G. Low-Cost Manufacturing of Precision Diesel Engine Components

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

DOE Technology Development Area Specialist: Dr. Sidney Diamond
(202) 586-8032; fax: (202) 586-1600; e-mail: sid.diamond@ee.doe.gov
ORNL Technical Advisor: D. Ray Johnson
(865) 576-6832; fax: (865) 574-6098; e-mail: johnsondr@ornl.gov

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Objectives

- Develop and demonstrate optimized, cost-effective fabrication processes for producing precision components for use in diesel engines.
- Develop and demonstrate optimized, cost-effective methods to detect, characterize, and minimize machining-induced damage in advanced materials for engine components.

Approach

- Collaborate with manufacturers and suppliers of heavy vehicle engine components to identify enabling technologies for the cost-effective machining of precision components, such as valves, valve guides, and fuel injection system components, from advanced materials.
- Utilize Oak Ridge National Laboratory's (ORNL's) instrumented machine tools and dimensional metrology and surface characterization instruments to correlate the microstructures of advanced materials with their machining characteristics.
- Work with a consortium of software developers and component manufacturers to develop improved models for high-speed machining of titanium alloys.

Accomplishments

- Developed a method to measure the wear of super-abrasive grinding wheels that use "witness blocks" of easy-to-machine material to profile worn and unworn areas of the wheel.
- Machined silicon nitride engine valves from dimensionally-characterized starting blanks provided by Caterpillar Corporation.
- Initiated a new project to correlate the microstructure and hard particle concentration of cermets with their machining behavior.
- Joined and participated in a consortium led by Third-Wave Systems (TWS) to model high-speed machining of titanium alloys.

Future Direction

- Continue to work with the TWS machining consortium to develop computer models and to provide supporting data for those models to enable low-cost machining of advanced, lightweight engine materials.
- Survey the state of the art and conduct systematic studies of the effects of hard particle concentration on the machining characteristics and surface quality of advanced composites based on metal-bond ceramic particles.

Introduction

Manufacturing involves the conversion of raw materials into finished, useful components and products. Historically, it represents a vital industrial component of the economic security of the United States. Manufacturing begins with processed materials, such as metals, ceramics, polymers and composites, and then shapes, joins, and finishes them to meet the functional requirements of machines, machine parts, and structures. Manufacturing comprises a broad range of engineering disciplines that are applied to an even wider range of unit processes. It is necessary, therefore, to focus on an area of manufacturing that, in the present case, enables both the near-term and the longer-term introduction of advanced materials and machining methods for diesel engine components into the commercial marketplace.

For more than 150 years, since the Industrial Revolution, U.S. industry has invested hundreds of billions of dollars in the development of machining technology and the purchase of equipment. However, with the egress of manufacturing to foreign sources in recent years, a significant amount of capital equipment and the knowledge base to develop new machining technology to enable the introduction of advanced materials has eroded. Experienced machinists have retired and, with fewer manufacturing jobs in the United States, they are not being replaced by motivated, young trainees from the next generation. The machine tool industry in the United States also has suffered significant losses and many, if not most, new machine tools are made by foreign sources. It is vital, therefore, to avoid full dependence on foreign sources and to maintain a base of machining science in the United States.

Approach

The approach taken in this project involves three areas of machining technology:

1. Machining engine parts from advanced materials, such as ceramic engine valves.
2. Modeling machining processes with state-of-the-art software.
3. Characterizing the machining response of newly-developed materials, such as composites.

Projects in each of these areas are separately discussed in the Results section.

Results

Machining of silicon nitride diesel engine valves. Silicon nitride valve blanks were received by ORNL from Caterpillar, and their straightness and diameters were measured using a coordinate measuring machine. The appropriate dimensions to use, considering several valve designs and the coordinate measuring machine data for the blanks, were then selected. A set of programming instructions was developed for use with the Weldon grinder. This program was then tested and verified using a bar of machinable alumina silicate ceramic. Profiles on the "dummy part" were checked with the coordinate measuring machine. Particular attention was paid to the dimensions of both the bevel and the blend section between the valve stem and head. The finished valve is shown in Figure 1.

