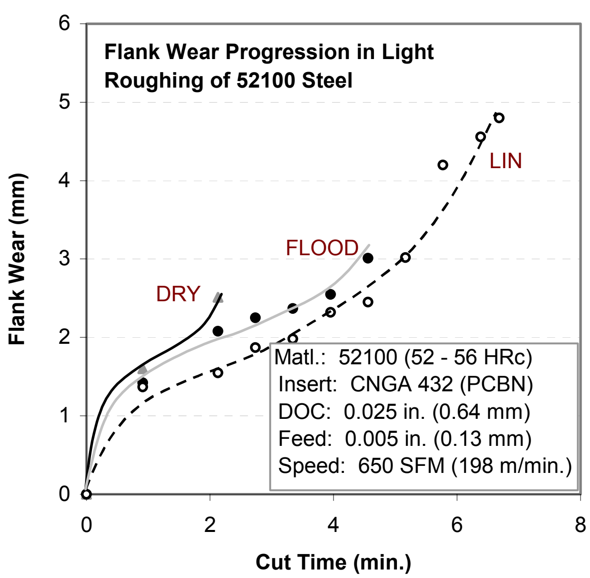
Two sets of hard turning tests were conducted on 52100 steel, involving ultra-finishing and light-roughing conditions. The tool life comparisons are shown in Fig. 8. Again, LIN clearly was better than either flood or dry in both ultra-finishing and light roughing conditions. Unlike ceramics, flood performed significantly better than dry. Tool failure was initiated by large flank and crater wear, and eventual chipping off of the brazed tip. An important understanding of the relative behavior of CBN and ceramic inserts can be seen by comparing Figs. 4 and Fig. 8(b). With a 5% higher feed/land ratio, the LIN/ceramic combination produced a 63% better tool life than the flood/PCBN combination.

POLYCRYSTALLINE DIAMOND (PCD)

A comprehensive review of mechanisms leading to the wear of diamond tools point to at least 7 most critical effects: adhesion and formation of build-up edge (BUE), abrasion including micro-cleavage, micro-chipping, fatigue fracture, tribo-thermal transformation to graphite, tribo-chemical, metal and oxidation-catalyzed graphitization, and dissolution in work material [24]. Thermal stability of diamond tools, limited to ~ 750°C, was reported to suffer further in the presence of metals reactive to carbon: Fe, Co, Mn, W, Ti, Ta, and Ni [25].



(a)

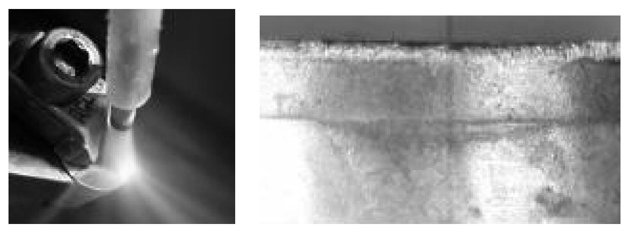


(b)

Fig 8: Tool Life Comparison in (a) Ultra-finishing (b) Light Roughing of 52100 Steel with PCBN

MACHINING TESTS WITH PCD TOOLS

Rough machining of WC-Co rolls were performed under LIN and flood cooling conditions. An external spray nozzle was used for LIN cooling, as shown in Fig. 9. Although LIN flowrate was high, it was observed that heat generated during cutting increased the temperature of the entire toolholder shank.



(a) (b)

Fig. 9: (a) LIN jetting (b) Worn tool, showing heat build-up in the braze layer

According to the industrial practice, the sharpness of the PCD tool engaged in cutting was monitored at the CNC panel by recording the spindle power or, more precisely, the spindle torque required to keep up with the cutting force developing at an increasingly dull cutting edge. Each tool life test was considered completed when the power drawn from the spindle approached or just exceeded 50% of available spindle power. Changes of spindle torque from one OD-cutting pass of the tool to another were plotted in Fig. 10 after correcting the raw readings for the change in workpiece diameter. It was observed that the wear was limited to the cutting edge area with deep abrasive grooves on the flank and a light discoloration on the rake. Thermal discoloration of the braze film under the diamond layer was also observed by the end of edge life in each test (Fig. 9(b)). Subsequent examination of worn PCD edges involved scanning electron microscopy (SEM) and elemental spot analysis using X-ray diffraction (XRD). With the high feedrate and depth of cut used in these roughing tests, chips collected were thick and serrated but cohesive, without the tendency for disintegrating into dust. Airborne dust emissions of Co and WC were not found from visual inspections of the air filters.

Spindle torque measurements (Fig. 10) indicate that cutting with LIN is less force and heat-intensive than cutting wet. The LIN-cooled tool cut about 40% more material at higher speed (120 ft./36.6 m /min.) than the flood-cooled tool (60 ft/18.3 m/min.) Also, when the flood-cooled tool was run at the same speed as the LIN-cooled tool (120 ft/min.), tool life was reduced substantially.

