H. Low-Cost Manufacturing of Precision Diesel Engine Components

P. J. Blau and J. Qu
Oak Ridge National Laboratory
P.O. Box 2008, MS-6063
Oak Ridge, TN 37831-6063
(865) 574-5377; fax: (865) 574-6918; e-mail: blaupj@ornl.gov

DOE Technology Development Area Specialist: James J. Eberhardt
(202) 586-9837; fax: (202) 586-1600; e-mail: james.eberhardt@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

---

Contractor: Oak Ridge National Laboratory, Oak Ridge, Tennessee
Contract No.: DE-AC05-00OR22725

Objectives

- Enable the use of advanced materials such as ceramic composites, cermets, and titanium alloys in diesel engines by understanding their machining characteristics on a basic and applied level.
- Develop new, ceramic-based cutting tool materials for high-speed titanium machining.
- Work with a small business (Third Wave Systems, Inc.) in the development of software packages for manufacturers to optimize high-speed machining processes.

Approach

- Quantify the grinding characteristics of TiC/Ni_3Al matrix cermets that are promising candidates for diesel engine fuel injector plungers and wear parts.
- Investigate the possibility of using cermets as cutting tool materials for high-speed titanium machining.
- Participate with a consortium of manufacturers led by Third Wave Systems, Inc., to develop finite-element analysis (FEA)-based machining modeling software and to acquire new machining process modeling capabilities.

Accomplishments

- Worked with a visiting faculty member from Louisiana State University to study the effect of wheel condition and grinding parameters on the machinability of Ni_3Al-bonded advanced composites with varying amounts of titanium carbide particles.
- Worked with the University of Michigan and the ceramic processing staff at Oak Ridge National Laboratory (ORNL), to prepare, characterize, and test experimental cermet composites as possible tooling inserts for the high-speed machining of titanium alloys.
- Tested and helped to evaluate a new software package designed to optimize high-speed drilling of titanium alloys.

Future Direction

- The current project ended in FY 2005. A new effort on synergistic process-enhanced grinding of advanced materials is planned to begin in FY 2006.

Introduction

Manufacturing broadly comprises the conversion of raw materials into useful products. It encompasses a broad range of engineering disciplines and unit processes, including machining and finishing. Since the industrial revolution of the late 1800s, U.S. industry has invested hundreds of billions of dollars in the development of manufacturing technology to promote economic health and security. However, with the continuing egress of manufacturing facilities to foreign soil, needed improvements in domestic manufacturing facilities and the knowledge base to develop new machining technology has been eroding. The machine tool industry in the United States has largely closed up shop, and most new machine tools are made by foreign sources. It is vital therefore, to avoid full dependence on foreign sources, to promote applied machining science within the United States.

Driven by the high price of fuel and increasingly stringent emissions regulations, the diesel industry is revising its engine designs. Some of these designs could benefit from the use of high-performance materials, but the ability to machine these hard, durable materials cost-effectively becomes a key enabler. Therefore, the current project is intended to enable the introduction and use of advanced materials for diesel engine components by better understanding and optimizing their machining characteristics.

Approach

Three tasks addressed new machining technology for diesel engine components. The first two are experimental studies and the latter an effort in modeling with experimental verification.

- Characterizing the machining characteristics of advanced composite materials containing an intermetallic-alloy binder with hard carbides.
- Developing and testing new cutting tool materials for machining lightweight alloys for fuel-efficient heavy vehicles.
- Working with software developers to test new process-specific computer modeling packages for machining of advanced materials.

Results

Grindability of TiC-Ni_3Al cermets

TiC-Ni_3Al metal matrix composites containing 40–60 vol % Ni_3Al were developed as candidate materials for diesel fuel injector plungers. They possess good mechanical properties and have thermal expansion coefficients similar to those of the steel typically used for injector bores. Previous studies have confirmed their high scuffing resistance in fuel-lubricated environments. However, cost-effective machining of these composites requires the achievement of a high material removal rate (MRR). That is difficult due to their relatively high toughness and the distribution of hard phases in the microstructure.

