FINISH-TURNING OF HARDENED POWDER-METALLURGY STEEL USING CRYOGENIC COOLING

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ABSTRACT:

A large fraction of automotive components made of hardened powder-metallurgy steels are subject to finish-turning before final assembly. Because of a characteristically poor machinability and high surface finish requirements, the conventional P/M turning operations usually require the use of flood-cooled polycrystalline CBN tools which leads to high machining costs, P/M component contamination, and negative impact on work environment and safety. This paper examines a new, cost-effective alternative for the P/M finish-turning which involves cryogenic fluid-cooled ceramic tools and eliminates the environmental and safety issues. Presented analysis includes comparative tool-life, cutting force, and surface integrity study for the structural steel sintered to the densities of 6.7 and 7.2 Mg/m^3 and heat-treated. Experimental results show that cryogen-cooled ceramic tools live longer than CBN and offer additional work surface improvements. Technical discussion entails economic aspects of finish-turning and areas for future research.

INTRODUCTION

It is estimated that about 30% of structural components made of powder metallurgy steels require some machining [1]. Since high-volume, net-shape production methods are still more expensive than the conventional press-and-sinter route [2], finish-machining to tight tolerances is critical in the case of pressed, sintered, and heat-treated or sinterhardened parts for automotive applications. Traditional grinding of such parts has been gradually replaced by lathe-based, hardturning technologies which offer higher rates of production, lower capital and operating costs, as well as reduced environmental pollution [3-5]. The primary method of hardturning P/M parts involves cubic boron nitride cutting (CBN) tools [6] and cutting fluids [7] which assure an acceptable dimensional accuracy and surface finish on the poorly conductive, porous work material. Although already a significant improvement over surface grinding, the new approach has two inherent drawbacks: (a) the cost of CBN edge is about one order of magnitude higher than the cost of carbide, cermet, or ceramic edges, and (b) the cutting fluid, infiltrating P/M pores, necessitates additional cleaning operations in the manufacturing process. The cost of cutting tools and cutting speed limits are important in view of poor machinability of P/M parts resulting from porosity and non-uniform microstructure that frequently contains undesirable oxide and carbide inclusions [8-10]. MnS and other free-machining additives are not always successful with high-strength P/M materials [9] and may, in some cases, degrade dynamic performance and corrosion resistance of the final product. Clearly, further improvements in finish-machining of hard P/M parts require new technologies which reduce tool cost and enhance cutting speeds, eliminate contamination of work parts and environment, minimize the need for machining additives and, by the virtue of marked cost reductions, enable skipping of the entire machining operations on soft semi-products, prior to the final heat-treatment step.

A new, promising hardturning technology has recently been developed for wrought bearings steels and cast or forged, hard steel roll products which involves machining with inexpensive, Al_2O_3-based ceramic tools cooled using minute amounts of a cryogenically cold, 2-phase liquid nitrogen (LIN) [11]. It has been demonstrated that, at the same tool life, the LIN-cooled alumina ceramics can cut hard metal faster than the CBN tools cooled with the conventional cutting fluid or operated dry. LIN is an inert, clean, nontoxic, and environmentally friendly cooling fluid which evaporates into air immediately after contacting the tool surface, i.e. offers many characteristics desired for an improved P/M machining process. Thus, the main objective of the present study is to explore applicability of the Al_2O_3-LIN hardturning method in finish-turning of hard, structural P/M parts as an alternative to the conventional CBN method. Additional objectives include analysis of surface integrity and hardness/density effects during machining using both methods.

EXPERIMENTAL

Iron, graphite, copper and nickel powders were premixed to obtain the FN-0208 (MPIF) composition, pressed into P/M disks, and sintered to achieve two different density levels: 6.67 g/cm^3 (6.67 Mg/m^3), 'low-density' material, 14.5% porosity fraction, and 7.20 g/ cm^3 (7.20 Mg/m^3), 'high-density' material, 7.7% porosity fraction. Half of the disks from each density group was subsequently heat-treated for a high-level apparent hardness – at least 30 HRC in the case of the low density material, and at least 40 HRC in the case of the high density material.

Two types of cutting tools and cooling conditions were selected for machining tests on the four resultant materials: CBN tool combined with the conventional, cutting fluid cooling, and an alumina-based, Al_2O_3-TiC "black ceramic" tool combined with cryogenic, liquid nitrogen cooling. The "low-content", TiN-bonded CBN tool (BN250) used in this study was previously shown to have a fully predictable, Taylorian wear behavior in interrupted cutting of hard steels, contrasting with non-Taylorian characteristics of the earlier grades of "high-content", metal-bonded CBN tools [12]. The Al_2O_3 tool (ZC4-grade, PVD TiN-coated) used here was previously found to work extremely well with cryogenic cooling on hard, wrought steels but failed by premature fractures if the conventional, room-temperature cutting fluid was applied [11]. Cryogenic, liquid nitrogen cooling of that tool was produced by spraying its rake surface with a 2-phase jet (cold vapor and liquid droplets) boiling at –195^{o}C (77.7K), Figure 1. Details of the cryogenic supply and control system retrofit used for lathe turning were presented elsewhere [13,14].

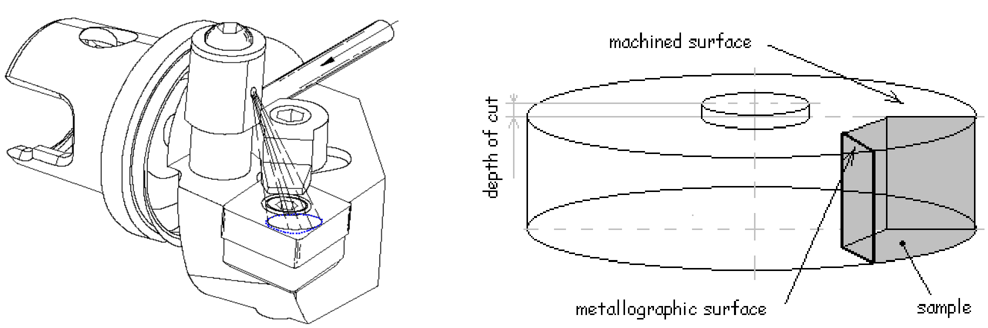


Figure 1: *Left* – toolholder mounted, liquid nitrogen nozzle and spray used for cooling cutting inserts. *Right* – method of preparing metallographic samples from machined disks of test material.