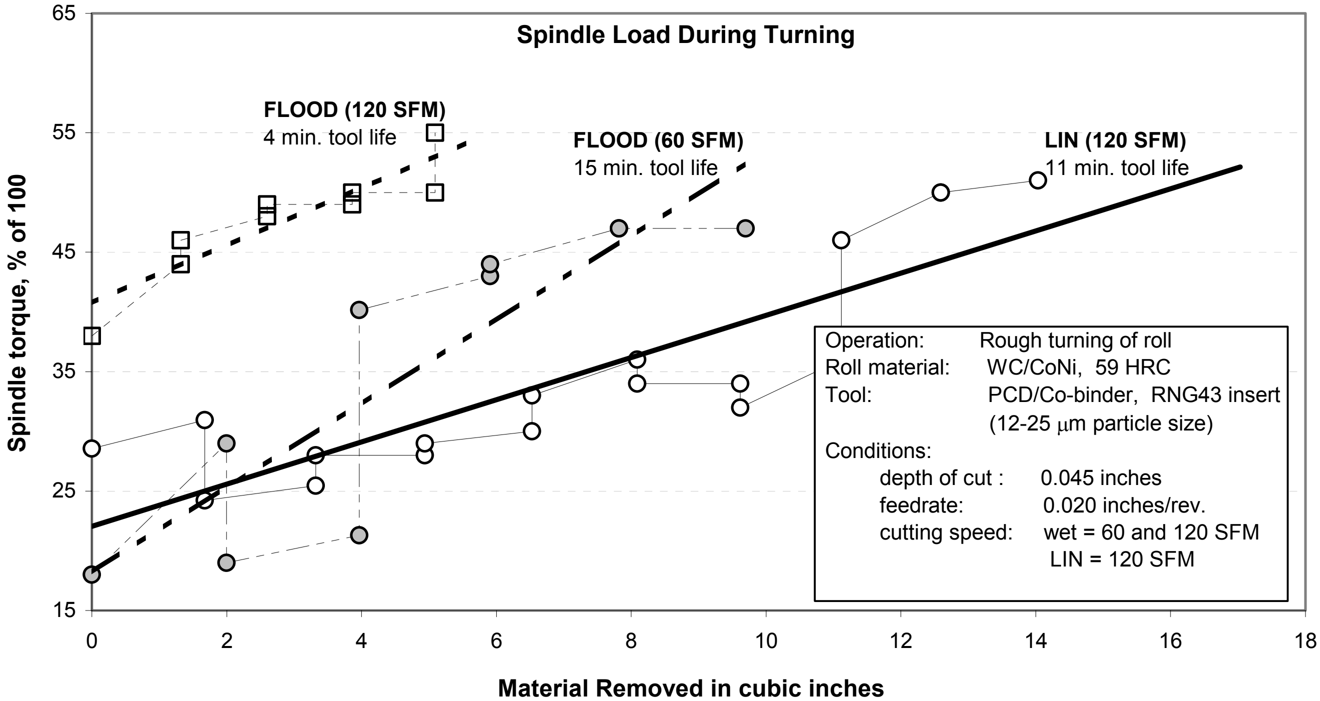


Fig 10: Spindle Load Comparison in machining of WC-Co rolls with PCD tools

Thus, the observed enhancement of PCD tool, known to be heat-sensitive, appears to result from a combination of "generic" LIN cooling as well as an unexpected effect of reducing the cutting force. In Fig. 11, the edge and rake surface stays "clean" or microcleavaged when cooled with LIN but builds-up a layer of workpiece material during wet machining. XRD tests confirm that the built-up material on the rakeface with flood cooling is primarily tungsten, whereas a cleaner surface is observed with LIN cooling. This may also explain the observed difference in the cutting forces between flood and LIN-cooled inserts.

Although the fundamental reason for the absence of chip adhesion with LIN requires further studies, it is postulated here that highly conductive PCD material "freezes" the chip underside on contact, which prevents welding between the chip and diamond particles and reduces the possibility of subsequent diamond particle pullout. Instead, the diamond particles are sheared and re-sharpened at the interface, which leads to a reduced cutting force and in turn, to a reduced heat dissipation. The mechanism of LIN "re-sharpening" of the PCD tool interface during turning of hard work materials has not been identified in the subject literature [24,25] but does complement the PCD wear mechanisms described there.

CONCLUSIONS

Cryogenic cooling of Al_2O_3, PCBN and PCD tools shows significant improvements in tool life over flood or dry operations. The performance improvement is attributed primarily, to an increase in hardness of the cutting tool and efficient heat removal from the cutting zone. An increase in toughness, a secondary effect, has also been observed. LIN-cooled oxide ceramic tools have also been shown to wear more predictably, unlike dry or flood-cooled inserts. With LIN cooling, alumina ceramic inserts showed significantly higher tool life than flood-cooled PCBN inserts under similar machining conditions. For PCD tools, the performance improvement is aided by a decrease in cutting forces, due to "clean" shearing and re-sharpening of the diamond particles. Other LIN benefits involve improvement in work surface quality, including elimination of material smearing at high cutting speeds and a reduction in surface roughness.

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