Working in collaboration with Prof. W. Liao, Louisiana State University, creep feed and conventional surface grinding characteristics of a TiC-Ni_3Al (50 vol %) composite were studied and compared with two baseline ceramic materials, alumina and silicon nitride. The investigation was conducted using an instrumented grinder with a 220-grit resin-bonded diamond wheels using the grinding conditions in Table 1. Selected properties of the workpiece materials and the measured maximum MRRs are shown in Table 2. The composite is tougher but lower in hardness than the two ceramics, but it had a much lower maximum MRR than alumina.

Table 1. Grinding conditions

Wheel diameter (mm)	228.6
Grinding width (mm)	11.43
Wheel speed (rpm)	4500, 2500
Depth of cut (mm)	0.051, 0.254, 1.016, 1.27
DOC[a] × work speed (mm^2/min)	164, 254, 328, 645

[a]DOC = depth of cut

Table 2. Hardness, toughness, and maximum MRRs

Material	Vickers microindentation hardness (GPa)	Fracture toughness ($MPa\text{-}m^{1/2}$)	Maximum MRR (mm^3/s)
$TiC\text{-}Ni_3Al$ (50 vol %)	9.5	12	62.5 for conventional[a] 48.4 for creep feed[b]
Si_3N_4	19.4	5	(Not measured)
Al_2O_3	24.8	3–4	>125

[a]Reciprocating surface grinding with relatively shallow DOCs.
[b]Deeper DOCs but with a slower feed rate.

Grinding forces, spindle power, vibration, and acoustic emission signals were monitored and analyzed. In general, the cermet required higher grinding forces and spindle power than the two ceramics for a given MRR (see Figure 1), but it also exhibited the best surface finish (see Figure 2). Higher fracture toughness is likely to be responsible for both results because it requires more power to overcome the higher toughness, but it also leads to less microfracturing of surface.

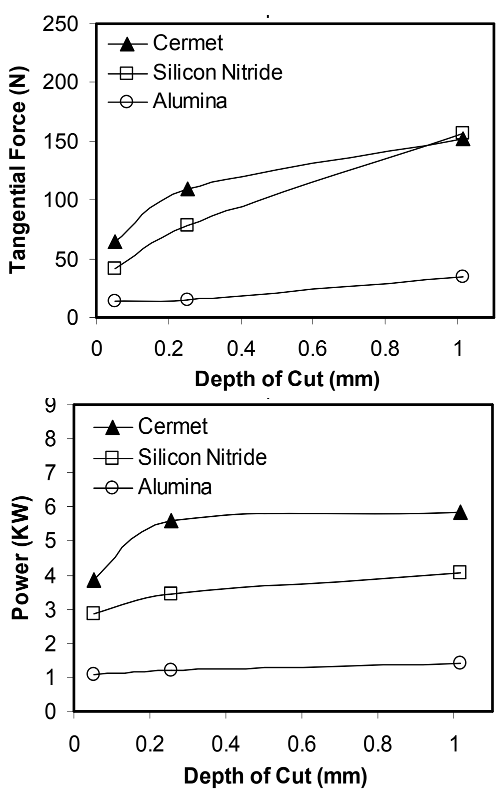


Figure 1. Grinding forces and power of grinding different work materials in steady-state wheel condition (MRR = 48.4 mm^3/s).

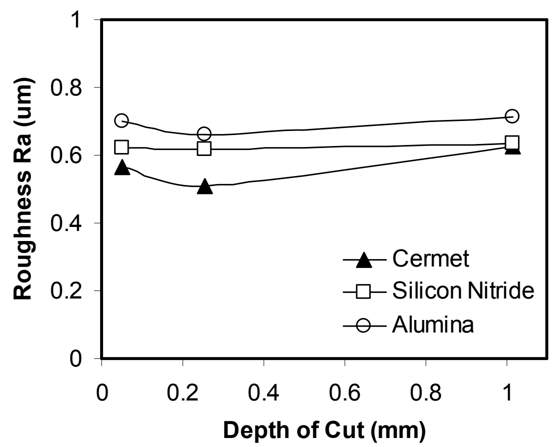


Figure 2. Arithmetic average surface roughness of different workpiece material surfaces ground under steady-state wheel conditions at a MRR of 48.4 mm^3/s.

