On Cutting Temperature Measurement During Titanium Machining With an Atomization-Based Cutting Fluid Spray System

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The poor thermal conductivity and low elongation-to-break ratio of titanium lead to the development of extreme temperatures (in excess of 550 °C) localized in the tool–chip interface during machining of its alloys. At such temperature level, titanium becomes highly reactive with most tool materials resulting in accelerated tool wear. The atomization-based cutting fluid (ACF) spray system has recently been demonstrated to improve tool life in titanium machining due to good cutting fluid penetration causing the temperature to be reduced in the cutting zone. In this study, the cutting temperatures are measured both by inserting thermocouples at various locations of the tool–chip interface and the tool–work thermocouple technique. Cutting temperatures for dry machining and machining with flood cooling are also characterized for comparison with the ACF spray system temperature data. Findings reveal that the ACF spray system more effectively reduces cutting temperatures over flood cooling and dry conditions. The tool–chip friction coefficient indicates that the fluid film created by the ACF spray system also actively penetrates the tool–chip interface to enhance lubrication during titanium machining. [DOI: 10.1115/1.4028898]

Keywords: titanium machining, temperature measurement, fluid film penetration, cooling and lubrication

1 Introduction

Titanium and its alloys possess unique physical and mechanical properties such as high strength-to-weight ratio, strong fracture and corrosion resistance, and biocompatibility that make them ideal for a variety of engineering applications including aerospace components, turbines, and biomedical devices [1]. However, the poor thermal conductivity (10–30% of steel) and low elongation-to-break ratio of titanium pose a serious challenge to machining processes, as extreme temperatures develop within the small tool–chip interface (e.g., one-third size of steel for the same cutting conditions). At temperatures higher than 500 °C, titanium and its alloys become highly chemically reactive with commonly used tool materials leading to accelerated tool wear. Several cooling solutions including flood cooling, high-pressure cooling, and cryogenic cooling have been applied to address this temperature issue during titanium machining [1,2]. Nath et al. [2] recently proposed the ACF spray system for titanium machining. They observed that the system that uses a very small amount of cutting fluid (e.g., 10–20 ml/min) improves tool life beyond flood cooling. While it is believed that the tool life improvement results from fluid film penetration of the cutting interface during titanium machining, the change in the cutting temperatures and temperature gradient inside the tool–chip interface caused by the fluid film penetration is needed to be characterized for better understanding of the cooling and lubrication mechanism of the ACF spray system.

Several cutting temperature measurement techniques including the inserted thermocouple, the tool–work thermocouple, spectral radiation thermography, and the recently proposed thin film thermal sensor have been investigated for machining different materials including titanium alloys [3–18]. The measurement of cutting temperature during titanium machining is highly challenging because of the smaller tool–chip contact size (about 0.5 mm in most machining situations employed in Ti machining) [1,2]. The smaller tool–chip interface is difficult to access with thermocouples. Kitagawa et al. [10] measured the cutting temperature during the turning of Ti–6Al–6 V–2Sn with and without flood cooling by inserting a 25 μm diameter tungsten wire into a premachined through hole in the tool perpendicular to the rake face 0.15 mm from the cutting edge. Although this technique demonstrates the feasibility of the inserted thermocouple technique in measuring cutting temperature during titanium machining, a single temperature measurement cannot express the characteristics of the temperature gradient around the tool–chip interface. El–Wardany et al. [9] demonstrated that the inserted thermocouple technique can measure the temperature at various locations of the tool–chip interface for hard to machine materials. However, the chip-breaker that is required to obtain the measurements interferes with the cutting dynamics, chip formation, and the application of cutting fluid.

Klocke et al. [11] studied the cutting temperature during the turning of Ti–6Al–4 V using a two-color pyrometer. The temperature was measured by a 0.5 mm fiber-optic wire inserted into a blind hole with a final placement of 0.15 mm under the rake face and 0.41 mm from the major flank face. While this temperature measurement technique is able to accommodate the application of cutting fluid, the single temperature measured is outside the tool–chip interface and is an average over the area of the exposed end of the 0.5 mm diameter fiber optic wire. More recently, Werschmoeller and Li [8] have proposed an embedded micro thin film thermocouple to measure temperatures in the tool–chip contact region, the technique, however, requires difficult and expensive MEMS fabrication and cannot currently be completely embedded in a conventional tool material like tungsten–carbide (WC).

The objective of this work is to determine the cutting temperatures at various locations in the cutting zone during titanium machining with the ACF spray system. The temperatures are obtained both by inserting thermocouples in the contact region and the tool–work thermocouple technique. The friction coefficients are also estimated from the force data to confirm the temperature reduction due to effective penetration of cutting fluid, thereby providing lubrication at the cutting interface.

The remainder of this work is organized as follows. Section 2 presents the experimental temperature measurement techniques used to measure the temperature gradient in the tool–chip interface

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Contributed by the Manufacturing Engineering Division of ASME for publication in the Journal of Manufacturing Science and Engineering. Manuscript received July 2, 2014; final manuscript received September 29, 2014; published online December 12, 2014. Assoc. Editor: Y. B. Guo.

