I. Cost-Effective Machining of Titanium Materials

Albert J. Shih
Mechanical Engineering
University of Michigan
Ann Arbor, Michigan 48109-9739
(734) 647-176; fax: (734) 936-0363; e-mail: shiha@umich.edu

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

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Objective

- Investigate new technologies for cost-effective machining of titanium alloys.
- Develop the cost-effective, high-speed machining processes.
- Investigate new tool material, geometry, coating, and process parameters to enhance process capability and product quality.
- Provide accurate prediction of temperature and stress for tool selection and design.

Approach

- Conduct turning test using new tool material.
- Develop high-speed titanium drilling technology.
- Carry out the finite-element modeling and inverse heat transfer analysis to study titanium turning and drilling processes.
- Validate the modeling with experimental results.

Accomplishments

- Compared the performance of new TiC-based tool material with WC-Co for turning titanium.
- Demonstrated the feasibility of high-speed drilling process over 180-m/min cutting speed for titanium.
- Achieved accurate predictions of the temperature distribution of the tool in titanium drilling.

Future Direction

- Continue the exploration of high-speed, cost-effective machining of titanium alloys.
- Advance the thermal analysis and management of the cutting tool.
- Conduct the 3-D finite-element-based thermal-mechanical coupled drilling modeling to advance the knowledge in mechanics of material deformation during the titanium chip formation process.

Introduction

Titanium and its alloys are lightweight, corrosion-resistant, biocompatible, and high-temperature materials. The poor machinability of titanium alloys has been summarized in several review articles.[1–4] Due to the inherent properties of titanium, particularly the low thermal conductivity, the tool temperature in machining of titanium is high and concentrated at the tool tip.[1] High temperature softens the tool material and promotes rapid diffusion wear and severe tool edge chipping.[5,6]

A new tool material, the TiC-Ni_3Al cermet, was developed at Oak Ridge National Laboratory with the goal to increase high-temperature stability and reduce the diffusion wear in titanium machining. Titanium turning tests are performed, and results are compared with that of a conventional WC-Co tool.

Among various machining processes, drilling has a major economical importance because it is typically utilized in final steps in production. Technical difficulties of cost-effective drilling of titanium include (1) high drill temperature, (2) severe drill wear, even at moderate feed rate and spindle speed, (3) limited cutting speed and productivity, (4) difficulty to eject long ribbon titanium chip, and (5) exit burr formation. The main objective of this year is to investigate the drilling mechanism and develop the new technologies to overcome the technical difficulties mentioned above.

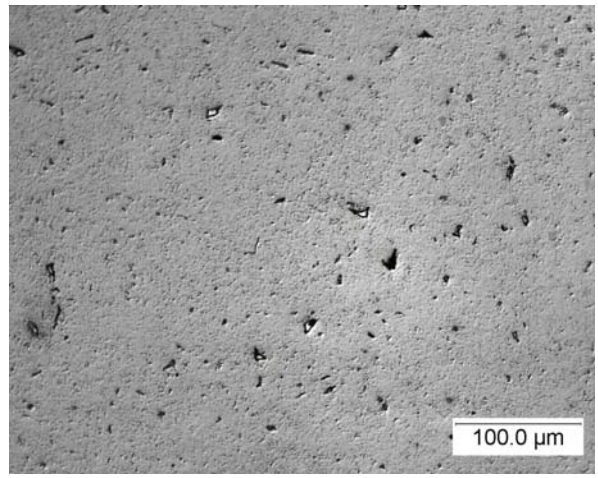
Approach

Tool Wear Test of TiC-Ni_3Al Material

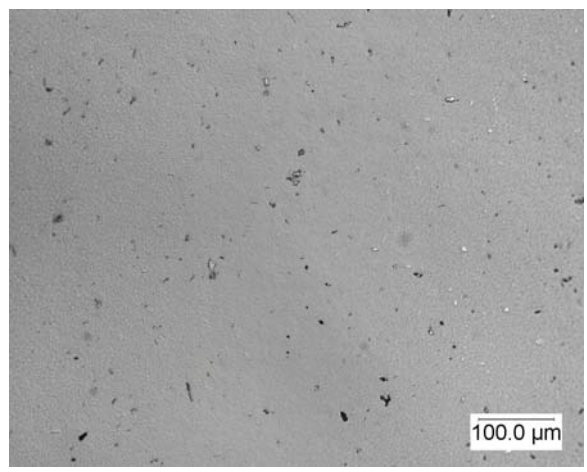
The TiC-Ni_3Al materials were made at ORNL. The tool blank face was machined by wire electro-discharge machining (EDM) and polished to the same geometry as the Kennametal TPG160308 tool. A set of turning tests was conducted using this new tool material at the University of Michigan to evaluate the wear of TiC-Ni_3Al tool.