Scanning electron microscopy (SEM) revealed the response of the cermet surfaces to differing degrees of grinding severity. More surface and subsurface damage occurred for creep feed grinding than for conventional grinding. However, no excessive cracking or pull-out of TiC particles was observed (see Figure 3). This indicates good bonding between the Ni_3Al matrix and the hard TiC particles that appear darker gray in the image.

New Cutting Tools and Process Modeling for High-Speed Titanium Machining

Experimental Cutting Tool Materials: Two $TiC\text{-}Ni_3Al$ cermets with 5 vol % and 9 vol % matrix material, respectively, were prepared with the cooperation of T. Tiegs at Oak Ridge National Laboratory. Their microindentation hardness is compared to that for a commercial WC-Co (6 vol %) tool

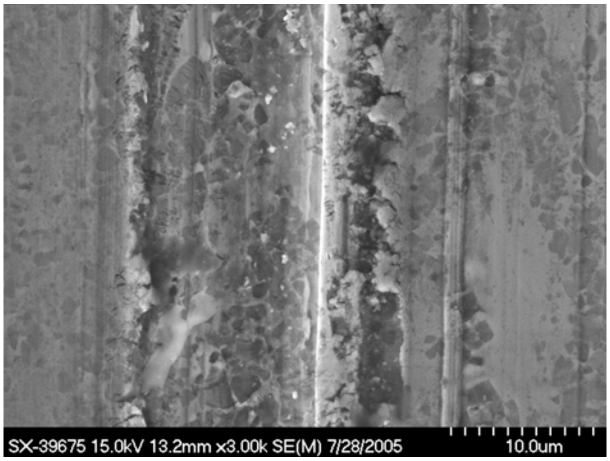


Figure 3. SEM image of a ground cermet surface showing one of the deeper cutting grooves. Ductile tearing is evident on the ridges of the groove, but there is little evidence for TiC particle pull-out.

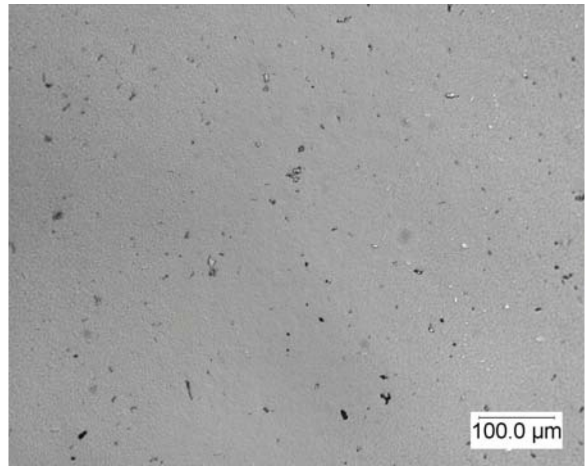
insert in Table 3. Figure 4 shows a more uniform and less porous microstructure for the TiC-Ni_3Al (9 vol %) composition than for the TiC-Ni_3Al (5 vol %).

Tool inserts for turning were prepared in the triangular shape shown in Figure 5. The material was cut by four-axis wire electro-discharge tapered sides and corners were manually polished by 600 grit SiC abrasive paper to remove the EDM recast layer.