Table 1: Testing and Examination Procedures

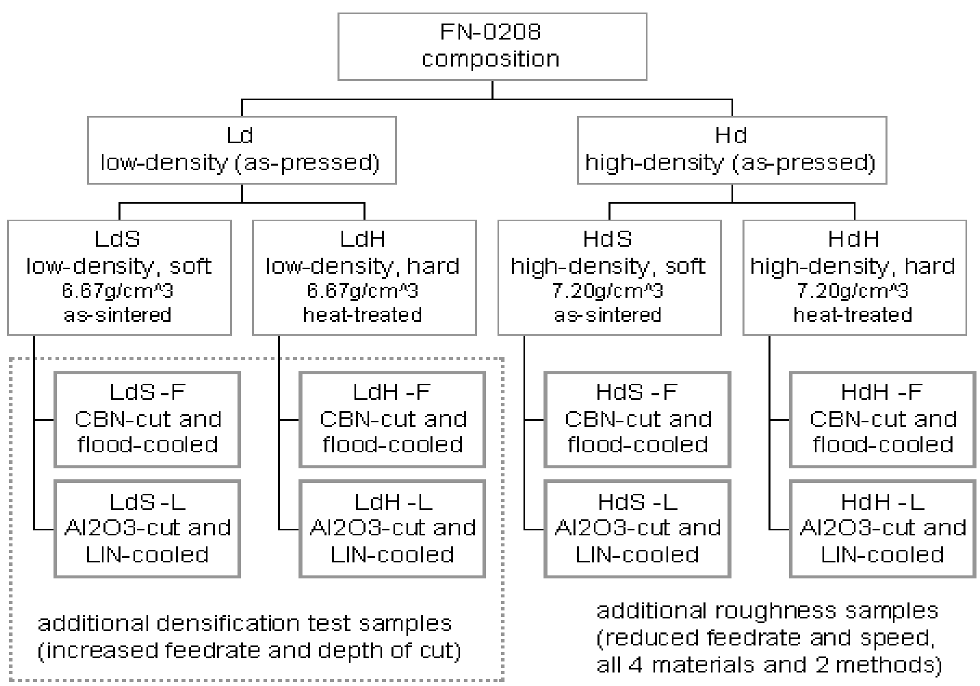
Test material	FN-0208 (MPIF-class.), composition: 0.8-0.9%C, 0.8%Ni, 2.0%Cu, bal.Fe. Pressed (with acrawax) into 1-inch thick disks and sintered to two apparent density levels: 6.67 and 7.20 g/cm^3 (6.67 and 7.20 Mg/m^3).
Heat treatment	Half of sintered disk samples, both from the 6.67 g/cm^3 group and from the 7.20 g/cm^3 group were additionally austentitized, quenched, and tempered to maximize hardness.
Tools	20 kW CNC lathe, constant speed operation. Toolholder: -5^o rake and –5^o inclination. Cutting inserts: [**1**] CBN – a “low-content” PCBN insert, grade BN250, uncoated, 2 cutting edges (popular, brazed tip type), CNMA-433, 0.005-inch land width (0.127 mm wide chamfer), -25^o+/-3^o angle. [**2**] Al_2O_3-based, fine-grained black ceramic, TiN-coated (PVD coating), 4 cutting edges, CNGA-433, 0.008-inch land (0.200 mm wide chamfer), -25^o+/-3^o angle. Note, the narrower width of the CBN land is expected to result in reduced cutting forces and less impact on work surface as compared to the Al_2O_3 insert. The use of CBN and Al_2O_3 inserts with different widths of land was dictated by the commercial availability.
Machining parameters, ‘baseline’ conditions	- cutting speed: 1,000 ft/min. (305 m/min. or 5.08 m/s) - feedrate: 0.007 inch/rev. (0.178 mm/rev.) - depth of cut: 0.008 inches (0.203 mm) - facing operation: 1 part machined = 1 facing pass through disk surface = 0.0263 min.
Cooling methods used during machining	[**1**] Flood cooling: conventional cutting fluid jetted via tubing to tool/work contact area at 20 psig (1.38 bar) supply pressure, 9% concentration in water. Flood cooling was used only with CBN inserts. Note, the use of flood cooling on Al_2O_3 inserts may result in an instant insert fracture at feedrates exceeding about half of the land width. [**2**] LIN cooling: insert cooling using a spray of boiling liquid nitrogen at –195^{o}C, 100 psig (6.89 bar) supply pressure. LIN sprays cutting insert surface via insert clamp that is modified into a compact, chip-resistant spraying nozzle. In this study, LIN cooling is used only with Al_2O_3 inserts but could be effective with the other types of tool materials.
Remarks on machining procedures	(a) Because of limited material hardenability, i.e. surface hardness gradient noted in heat-treated samples, only two cutting passes were allowed on each side of the heat-treated disk samples. No surface hardness gradient was observed in as-sintered samples where multiple cutting passes were allowed. (b) Tool life measurements were repeated in case of rapidly wearing or chipping inserts, and the reported lives are average values.
Hardness and metallographic procedures	Apparent hardness was measured on disk surfaces before machining using conventional HRB and HRC methods and, then, converted to HV scale. True or particle hardness is an average of 30 microhardness measurements on as-polished, metallographic cross-sections using Vickers 50-G-load method. Although the light-load microhardness measurements are expected to overestimate true hardness vis-à-vis apparent hardness, both hardness values are valid when comparing samples with different specific densities and heat-treatment histories. Additional comparisons of profiles of subsurface microhardness between unmachined and machined samples were corrected for the depth of material removed during machining. Scanning electron microscopy (SEM) was carried out in secondary image mode on as-machined surfaces tilted by 30^o off the normal direction. Nital etching (5%HNO_3) was used on metallographic sections normal to as-machined surface prior to optical microscopy examination for the presence of white layers generated during machining on surfaces of certain samples.
Cutting force measurement	Measurements of cutting force (F_c, tangential), feed force (F_f, radial in the present case of face cutting), and normal, force (F_n, coaxial with spindle, i.e. normal to the machined surface) were taken using a 3-component force Kistler dynamometer; the results were averaged for the time-length of the measurement. Scalar or total cutting force was calculated as: $F = (F_c^2+F_f^2+F_n^2)^{1/2}$.