Figure 1 shows the optical microscopic image of the polished TiC-Ni_3Al. The TiC with 5% Ni_3Al shows relatively high porosity, compared to commercial tool material. The high porosity results in the brittleness of tool under high stress. Increasing the content of Ni_3Al to 9% reduces the material porosity, but sacrifices the hardness of TiC-Ni_3Al, as shown in the hardness indention results in Table 1.

The tool wear tests were conducted at 24.4-, 48.8-, and 195-m/min cutting speeds in lathe turning with 0.25-mm/rev feed and 1-mm depth of cut. Both TiC-Ni_3Al and WC-Co tool were evaluated, and the cutting forces and tool life were compared.



(a) TiC-Ni_3Al (5%)



(b) TiC-Ni_3Al (9%)

Figure 1. Microstructures of TiC-Ni_3Al cermets.

Table 1. Micro-indentation hardness

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

High-Speed Drilling of Ti-6Al-4V

High cutting speed is essential to reduce the machining cost and increase the productivity. It is particularly important, but difficult to achieve, in the machining of titanium and titanium alloys. As shown in Table 2, the drilling speed for titanium alloys is very low in industrial applications. This has

Table 2. Comparison of drilling speed

Drill material	Al alloys	Cast iron	Ti-6Al-4V
HSS[7]	105	49	11
WC-Co[7]	245	90	46
Other[8]	533	235	—

hindered the productivity and increased the cost of machining titanium. The goal of this research is to enable the high-speed drilling of titanium.

Three types of drills, (1) M2 HSS twist drill (Greenfield Industries 44210), denoted as HSS Twist, (2) WC-Co web thinned point twist drill (Kennametal KWCD00344), denoted as WC-Co Twist, and (3) WC-Co spiral point drill (Kennametal K285A01563), denoted as WC-Co Spiral, are evaluated. All drills are double-flute with 4 mm in diameter. The workpiece material is 6.35-mm thick Ti-6Al-4V plate.

The titanium drilling tests were conducted at a constant feed of 0.051 mm per revolution or 0.025-mm feed per tooth. By changing the spindle speed, various drill feed rates and peripheral cutting speeds could be achieved. Cutting fluid plays an important role to reduce the tool and workpiece temperatures and enhance the tool life.[6] Two ways to supply the cutting fluid, internally from two through-the-drill cutting fluid holes and externally from outside the drill, were studied. The cutting fluid was 5% CIMTECH 500, a synthetic metal-working fluid. The thrust force and torque during drilling were measured.

Four sets of experiments, denoted as Exps. I, II, III, and IV, were conducted. Exp. I was conducted using the HSS Twist drill at three peripheral cutting speeds, 9.1, 13.7, and 18.3 m/min, without cutting fluid. This is the baseline test. To study the effect of cutting fluid, Exp. II was conducted with external cutting fluid supply using HSS Twist drill at higher peripheral cutting speeds at 13.7, 18.3, and 27.4 m/min. Exp. III was conducted to compare the thrust force, torque, energy consumption, and burr formation of three types of drill (HSS Twist, WC-Co Twist, and WC-Co Spiral) at 18.3-m/min peripheral cutting speed without cutting fluid. Exp. IV was high-speed drilling of titanium using the WC-Co Spiral drill at 183-m/min peripheral cutting speed. Drilling under dry as well as with internal and external cutting fluid supply conditions was evaluated.

Figure 2 illustrates three stages, marked as A, B, and C, in drilling. Stage A occurs when the drill has

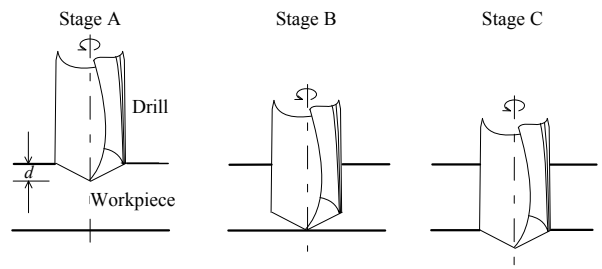


Figure 2. Illustration of three stages A, B, and C in drilling.

traveled by a distance *d*, which is called the drill point length, from the initial contact. For the HSS Twist, WC-Co Twist, and WC-Co Spiral drills used in this study, *d* is 1.24, 1.19, and 0.74 mm, respectively. Neglecting the deformation of the workpiece, the drill cutting edge becomes fully engaged with the workpiece at this stage. When the drill tip reaches the back surface of the plate, as shown in Figure 2, it is marked as Stage B. Stage C is defined when the drill cutting edge is disengaged with the workpiece without considering the deformation of the workpiece and burr formation.