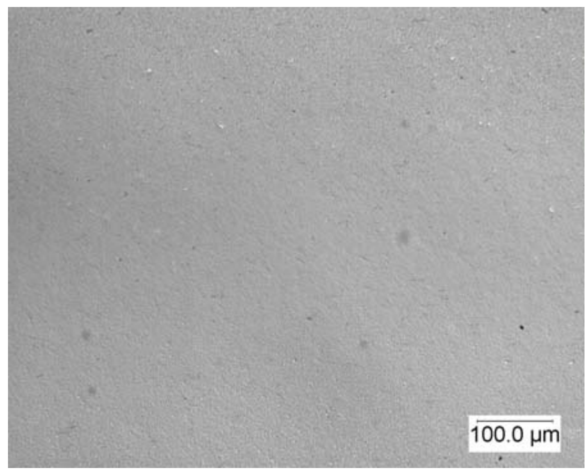
These TiC-Ni_3Al tool inserts were used to turn Grade 2 (commercially pure) titanium at University of Michigan (UM) using 80-, 160-, and 640-ft/min cutting speeds, 0.01-in./rev feed rate, and 0.04 in. DOC. Compared with commercial WC-Co tools, the TiC-Ni_3Al tools showed moderately higher cutting forces. This could partially be due to the imperfect tool geometry and low sharpness of the manually polished cutting edges. The tool wear and tool life issues were also briefly studied at UM. Table 4 summarizes these results. Unlike the progressive wear on the WC-Co tool, chipping was the dominant failure mode of the TiC-Ni_3Al tools, especially at

Table 3. Microindentation hardness comparison

Material	HV (GPa, 200 g)
TiC-Ni_3Al(5%)	20.6
TiC-Ni_3Al(9%)	17.3
WC-Co(6%)	18.5



(a) TiC-Ni_3Al (5 vol %)



(b) TiC-Ni_3Al (9 vol %)

Figure 4. Microstructures of TiC-Ni_3Al cermets.

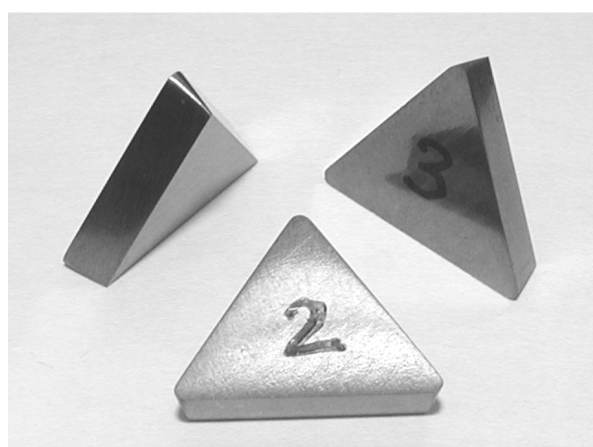


Figure 5. Tool inserts made of TiC-Ni_3Al cermets.

Table 4. Tool life in machining of titanium

Tool life (s)	Cutting speed (ft/min)		
	80	160	640
$TiC\text{-}Ni_3Al$ (5%)	245.3	18.4	15.3
$TiC\text{-}Ni_3Al$ (9%)	*Not tested*	>294.4	9.2 (tip 1) 33.7 (tip 2)
WC-Co	*Not tested*	*Not tested*	69

machining (EDM), the top and bottom surfaces were ground by a diamond grinding wheel, and the high cutting speeds. Due to the high porosity as shown in Figure 4(a), $TiC\text{-}Ni_3Al$ (5 vol %) tools broke at all cutting speeds. The $TiC\text{-}Ni_3Al$ (9 vol %) tools survived at 160 ft/min with progressive wear after 294.4 s, but broke fairly quickly at 640 ft/min. The wide variability in tool life (9.2 and 33.7 s at high cutting speed) for $TiC\text{-}Ni_3Al$ (9 vol %) tools suggests either nonuniformity of the microstructure or inconsistent cutting edge sharpness, or both. The performance of the $TiC\text{-}Ni_3Al$ (9 vol %) tools might be improved by automated production grinding, but in light of the current results and the fact that the current project is ending, no further studies of this material are planned.

Machining model testing and verification: Work continued on the testing and validation of software for high-speed machining. Good correlations have been obtained between computer modeling using Thermal Wave Systems (TWS) *AdvantEdge*™ software and lathe turning experiments.

For example, in titanium machining, cutting chips are known to catch fire when their temperature rises above about 1200°C. The TWS *AdvantEdge*™ was used to simulate chip ignition in titanium turning. Machining simulations and verification experiments were conducted on a Ti-6Al-4V workpiece using a Micrograin AR6 (WC-Co) tool. The feed rate was 0.1 mm/rev, and DOC ranged from 30 and 75 µm. Table 5 data show very good agreement between the simulation and the experiments. The simulated temperature profiles of the titanium chips at different DOCs are illustrated in Figure 6.