Participation in the machining consortium. In FY 2004, a new collaboration began with TWS of Minneapolis. TWS has been leading a U.S. Air Force Phase II Small Business Innovative Research project, "Improved Titanium Machining Processes," to develop an advanced machining modeling package based on finite element modeling (FEM). TWS has established a consortium of aerospace and ground transportation component manufacturers that are interested in improving machining processes for titanium alloys. Benefits from membership in the consortium are

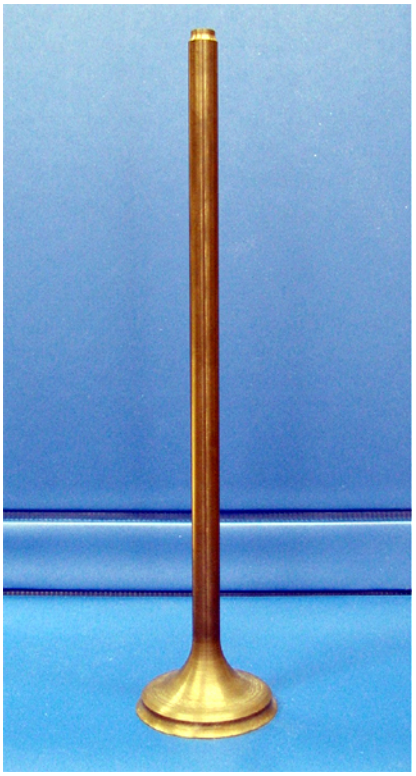

Figure 1. Silicon nitride diesel engine valve machined at ORNL.

1 Members share the latest technologies for titanium machining from other consortium members, such as TWS, Kennametal, Caterpillar, Stork Fokker (Netherlands), and EADS (Germany).
2. Members have the use of the advanced FEM-based machining modeling package called AdvantEdge™.
3. Participants help define the direction of the machining technology being developed, specifically, working with the University of Michigan to develop and verify models for drilling, boring, and face milling of titanium, in addition to having access to other models in the current modeling package.
4. ORNL helps the consortium by conducting material characterization to help select new cutting tool materials and tool coatings for improved machining of titanium.
5. New modeling capabilities will not be limited to titanium but will represent a new in-house resource for materials development programs and the High Temperature Materials Laboratory Machining, Inspection, and Tribology User Center.

The basis for our interest in the TWS consortium stems from recent technology that promises to reduce the cost of titanium raw material[1–3] and therefore expand titanium's potential use as a lightweight material in engines and brakes.[4] However, the difficulty of high-speed machining of titanium alloys is a major technical barrier. Because of the metal's poor thermal conductivity (6.8 W/m-K), the cutting heat cannot be dispersed efficiently, and the tool tip temperature is much higher than that generated in cutting most other metals. The high tool temperature promotes the diffusion tool wear and limits the cutting speed. Serrated chips with adiabatic shear band are usually produced in titanium machining because of the thermal-mechanical instability. The chip shear band formation creates fluctuation in cutting forces, leading to tool chipping. Therefore, research is needed in titanium machining, including advanced process modeling and development of new tool materials/coatings.

Jun Qu of ORNL and Paul Becker of the University of Tennessee attended the 2004 TWS AdvantEdge international users' conference in March in Gaithersburg, MD, and Jun also took the short course in modeling metal cutting offered by TWS in April.

Output from the model. The TWS modeling package AdvantEdge can be used to improve cutting speeds and evaluate tooling performance by simulating and predicting cutting forces and tool/workpiece/chip temperatures. AdvantEdge may also be used to address other important issues, such as chip breakage, tool wear, and residual stresses.

Simulations were first run on several steel and aluminum alloys using different tool materials, tool geometries, and cutting parameters to become familiar with the modeling technique and test the feasibility of AdvantEdge. Then the focus was shifted to titanium alloys. For example, AdvantEdge was used to simulate performance in cutting (turning) Ti-6Al-4V alloy with different tool inserts (bare WC-Co and TiAlN coatings with thicknesses of 3 and 6 μm). The cutting speed was set to 195 m/min with a 0.381-mm feed and a 1.02-mm depth of cut. The steady-state temperature maps of the cutting areas are shown in Figure 2. Figure 3 displays the ex-

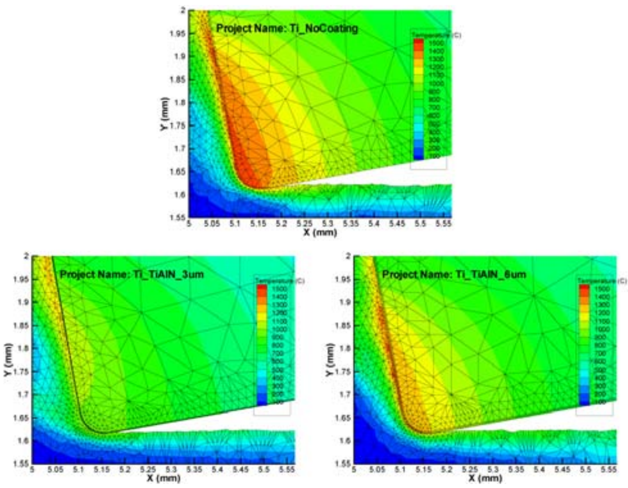

Figure 2. Temperature maps of coated and uncoated tools cutting Ti-6Al-4V.