Table 2: Additional Machining Tests

Work surface roughness in finish-turning	Modified machining conditions were used on all four types of work material samples to evaluate work surface roughness (Ra, arithmetic average) in a simulated superfinishing of P/M parts: - cutting speed: 500 ft/min. (152 m/min.= 2.54 m/s) – baseline reduced by 50% - feedrate: 0.0035 inch/rev. (0.089 mm/rev.) – baseline reduced by 50% - depth of cut: 0.008 inches (0.203 mm) – baseline unchanged
Work surface densification effects during machining	Modified machining conditions were used on two types of low-density samples, soft (as-sintered) and hard (heat treated), to investigate ‘in-process’ densification of as-machined surfaces: - cutting speed: 1,000 ft/min. (305 m/min. or 5.08 m/s) – baseline unchanged - feedrate: 0.012 inch/rev. (0.305 mm/rev.) – baseline increased by 71% - depth of cut: 0.014 inches (0.356 mm) – baseline increased by 75%

One set of machining parameters, or baseline cutting speed, feedrate and depth of cut (defined in Table 1), combined with the four different work materials and the two different cutting tools and coolants, were used to measure tool life and cutting forces, and produce eight unique types of samples subject to the further microstructural examination detailed above. Metallographic samples were cut from the as-machined P/M disks as shown in Figure 1. Another, less-aggressive set of machining parameters resembling typical finish-turning was used on all types of work material studied to examine surface roughness effects. Finally, the last and most aggressive set of machining parameters was used on the low-density, soft and hard materials in order to explore densification and hardening effects during machining process. Table 2 details the roughness and densification test parameters while Table 3 outlines the entire test matrix.

Table 3: Test Matrix and Sample Designation

Baseline samples (8), roughness samples (8), and sub-surface densification samples (4).	

It should be noted that the use of ultra-hard CBN and Al_2O_3 tools is necessary only in the case of hard, heat-treated or sinter-hardened P/M materials, while softer but tougher and more chemically compatible tools, such as WC/Co-carbides or TiC/TiN-cermets are more suitable for turning soft, as-sintered P/M parts, at least within the range of conventional cutting speeds. The reason for which the CBN and Al_2O_3 tools of this study are tested on hard as well as soft P/M parts is to explore the effect of work material hardness and density without changing tool materials.

RESULTS AND DISCUSSION

Fig. 2 presents apparent and true hardness of work material before machining, and Fig. 3 shows typical microstructures obtained before and after machining. The effect of cutting method (CBN-flood vs Al_2O_3-LIN) on subsurface microstructures and cutting forces was insignificant. Irrespective of material density and cutting method, all hard, heat-treated samples developed a very thin white layer at the machined surface. The presence of white layer correlates to high values of true hardness. Cutting force measurements show that white layer forms when the scalar ratio of the tool feeding force, F_f, and the normal force, F_n, to the tangential, cutting force, F_c, calculated as $R = (F_f^2 + F_n^2)^{1/2} / F_c$ is larger than 1.5. The result is consistent with research on white layers formed during hardturning of wrought steels [15] and indicates a highly localized, catastrophic shear of work material as the operating mechanism [16]. Although the effect of white layers, developed in hardturning as well as in surface grinding, on fatigue strength and other dynamic properties of machined parts is a subject of continuing debate, it is generally believed that cold-formed white layers improve part performance. Comprising highly refined, nanocrystalline ferrite and carbides [16,17], white layers may be expected to enhance surface performance of porous P/M surfaces. Nevertheless, more research is needed in this area.

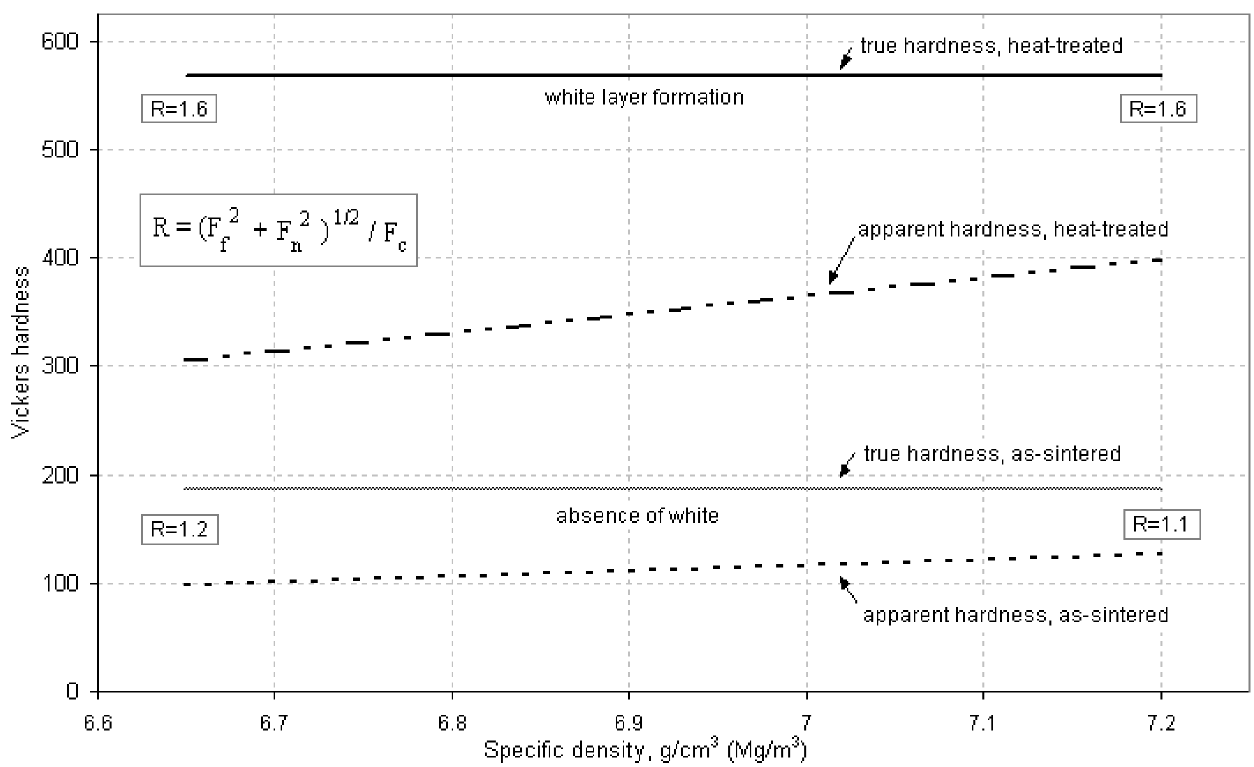
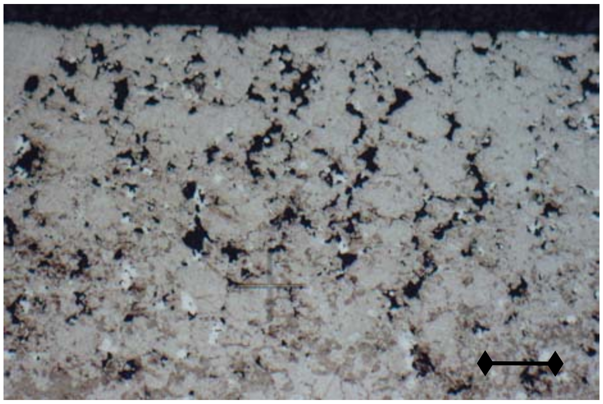
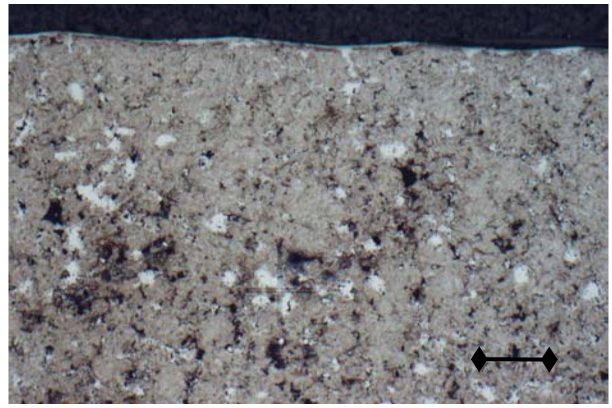
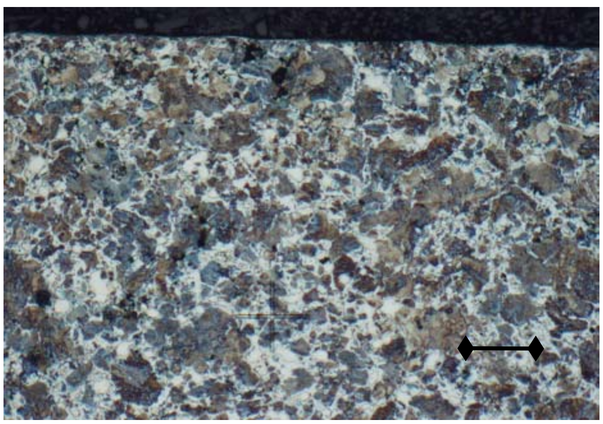