Characterization of tool coatings: The physical, mechanical, and thermal properties of the tool coatings significantly affect the cutting performance and tool life. Selected production tool coatings have been characterized to provide input for machining models. The data are given in Table 6. The coating thickness and microstructure were examined by SEM as shown in Figure 7. There was a relatively large range of coating thickness (2.5–6.0 µm), despite the manufacturers' claims that they were all supposed to be 3 µm. Nanoindentation showed similar hardness and lower modulus of elasticity of these coatings compared to that of the WC substrate. The thermal conductivities of these thin coatings were measured using a new photoacoustic technique at the Microscale Thermophysical Properties Laboratory at Purdue University. All coatings exhibited

Table 5. Simulation and experimental results for titanium chip ignition

DOC (µm)	30	75
Simulation	No ignition (Chip T_{max} < 1000°C)	Ignition (Chip T_{max} > 1400°C)
Experiment	No ignition	Ignition

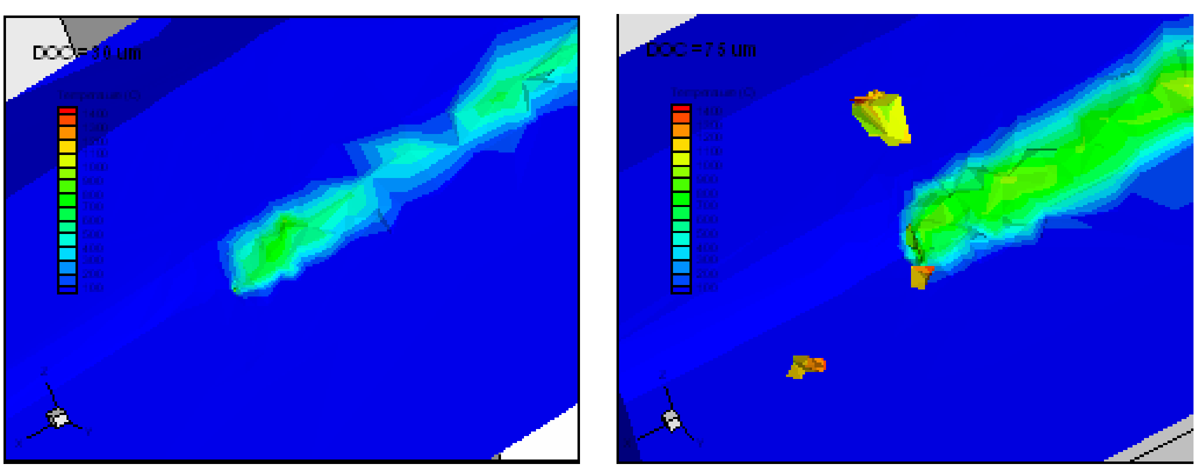


Figure 6. Simulation of titanium chip ignition (left: no ignition left, right: ignition).

Table 6. Physical, mechanical, and thermal properties of tool coatings

Grade (kennametal)	Tool insert material	Coating characteristics			
		Thickness (μm)	Nanoindentation		Thermal conductivity (W/m-K)
			H[a] (GPa)	E[b] (GPa)	
K313	WC-Co (6% Co)	—	23.2	545.2	80.99
KC730	K313+PVD **TiN**	2.5	23.1	408.5	18.69
SP39AH	K313+PVD **TiCN**	6.0	25.5	448.7	17.53
KC5010	K313+PVD **TiAlN**	3.0	25.0	355.3	1.86

[a]H = nanoindentation hardness number.
[b]E = elastic modulus obtained from nanoindentation.