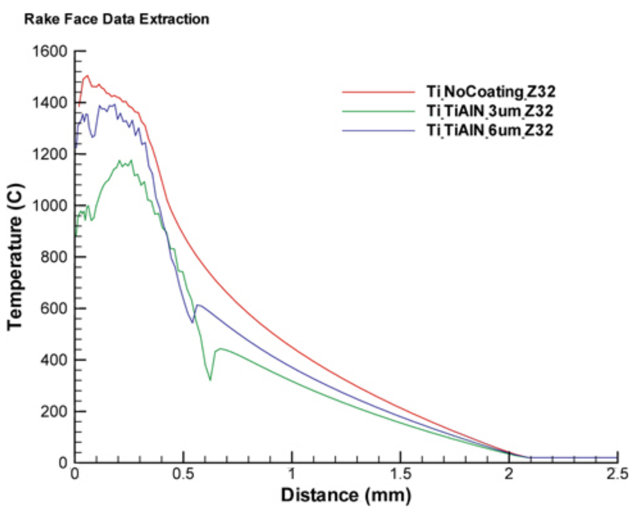

Figure 3. Rake face temperature profiles.

tracted rake face temperature profiles. Apparently, the temperature at the uncoated tool tip is higher than that of the coated tips. It is interesting to note that the tip with the 6-µm coating is hotter than the tip with the 3-µm coating. This implies that a thicker coating may not improve tool performance. Thicker coatings also increase the production cost and are more vulnerable to spalling. In fact, 3 µm is the current industry standard thickness for TiN and TiAlN tool coatings. Besides having lower cutting temperatures, coated tools generate smoother cutting surfaces, as illustrated in Figure 3.

Tooling studies. In addition to process modeling, new tool materials for titanium are being explored. One potential tool material is a TiC (particles)–Ni_3Al (matrix) composite that was initially developed for heavy-duty diesel fuel injector plungers. It contained 40–50 vol % TiC and 50–60 vol % Ni_3Al. Experimental work at the University of Michigan has proved that this composition is inadequate for cutting tools. Rather, TiC–Ni_3Al materials with high concentrations of TiC (90–95 vol %) are being prepared and will be tested in FY 2005.

The physical properties of five production tool materials and coatings are also being characterized. The coating thicknesses and microstructures of each material were examined by both scanning electron microscopy and scanning acoustic microscopy, a novel nondestructive method for observing micrometer-sized surface flaws. The coating hardness and modulus of elasticity have been measured by nanoindentation. The thermal conductivity and thermal diffusivity of the tool coatings significantly affect the cutting performance and tool life. The thermophysical properties of these thin coatings will be measured using a newly developed photoacoustic technique at the Microscale Thermophysical Property Laboratory at Purdue University.

In titanium machining, the high tool wear, particularly diffusion wear, significantly limits the cutting speed and tool life. Measurement and characterization of the tool wear are upcoming to investigate the wear mechanisms and explore an effective method to quantify the wear at the tool tips.

Machining of hard composite materials. Composite materials are used because they can draw from the advantageous properties or two or more materials to create a new material with properties better than those of either constituent alone. They find a wide variety of uses in structural and nonstructural applications. Composite materials in which the various phases in the microstructure differ greatly in hardness represent one of the most challenging problems for machining in cases when it is necessary to achieve high-precision surface finishes and minimal surface damage. Fine particles of grit embedded in the grinding wheel can produce differential grinding of the hard and soft phases. Pull-out of the hard particles may leave holes and other artifacts that can affect surface quality. In the coming year, a series of cermets with different concentrations of hard phases will be prepared by ORNL and used to study the behavior of cermets and metal matrix composites.

In preparation, ORNL is conducting a survey of machining practices for drilling, turning, and grinding cermets and metal matrix composites. Then the cermets will be machined under a range of conditions to study how multi-phase composites respond to varying levels of aggressiveness in material removal parameters. The focus will be on understanding the relationship between microstructure, hard particle concentration, and surface quality in machined composite materials.

Conclusions

- Two diesel engine valves were machined from silicon nitride materials supplied by Caterpillar. In preparing these valves, it was necessary to compensate for a lack of straightness in the stem portion of the blank. A precision coordinate measuring machine first was used to characterize the starting blank, and special mounting methods then were used to ensure that the final part could be prepared from imperfectly shaped stock.
- A new effort in computer-assisted modeling of high-speed machining processes for titanium was initiated through participation in a consortium with TWS. Initial results are encouraging, and the software provides a new capability to ORNL's machining program.
- In FY 2005, there will be a new activity directed toward understanding the machining characteristics and resulting surface quality of composite materials. This work will support the development of precision machining processes for difficult-to-machine materials with relatively hard and soft phases in the microstructure.

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