Figure 2: Apparent and true hardness vs density for as-sintered (soft) and heat-treated (hard) materials.







Upper left – unmachined LdH material (low-density, heat-treated) showing interconnected porosity protruding to the outer surface. *Upper right* – the same, LdH material after machining using an increased feedrate and depth of cut – 0.012 inches/rev. and 0.014 inches (0.305 mm/rev. and 0.356 mm). Subsurface porosity is reduced, and the surface displays a thin white layer of a poorly etching, adiabatic shear-refined material. *Bottom left* – HdS material (high-density, soft) after machining using baseline condition – 0.007 inches/rev., 0.008 inches, and 1,000 ft/min. (0.178 mm/rev., 0.203 mm, and 5.08 m/s). Machined surface is smooth, white layer-free, with evidence of interconnected, residual porosity.

Figure 3: Cross-section through P/M disk surface, etched, original magnif. x 100, bar length 240 μm.

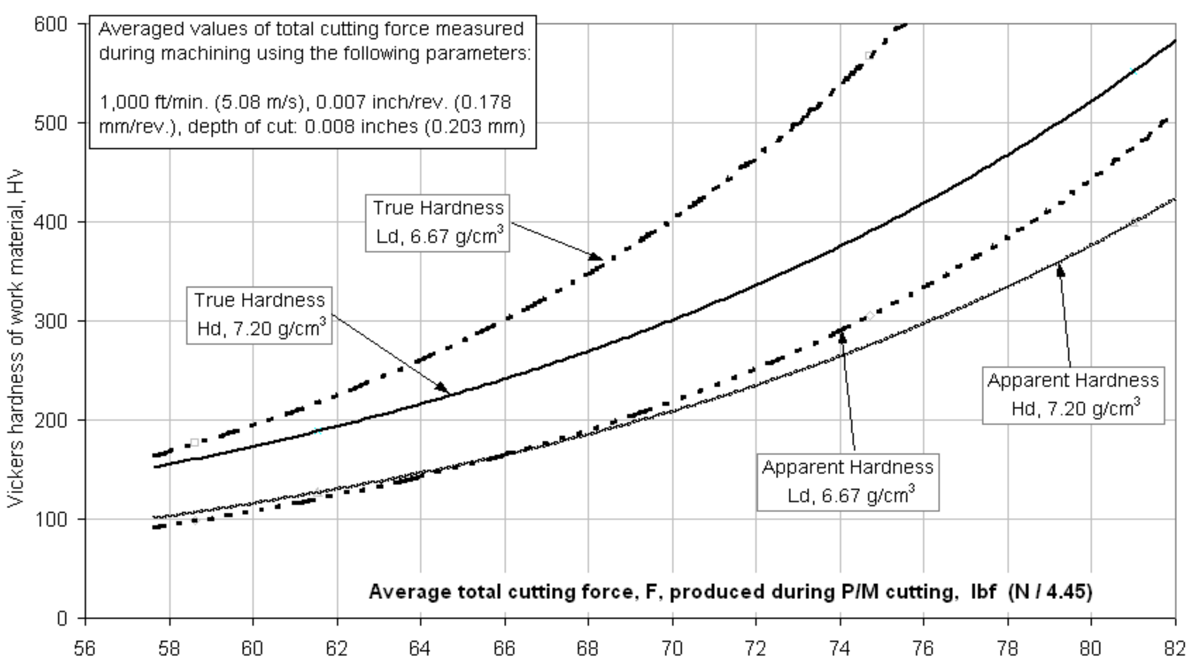


Figure 4: Total cutting force produced during cutting of as-sintered (soft) and heat-treated (hard) materials as a function of apparent and true hardness. Values are averaged for both cutting methods.