The torque and force changed throughout the drilling process. The value of thrust force and torque at Stage A, denoted as F_A and T_A, and maximum thrust force and torque during drilling, denoted as F_m and T_m, respectively, were compared to distinguish different drilling conditions.

Besides thrust force and torque, another parameter to compare drilling setup is the energy *E* required to drill a hole.

$$E = \int_l F dl + \int_l \frac{2\pi T}{f} dl \quad ,$$

where *l* is the depth of drilling, *F* is the thrust force, *T* is the torque, and *f* is the feed per revolution. In titanium drilling, the *E* is dominated by the torque term, which typically accounts for more than 95% of the *E*.

Inverse Heat Transfer Solution of Tool Temperature in Drilling of CP Titanium

Understanding the heat generation rate and tool temperature distribution is important in titanium drilling. The inverse heat transfer method, which utilizes the temperature measured by thermocouples embedded on the drill flank surface as the input, is applied to predict the heat flux on the drill chisel and cutting edges. Thermocouples are routed from the

frank surface, via through-the-drill cutting fluid holes, to outside the tool.[9] During drilling, these thermocouples do not contact nor interfere with the chip. A validation process can be performed by comparing the drill temperature distributions to thermocouple measurements.

The drilling experiment was conducted in a Mori-Seiki TV-30 vertical machining center. Figure 3 shows the experimental setup with the stationary 9.92-mm-diameter spiral point drill and the 38-mm-diameter CP titanium bar rotated by spindle. The drill was stationary because four thermocouples embedded on the flank face could be routed through cutting fluid holes in the drill body to a data acquisition system during drilling.[9] The drill and machine spindle axes were aligned by a test indicator to less than 10-µm eccentricity. Under the drill holder was a Kistler 9272 dynamometer to measure the thrust force and torque. Figure 4 shows the locations of four thermocouples, denoted as TC1, TC2, TC3, and TC4, on the drill frank surface.

Three drilling experiments were conducted at three spindle speeds, 780, 1570, and 2350 rpm, which corresponded to 24.4-, 48.8-, and 73.2-m/min drill peripheral cutting speed, respectively. The feed remained fixed at 0.051 mm/rev. All the experiments were conducted dry without cutting fluid.

Figure 5 shows the finite-element mesh of the drill, which is modeled by 68,757 four-node tetrahedral elements. As shown in Figure 5(b), 13 nodes are located on the chisel edge, and 11 nodes are placed on each cutting edge to achieve good resolution in the analysis of drill temperature distribution in titanium drilling.

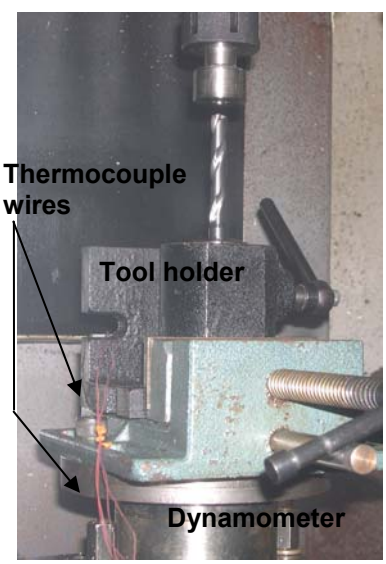


Figure 3. Experimental setup with workpiece in the holder of spindle and drill in a vertical tool holder.

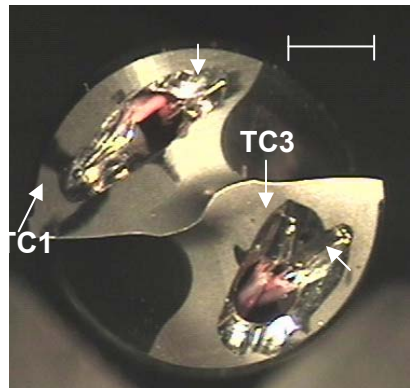


Figure 4. Thermocouple locations in the drill flank face.