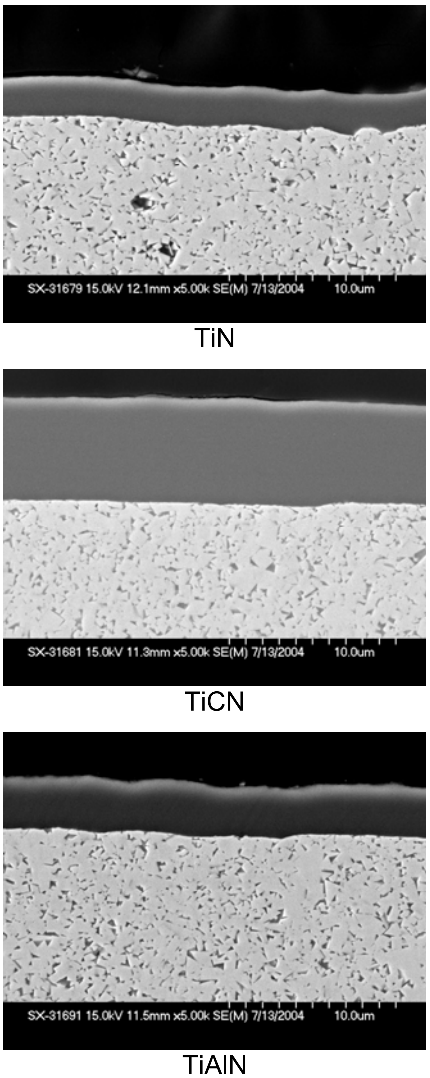


Figure 7. Cross sections of tool coatings clearly indicated a variation in thickness.

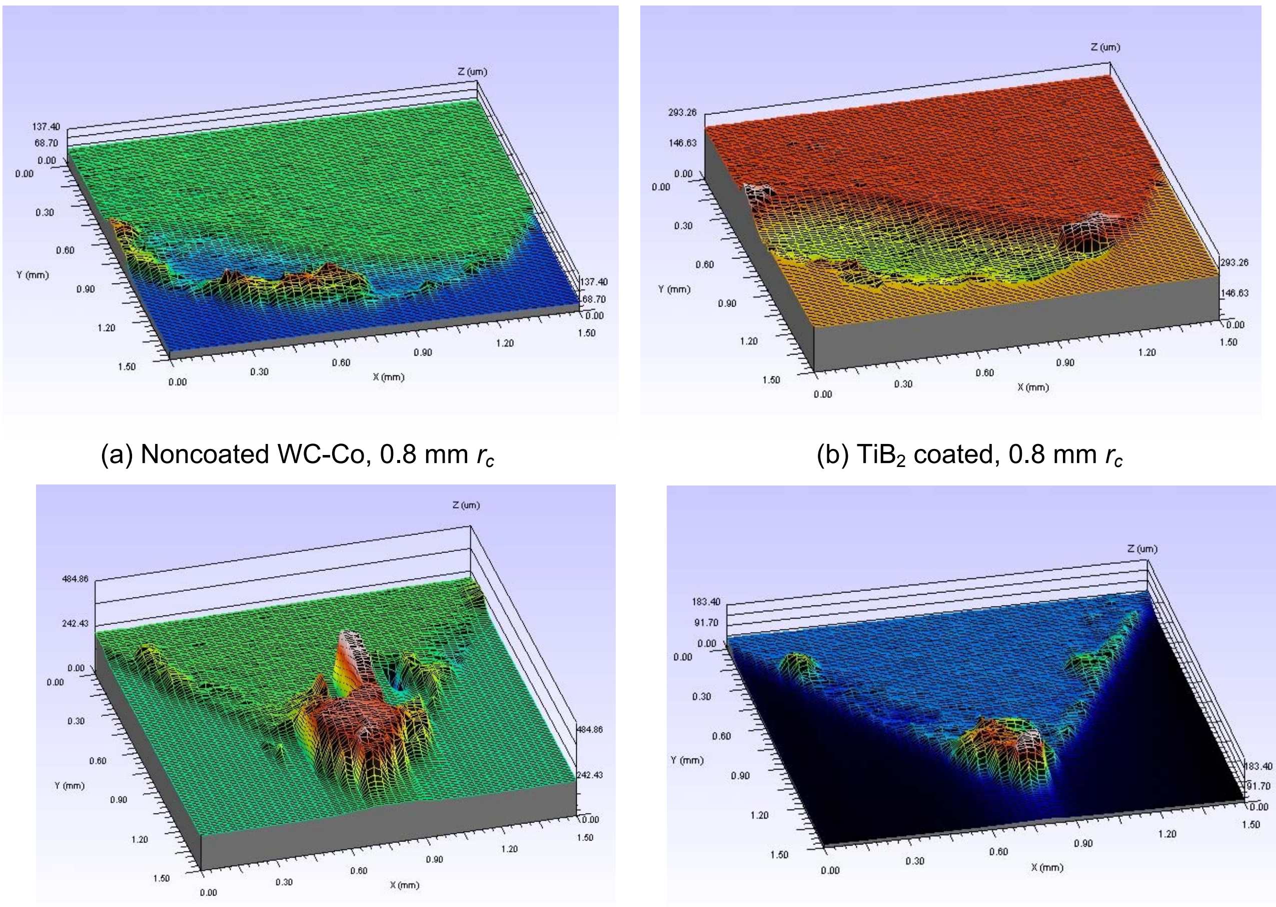
much lower thermal conductivity than the WC substrate. Results imply that the longer tool lives obtained from the coated tools were not due to better thermo-physical properties (they were actually worse than the substrate), but from improved tribological characteristics, such as less adhesion to reduce edge buildup. The latter is described in the next section on tool wear characterization.