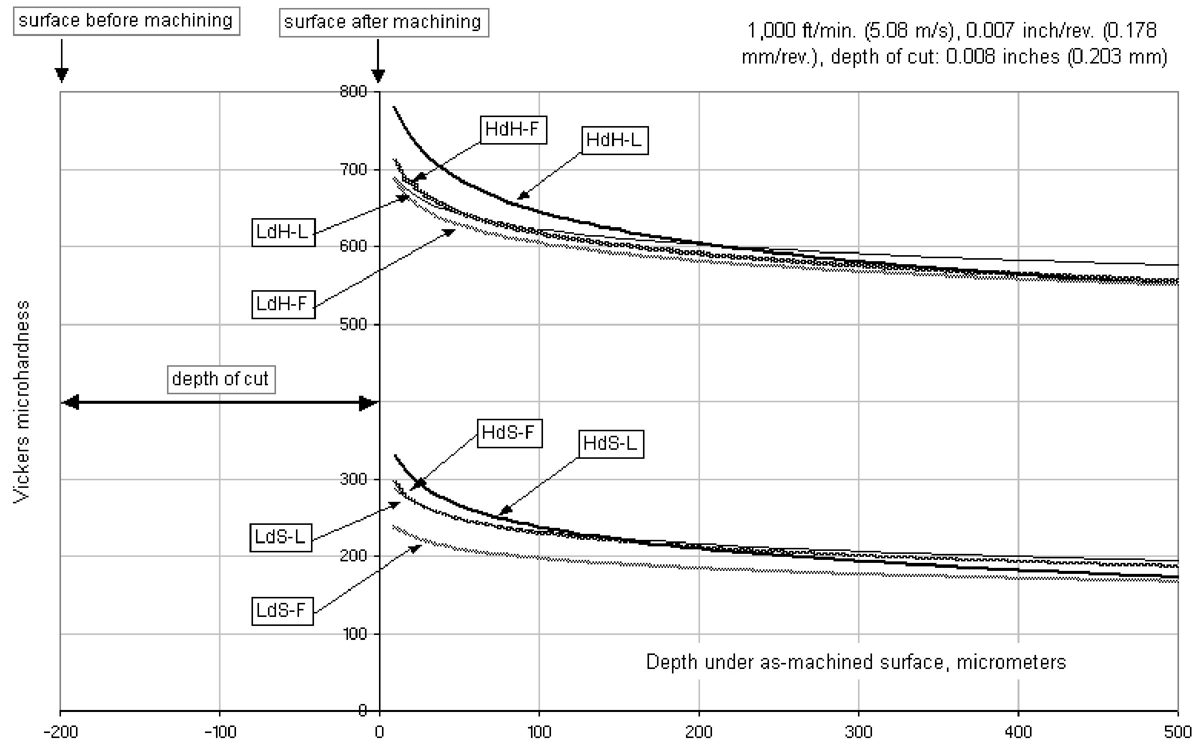


Figure 5: Microhardness profiles under as-machined surfaces of eight P/M disks.

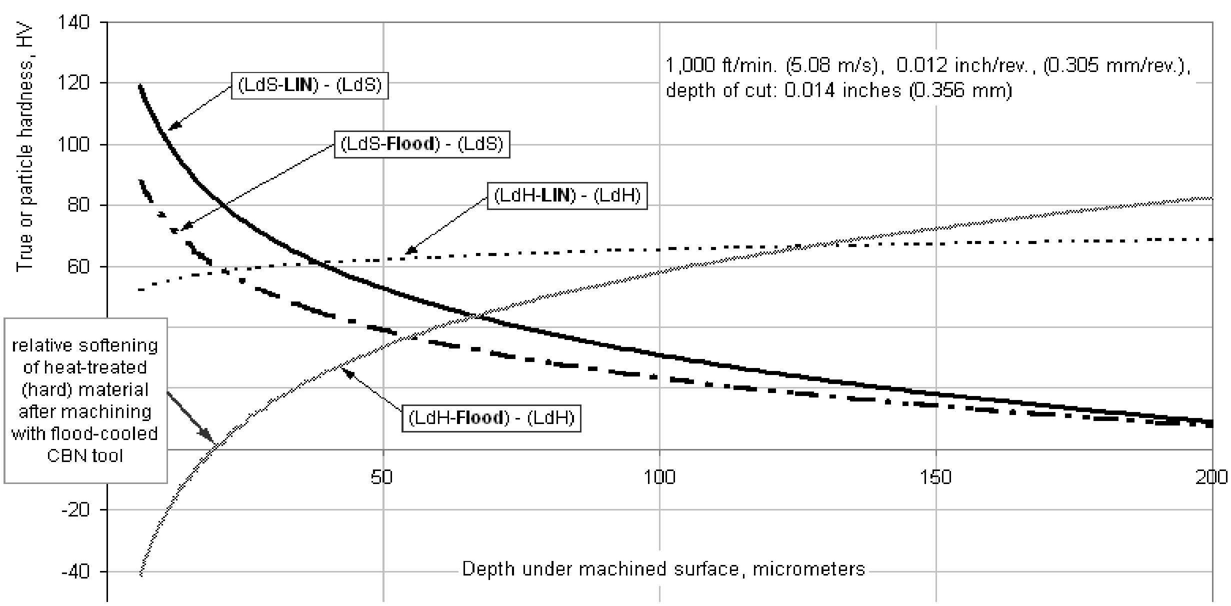


Figure 6: Subsurface hardness changes produced by heavy cutting of low-density material; calculated from the difference between the hardness of as-machined material and hardness of unmachined material at the same, absolute depth.