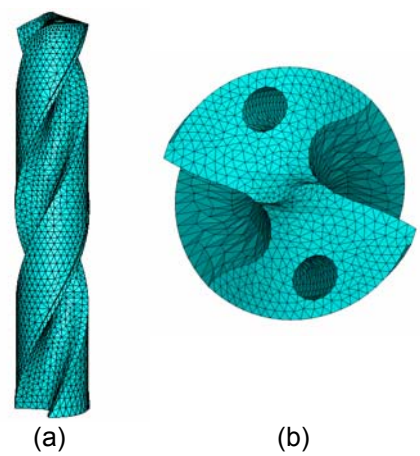


Figure 5. Mesh for the 3-D finite-element thermal model: (a) side view and (b) top view.

Results

Tool Wear Test of TiC-Ni_3Al Material

Cutting forces are summarized and compared with a WC-Co tool in Figure 6. Consistently, the TiC-Ni_3Al tools showed higher cutting forces than that of the WC-Co tool. This was likely due to the imperfect tool geometry with less sharp cutting edges of the TiC-Ni_3Al tools.

The tool life was also evaluated. The major failure mode of TiC-Ni_3Al tools is the catastrophic tool breakage. Table 3 summarizes the tool life of the TiC-Ni_3Al tools compared to the WC-Co tool. Due to the high porosity, TiC-Ni_3Al (5%) tools broke at all cutting speeds. The TiC-Ni_3Al (9%) tools

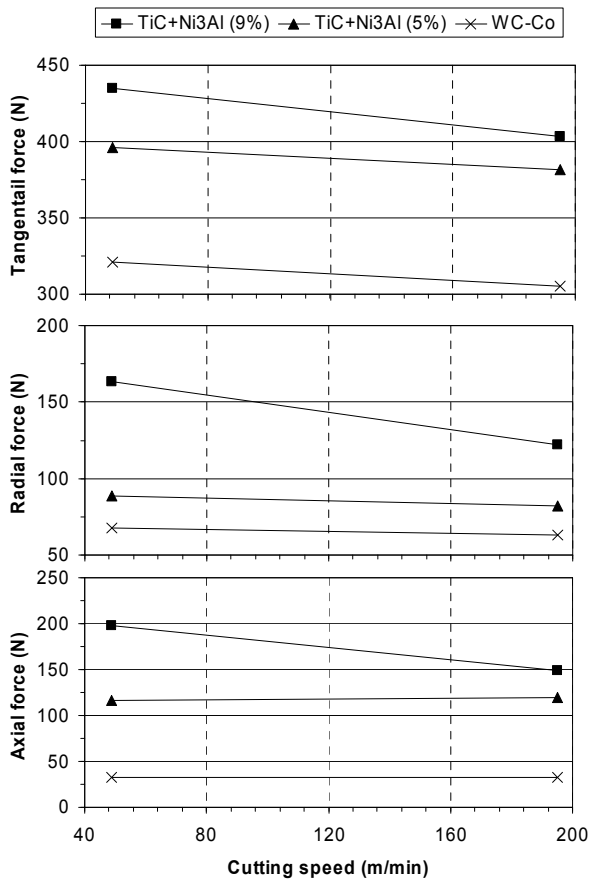


Figure 6. Cutting forces of TiC-Ni_3Al and WC-Co tools in lathe turning of titanium.

Table 3. Tool lives in machining titanium

	Cutting speed (m/min)		
	24.4	48.8	195
TiC-Ni_3Al (5%)	245.3	18.4	15.3
TiC-Ni_3Al (9%)	*Not tested*	>294.4	9.2/33.7
WC-Co	*Not tested*	*Not tested*	69

survived at 48.8 m/min with progressive wear after 294 s, but broke early at 195 m/min. Significantly different tool lives, 9.2 and 33.7 s, at high cutting speed (195 m/min) were obtained on two tips of a TiC-Ni_3Al (9%) tool insert, indicating the non-uniformity of the microstructure or the non-consistent condition of the cutting edges. The higher Ni_3Al content improves the performance of TiC-Ni_3Al tool material, but some efforts like better preparation of tool edge and surfaces are still needed to achieve or exceed the performance of WC-Co. We are working with Kennametal to grind the TiC-Ni_3Al tool to the right geometry.