Tool wear characterization: In titanium machining, the high tool wear, particularly "diffusion wear," significantly limits the cutting speed and tool life. The wear of four turning WC-Co based tools with different coatings and/or corner radii was measured and characterized. The four tool inserts were collected at the point of tool failure (dramatic increase in the cutting force) in titanium machining, as shown in Table 7.

The wear patterns on tool tips were mapped by laser profilometry (Rodenstock RM600). Results are shown in Figure 8. Different "tool failure" mechanisms were observed: the tools with 0.8-mm corner radius showed high crater wear [Figures 8(a) and 8(b)], while the 0.1-mm corner radius tools failed because the work material transferred and built up on the cutting edge. Energy dispersive X-ray analysis confirmed a high titanium concentration on the builtup material. The volumes of the crater wear and edge buildup were then quantified using the True Map™ 3D image analysis package, and summarized in Table 7. The TiB_2 coated tool (0.8 mm r_c) had slightly higher wear rate compared to the noncoated tool, but last much longer. That is possibly due to its slower rate of edge buildup, which dramatically reduces the edge sharpness and causes high adhesion to the work material. For a corner radius of 0.1 mm, the TiB_2 coated tool significantly outperformed the TiAlN coated tool due to the much lower edge buildup rate, as shown in Table 7.

Table 7. Tool wear results

Tool coating	Corner radius r_c (mm)	Tool life (s)	Crater wear rate (mm^3/s)	Edge buildup rate (mm^3/s)
N/A	0.8	69	1.0×10^{-4}	0.4×10^{-4}
TiB_2	0.8	199	1.3×10^{-4}	0.1×10^{-4}
TiAlN	0.1	38	—	11×10^{-4}
TiB_2	0.1	115	—	0.9×10^{-4}



(a) Noncoated WC-Co, 0.8 mm r_c

(b) TiB_2 coated, 0.8 mm r_c

(c) TiAlN coated, 0.1 mm r_c

(d) TiB_2 coated, 0.1 mm r_c

Figure 8. 3-D profiles of the worn tool tips.

Presentations and Publications

R. Li, A.J. Shih, and J. Qu, "High Speed Machining of Titanium at ORNL/UM," 2005 Third Wave AdvantEdgeTM International Users' Conference, Dearborn, Michigan, May 4, 2005.

J. Qu, T. W. Liao, P. J. Blau, J. E. Shelton, and T. N. Tiegs, "Grindability of TiC-Ni_3Al Metal Matrix Composites," to be presented at The 30th International Conference & Exposition on Advanced Ceramics & Composites, Cocoa Beach, Florida, January 22–27, 2006.