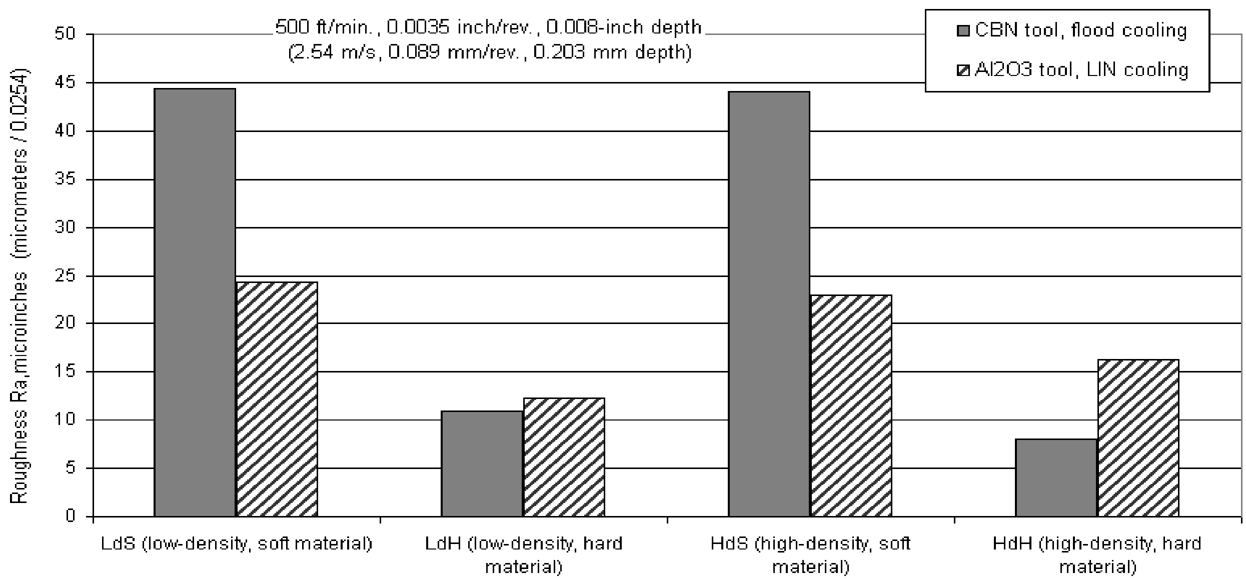
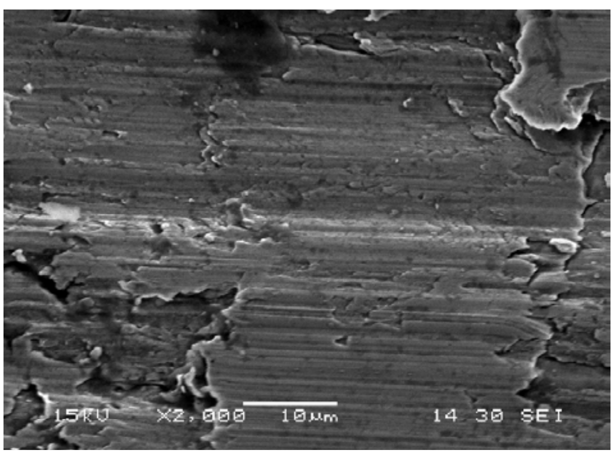
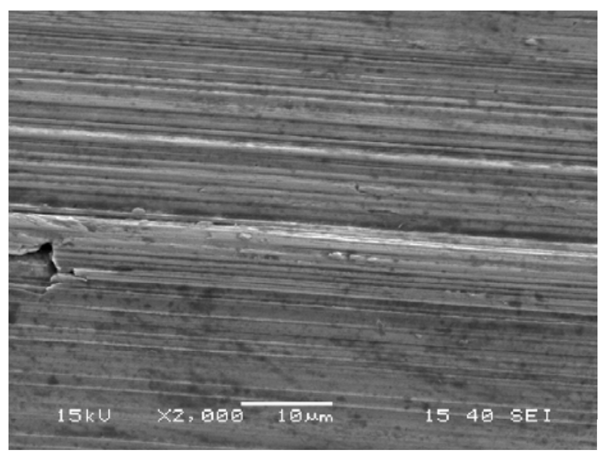
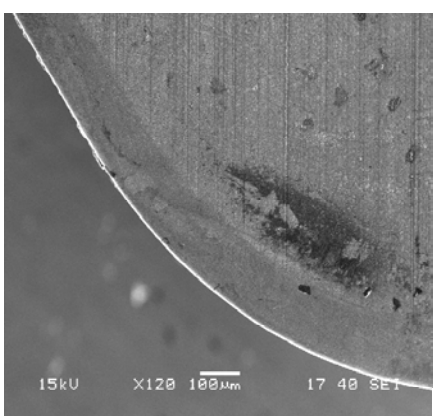


Figure 7: Surface roughness in finish-turning operation.







Upper left – As-machined surface produced with flood-cooled CBN tool, fresh cutting edge, topographic view at 30^o tilt angle, SEM original magnif. x 2,000. The white horizonal line in the middle of image is the crest between two feed-mark grooves. An uneven, plastic flow of work material and smearing around pores protruding to the surface are evident. *Upper right* – The same material and machining conditions with liquid nitrogen-cooled Al_2O_3 tool; material flow and smearing is significantly reduced. *Bottom left* – Top view of the cutting edge, land and adjacent rake area of the CBN insert which produced the surface shown on the upper left image, SEM original magnif. x 120. Absence of edge and flank wear indicate that the work material smearing and resultant surface roughness can be linked to the thermomechanical conditions under the cutting edge and not to the worn edge's profile.

Figure 8: Topography of as-machined surfaces of low-density, soft material (LdS), and an example of typical profile of cutting edge after producing these surfaces; finishing at 500 ft/min. (2.54 m/s) cutting speed, 0.0035 inch/rev. (0.089 mm/rev.) feedrate, and 0.008 inch (0.203 mm) depth of cut.

The correlation between the total cutting force, calculated as $F = (F_c^2+F_f^2+F_n^2)^{1/2}$, and work material hardness is mapped in Fig. 4. Apparent hardness of P/M material is a better force predictor even though it fails to predict white layer and tool life as it will be shown later. Following machining, both soft (LdS & HdS) and hard (LdH & HdH) materials became surface hardened, but the degree of that hardening is somewhat higher for the Al_2O_3-LIN cutting (L) than for the CBN-flood cutting (F), Fig. 5. Since higher surface hardness and density are usually associated with an improved part performance [18-21], the results suggest that the Al_2O_3-LIN cutting method may positively affect service performance. Surface hardening and densification were, thus far, reported only for cutting at much lower cutting speeds [10].

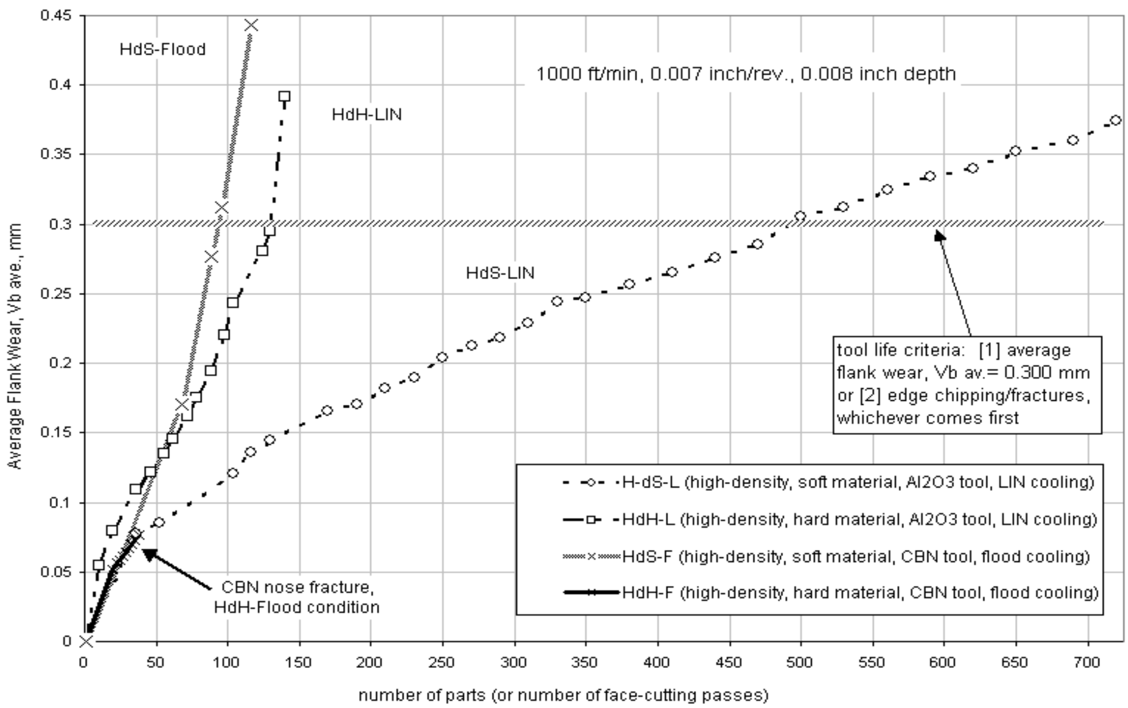


Figure 9: Tool life for high-density P/M materials, illustration of life measurement method.