High-Speed Drilling of Ti-6Al-4V

Table 4 summarizes the Stage A and peak thrust force and torque, and energy consumption in Exps. I–IV. Performance of each type of drill is discussed as follows.

The HSS Twist drill has limited cutting speed and material removal rate in drilling titanium. The drill tip melted in the second hole due to high temperature at 18.3- and 27.4-m/min peripheral cutting speeds under dry and external cutting fluid supply conditions, respectively.

The WC-Co Spiral drill has the lowest thrust force and torque among all three drills. This drill is selected for high-speed titanium drilling. The drill can perform at 183-m/min peripheral cutting speed (14700 rpm) under the dry as well as with external and internal cutting fluid supply conditions. As listed in Table 5, the tool life is short without the supply of cutting fluid. Using flood external cutting fluid supply just slightly increased the tool life because the high spindle speed generates high centrifugal force, which prevents the cutting fluid from reaching the cutting region. The internal cutting fluid supplied through machine spindle and drill makes significant improvement of the tool life because the cutting fluid can reach the tool-chip interface and also assist the chip ejection.

Figure 7 shows the thrust force and torque in drilling at 183 m/min with internal cutting fluid supply before the drill breakage. Gradual increase of the thrust force and torque can be observed.

Inverse Heat Transfer Solution of Tool Temperature in Drilling of CP Titanium

Temperatures at four thermocouples are shown in Figure 8. Good matches between experimental and modeling temperature can be recognized at three drilling speeds.

The temperature distribution near the tip of the spiral point drill after 12.7-mm depth of drilling the

Table 4. Experiment design, summary of the Stage A and peak thrust force and torque, and energy consumption in Exps. I–IV

Exp.	Drill type	Cutting fluid	Peripheral cutting speed (m/min)	F_A (N)	T_A (N – m)	F_m (N)	T_m (N – m)	E (J)
I	HSS twist	No	9.1	401–413	0.40–0.44	401–413	0.56–0.58	391–400
			13.7	464–486	0.39–0.40	464–486	0.72–0.79	426–455
			18.3	390	0.36	390	0.80	453
II	HSS twist	External	13.7	417–420	0.40–0.44	417–420	0.5–0.54	367–390
			18.3	430–446	0.39–0.41	430–446	0.70–0.76	387–427
			27.4	400	0.3	410	0.75	412
III	HSS twist	No	18.3	390	0.36	390	0.80	453
	WC-Co twist			233–235	0.28–0.32	235–257	0.71–0.82	603–628
	WC-Co spiral			166–169	0.38–0.42	177–178	0.46–0.48	351–375
IV	WC-Co spiral	No	183	178–185	0.24–0.27	178–185	0.82–1.47	497–596
		External		175–178	0.28–0.31	175–190	0.53–1.45	504–574
		Internal		162–210	0.25–0.55	182–230	1.07–1.17	586–783

Table 5. WC-Co tool life (number of holes) at high drilling speed (183 m/min)

Dry	External cutting fluid	Internal cutting fluid
10	14	101

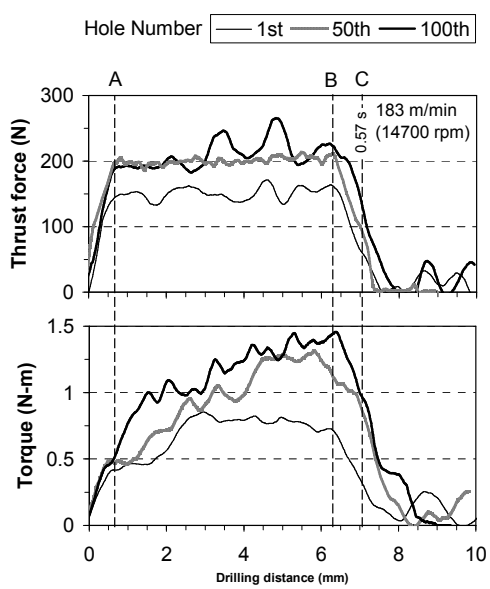


Figure 7. Thrust force and torque of high-speed drilling of Ti-6Al-4V at 183-m/min peripheral cutting speed with internal cutting fluid supply.