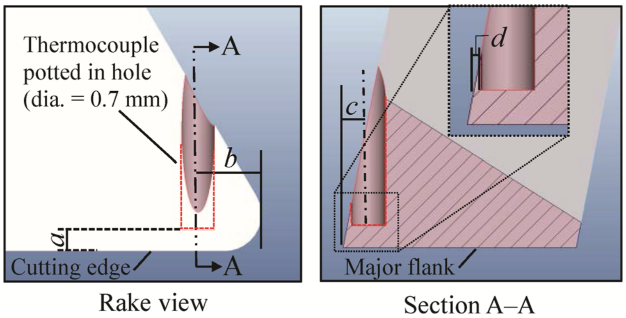


Fig. 1 Inserted thermocouple measurement setup

during titanium machining. Section 3 contains the experimental results and discussions. Section 4 features concluding remarks.

2 Experimental Design and Procedure

The techniques to measure the cutting temperatures of the tool–chip interface during titanium machining are described in Sec. 2.1. The ACF spray system and the spray characteristics pertinent to this study are given in Sec. 2.2. The titanium machining experimental design in terms of data collection equipment, and the cutting conditions investigated are presented in Sec. 2.3.

2.1 Temperature Measurement Techniques

Inserted Thermocouple Setup. The tool–chip interface during titanium machining is often observed to be about or less than 0.5 mm from the cutting edge [1,2]. In order to assess the cutting temperature variation within this region, thermocouples need to be placed at different locations within this narrow interface. In this study, the thermocouples are inserted in the holes machined by electrical discharge machining (EDM) perpendicular to the tool flank, allowing thermocouple placement as close as 0.15 mm from the cutting edge, as shown in Fig. 1.

Although, the temperatures inside the tool–chip interface are of interest, thermocouple placement in the cutting interface risks immediate damage from the chip formed during machining. To avoid damage, the thermocouples are inserted into blind holes machined into the WC tool inserts. The dimensions (i.e., *a*, *b*, *c*, and *d* in Fig. 1) of these blind holes are chosen to control the position of the thermocouple relative to the cutting edge and to maintain tool insert strength post–EDM. Dimension "*c*" (see Table 1) was varied to maintain a constant dimension "*d*" of 0.15 mm, as the distance from the thermocouple tip to the major flank, "*a*," was varied (see Fig. 1).

The thermocouples are rigidly positioned in the blind holes using JB weld metal adhesive, as shown in Fig. 2. During machining, there is still a risk of chips being entangled with the inserted thermocouple wire at the entrance of the blind hole (see Fig. 1) and causing the thermocouple to be detached from the hole. In order to better protect the thermocouple during machining, a copper guard was placed over the wire, as shown in Fig. 2. The copper guard was fixed to the tool with JB weld metal adhesive. Several test runs were then conducted to ensure that the thermocouple maintained a consistent position throughout for at least 1 min of machining and exhibited consistency tool-to-tool. These test runs also indicated that the tool becomes weakened by the

Table 1 Blind hole dimensions on the inserts

a (mm)	*b* (mm)	*c* (mm)	*d* (mm)
0.15	1.25	0.47	0.15
0.25	1.25	0.49	
0.35	1.25	0.51	
0.45	1.25	0.53	

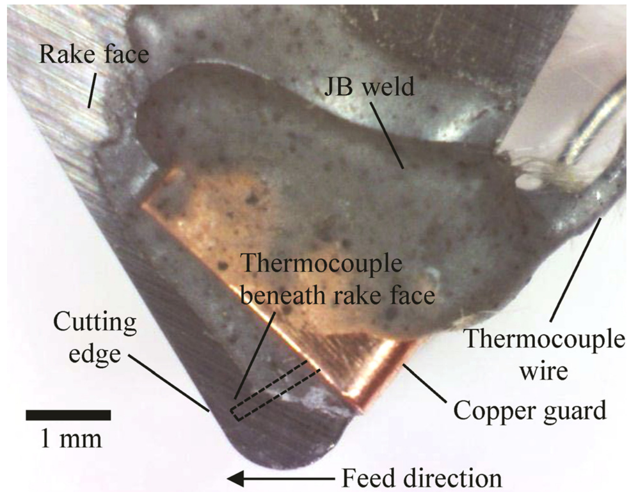


Fig. 2 Inserted thermocouple with copper guard

blind hole for distances to the major flank (i.e., "*a*") less than 0.15 mm (see Fig. 1).

It is believed that there is a large temperature gradient along the tool rake face due to the smaller size of the tool–chip contact and poor conductivity of titanium [1,17]. Since it is difficult to measure the temperatures close to the cutting edge using the inserted thermocouple technique, the tool–work thermocouple technique is also utilized as it measures the average temperature of the entire tool–chip contact region [19].