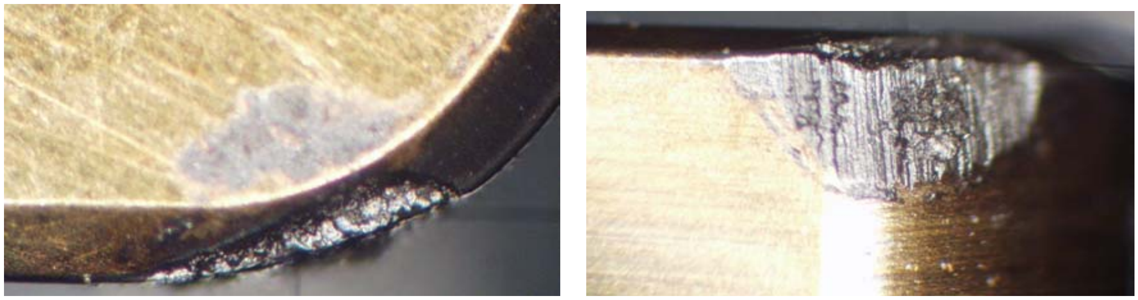


Figure 10: Top (*left*) and flank (*right*) view of a terminally worn alumina insert, original magnif. x 50. Typical wear patterns of liquid nitrogen-cooled alumina tools are uniform, fully predictable, and involve both flank abrasion and land cratering.

Contributions of thermal, densification, and work hardening factors can be inferred from the differential microhardness profiles shown in Fig. 6. and displaying the delta hardness between the machined and not machined material. As expected, the low-density material (Ld) is hardened by the combined effect of subsurface densification, evident in Fig. 3, and cold work that is apparently higher in the case of Al_2O_3-LIN cutting. However, the subsurface hardness of machined, heat-treated material is not really increasing during machining operation – the original hardness is simply retained during the Al_2O_3-LIN cutting and it drops below the original value during the CBN-flood cutting. The effect can be explained by a more effective cooling of work material in LIN machining which prevents overtempering of the heat-treated case – due to limited hardenability, the original material displays a steep hardness gradient [22] that is thermally flattened by an apparently hotter CBN-flood cutting.

Surface roughness was measured and topography examined for the machining parameters resembling typical finish-turning, Fig. 7-8. The Al_2O_3-LIN cutting was found to significantly improve surface finish in the case of soft materials (LdS & HdS) but not in the case of hard ones. In general, the finish (1/Ra) scaled with the true hardness of P/M material rather than density and, in contrast to wrought steels [23], showed less dependence on cutting edge profile. Similar, strong correlation between the surface finish and material hardness, observed in ductile and brittle-mode grinding, was analyzed using ductility index, Ξ; $\Xi = (K_{1c}/H)^2$ and $Ra \sim \Xi$, where: K_{1c} – fracture toughness and H – microhardness [24]. With the unit of length, the index is proportional to the size of plastic zone near the tip of crack forming chip. Present results indicate that a transient hardening of soft P/M material surface by LIN cooling can, apart from the conventional heat treatment, reduce the index. With the onset of adiabatic surface shearing on hard, heat-treated samples (LdH & HdH), different surface-forming mechanisms come to play which make the index less relevant. Thus, the correlations between surface roughness, tool life, force and machining conditions are not straightforward in the case of hardened P/M materials, find no explanations in the prior studies on the subject [25, 26], and require an additional, tribology and plastic deformation-focused research effort.

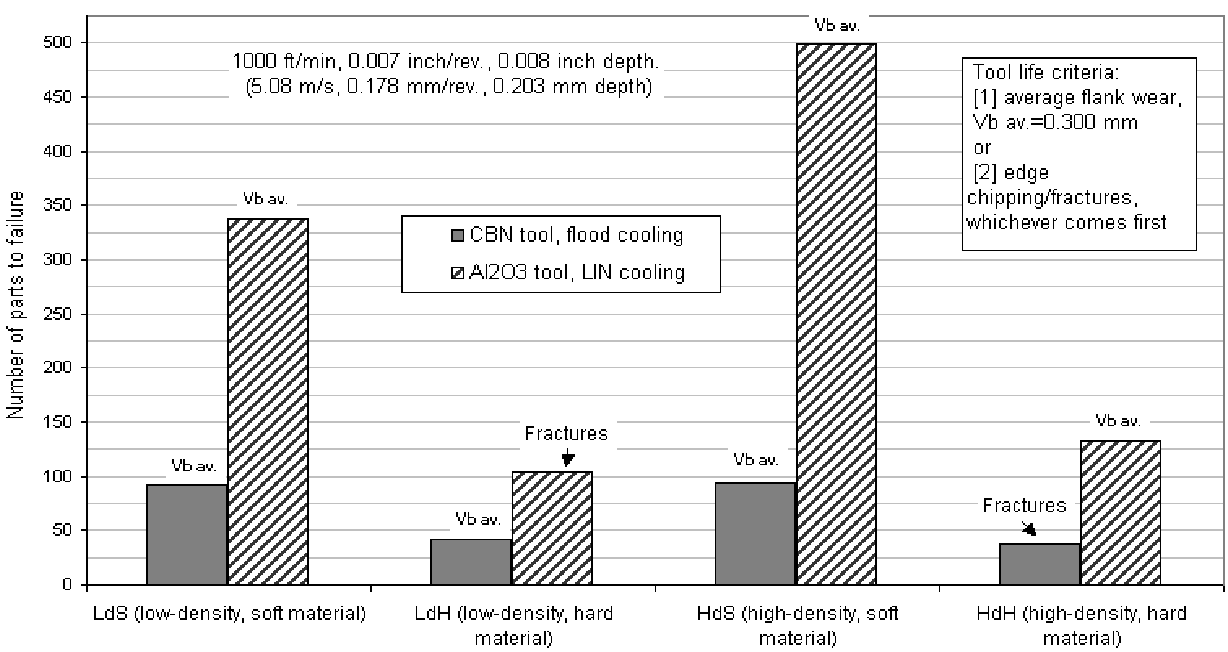


Figure 11: Effect of cutting method and properties of P/M work material on life of tool edge.