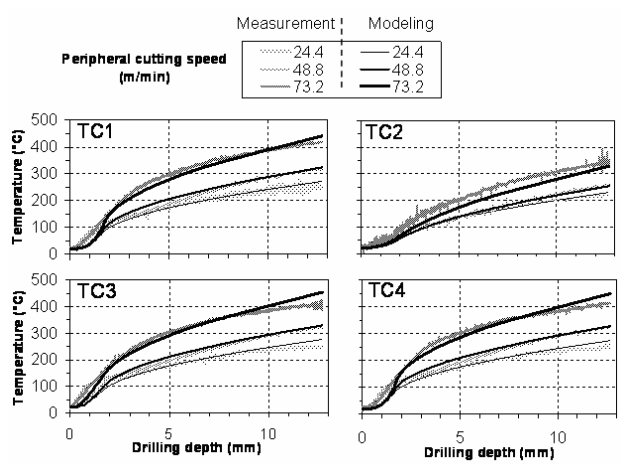


Figure 8. Comparison of the measured and calculated temperature at four thermocouple locations in titanium drilling.

titanium is shown in Figure 9. High temperature is concentrated along the cutting edge at the drill tip.

High cutting speed generates high temperature in the drill. The peak temperature increases from 445 to 893°C when the drill peripheral cutting speed is increased from 24.4 to 73.2 m/min. The peak temperature is located on the cutting edge near the drill margin for all three cutting speeds.

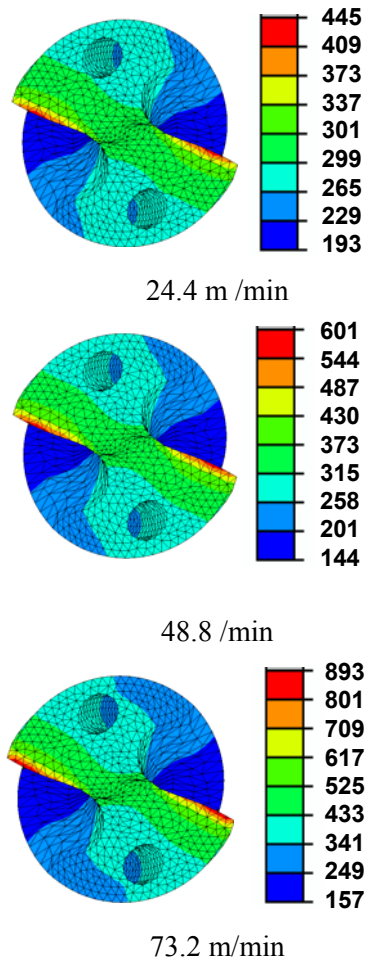


Figure 9. Temperature distributions at the drill tip.

Conclusions

This study demonstrated that high-speed, cost-effective machining of titanium and titanium alloys was possible. Exploratory evaluation of TiC-Ni_3Al cermet for machining of titanium had been conducted. Cutting forces were measured and compared with the results when using WC-Co tool at different cutting speeds and feeds. The porosity of the material was improved with higher Ni_3Al content, but the manufacturing technique and surface and cutting edge preparation of the tool inserts had been identified for further improvement.

This study demonstrated the feasibility of cost-effective drilling of Ti-6Al-4V with peripheral cutting speed over 180 m/min (600 sfpm) using commercially available advanced drill geometry and tool material. The limitation of HSS drill on cutting speed and material removal rate was apparent. The test of three drills at the same process conditions demonstrated benefits of the spiral point drill design. The WC-Co Spiral drill outperformed the HSS Twist and WC-Co Twist drills in terms of thrust force, torque, energy consumption, and burr size. The importance of cutting fluid supply on drill life was identified. The improvement of drill life from dry to external cutting fluid supply was limited at high-speed drilling. Internal cutting fluid supply was proven to be critical on the drill life.

The inverse heat transfer method was developed to analyze the tool temperature in titanium drilling. High drill temperature was observed in drilling titanium, particularly at high cutting speed. Temperature measured at various thermocouples provided not only the input for inverse heat transfer solution but also the validation of the finite-element drill temperature model. The proposed method has been validated by reasonably good agreement with experimental measurements. Detailed finite-element analysis of the drill temperature distribution was performed to gain insight in titanium drilling.

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Presentations and Publications

R. Li and A. J. Shih, "Finite Element Modeling of 3D Turning of Titanium**,**" presented at the 2004 ASME IMECE Anaheim, California, November 2004.

R. Li and A. J. Shih, "Finite Element Modeling of 3D Turning of Titanium," *International Journal of Advanced Manufacturing Technology* (in print).

R. Li and A. J. Shih, "Inverse Heat Transfer Solution of Tool Temperature in Titanium Drilling," *Journal of Manufacturing Science and Engineering* (submitted).