Tool life was compared for all eight baseline machining conditions using the ISO 0.3-mm, average flank wear criteria as illustrated in Fig. 9. Plotted in Fig. 11, tool life is inversely proportional to material hardness and, mostly in the case of Al_2O_3-LIN cutting, inversely proportional to porosity fraction. In spite of that additional dependence, the life of LIN-cooled Al_2O_3 tools is many times longer than the life of flood-cooled CBN tools in all examined cases. This is opposite to the reported, fracture-limited, short life of Al_2O_3 tools in dry (not cooled) machining of both soft and hard P/M materials [27-30]. Present results indicate the feasibility of cutting P/M parts faster, and without shortening of tool life, if the LIN-cooled Al_2O_3 tool is substituted for the conventional, and significantly more expensive CBN tool.

The effect of cutting method on tool life shown in Fig. 11, was replotted within the cutting force–material density coordinate system, Fig. 12. The result is surprising – the cutting force does not correlate to tool life with the change in material density or with the use of lubricating, cutting fluid. Only if the test results combining the same material-density/cooling-method samples are considered separately, tool life shows an inverse proportionality to cutting force (or hardness) as it would be expected. Thus, tool life can't be anticipated from the simple force analysis once the cooling method or work material characteristics have been changed. This conclusion shows the limited validity of the force/tool life analyses reported earlier for P/M materials [1,31], with additional implications in the other areas of machining technology.

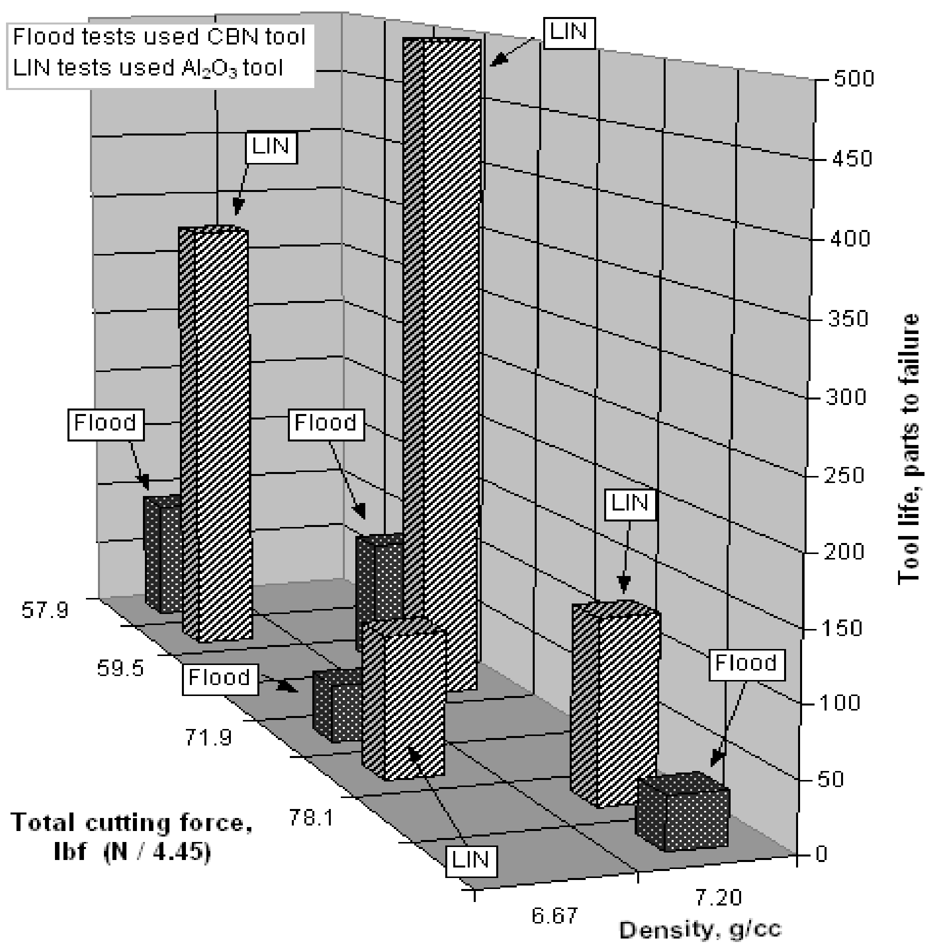


Figure 12: Tool life as a function of machining method, total cutting force, and specific density of P/M material

CONCLUSIONS

1. Cryogenic nitrogen cooled Al_2O_3-based cutting tools were found to live significantly longer than the conventionally cooled CBN tools during machining of hard and soft P/M parts characterized by low as well as high density. Thus, the use of cryogenic cooling in finishing of P/M parts enables the industry to reduce manufacturing costs by decreasing tooling costs and/or increasing productivity, reducing capital intensity required to reach specific production targets, elimination of part cleaning operations, and minimizing environmental impact of machining operations. Our subsequent field demonstration tests of the LIN-Al_2O_3 technology in the industrial production area have shown that the new hardturning economics are sufficiently favorable to eliminate the need for rough machining of structural P/M parts in soft condition which leads to the further savings.

2. The use of cryogenic cooling results in a somewhat harder and less thermally affected surface of machined part. Further research is planned to quantify anticipated performance enhancement of P/M parts machined using cryogenic cooling.

3. It was observed that with the change of work material density or tool cooling method, cutting force cannot be used to predict tool life. Cutting force was found to be a sensitive measure of apparent hardness and predict tool life only for P/M parts characterized by the same fraction of porosity and machined using the same cooling method. The observed anomaly indicates the impact of micro-interruptions on tool life during machining of P/M materials and the significance of tool cooling. Present results point to the need for enhancing the machining theory into the areas of work material microstructure and tool material cooling.

4. Formation of an adiabatic-shear, nanocrystalline white layer was observed on as-machined surfaces of all hard P/M materials analyzed regardless of their porosity fraction. Since hardturning resultant, thin white layers are typically compressively stressed, further research should focus on quantifying anticipated improvement of fatigue strength and wear resistance of hard P/M parts with white layers.

5. A strong correlation was found between true hardness of P/M parts and their surface finish which points to the effect of metal plasticity within the primary as well as tertiary shear zones. Additional, tribology and plastic deformation-oriented studies are needed here to clarify correlations to the other process parameters – cutting edge condition, tool life, cutting force, and cooling/lubricating conditions.

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