Tool–Work Thermocouple Setup. The tool–work thermocouple temperature measurement technique assembles a thermocouple considering the tool and the workpiece as the two dissimilar metals. During machining, the tool rake face–chip interface becomes the hot junction, as seen in Fig. 3. The thermoelectric voltage generated at the cutting interface is then measured and is correlated to the cutting temperature. Two lead wires complete the thermoelectric circuit, connecting the machine housing and the tool to the oscilloscope (Tektronix TDS 2024B) via the signal amplifier (Omega OMNI–AMP–I) for thermoelectric voltage measurement. The tool is electrically insulated from the turning machine by lining the tool holder with high-temperature mica in order to prevent the thermoelectric signal from being ground out. A brush junction (see Fig. 3) was used to connect the tailstock to the signal amplifier, completing the thermoelectric circuit. Parasitic thermoelectric voltages generated at the lead wire–tool and the lead wire–workpiece junctions were reduced by using alumel as the lead wire material and maintaining constant junction temperature (room temperature about 20 °C) [19].

The thermoelectric circuit, composed of a WC tool and a Ti–6Al–4 V workpiece for this study, must be calibrated in order to associate the measured thermoelectric voltage to a given temperature from a heat source. During calibration, both the tool and the workpiece were represented by 3.175 mm diameter WC and Ti–6Al–4 V rods, respectively. The two rods were brazed together at one end and were placed in a small furnace alongside a K-type

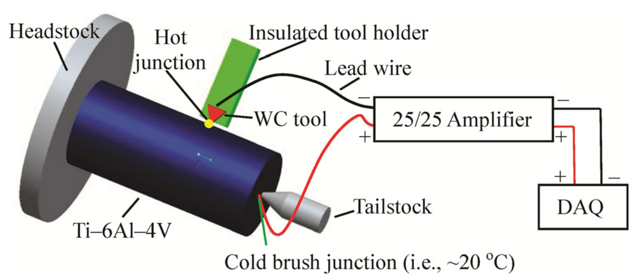


Fig. 3 Tool–work thermocouple measurement setup

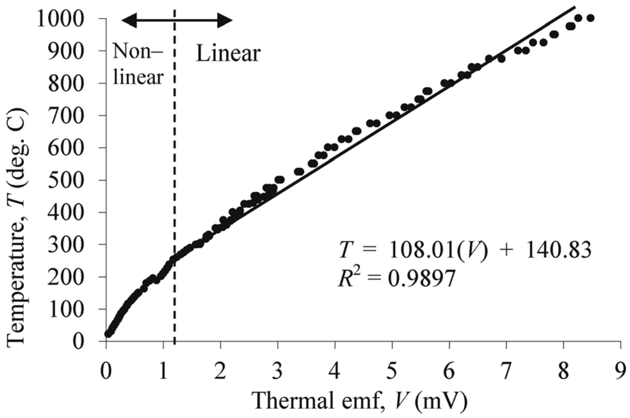


Fig. 4 Tool–work thermocouple calibration curve

thermocouple. The contact area of the brazing between the rods was chosen to be approximately 1 mm^2 to represent the similar size order of the tool–chip interface area. Using an oxygen–acetylene torch, the furnace containing the brazed end of the rods and the K-type thermocouple were heated, and the thermoelectric voltage was then measured across the ends of the rods outside the furnace that are kept at room temperature (cold junction). The K-type thermocouple was employed to measure the actual temperature at the rod junctions inside the furnace. The resulting calibration curve exhibits a nonlinear portion from about 0 to 1.20 mV, as seen in Fig. 4. The cutting temperatures of interest in this study are above 250 °C; therefore, a line is fit to the linear section (i.e., beyond 1.20 mV) of the resulting calibration curve using the method of least squares. Note that the error between the experimental data and the fit line is found to be less than 5%.

2.2 ACF Spray System. The ACF spray system features two coaxial nozzles of different diameters, as seen in Fig. 5(*a*), that are used to dispense droplets of cutting fluid toward the tool–chip interface [2]. Uniformly sized droplets (diameter in tens of μm) produced by an ultrasonic atomizer flow through the droplet nozzle at a low velocity, and then are entrained by the high-velocity gas flowing though the gas nozzle to produce a focused axisymmetric jet of droplets. This jet is impinged onto the stationary tool rake face during turning experiments. The impact energy of the majority of the droplets is controlled by the ACF spray parameters (e.g., gas velocity, impingement angle, flow rate, nozzle design, etc., as seen in Fig. 5(*b*)) to obtain the "spreading" droplet impingement regime, ideal for machining applications. The impinging droplets of cutting fluid create a thin film that spreads toward the tool–chip interface during machining, as shown in Fig. 5(*b*). It is believed that the tool–chip interface penetration of the fluid film created by the ACF spray system is the mechanism by which tool life is improved [2,20,21]. In this system, two high-velocity gases, air and a mixture of air–CO_2 (at the volumetric ratio 66:34), were used in order to determine the effect of gas composition and temperature on cutting interface temperatures. Note that the impinging temperature of air alone is about 18–20 °C as compared to that about 2–3 °C with air–CO_2 mixture. CO_2 not only helps reducing the dispensing temperature but also suppressing the smoke from the cutting zone (due to its higher molecular weight than O_2) during titanium machining with the ACF spray system [2].

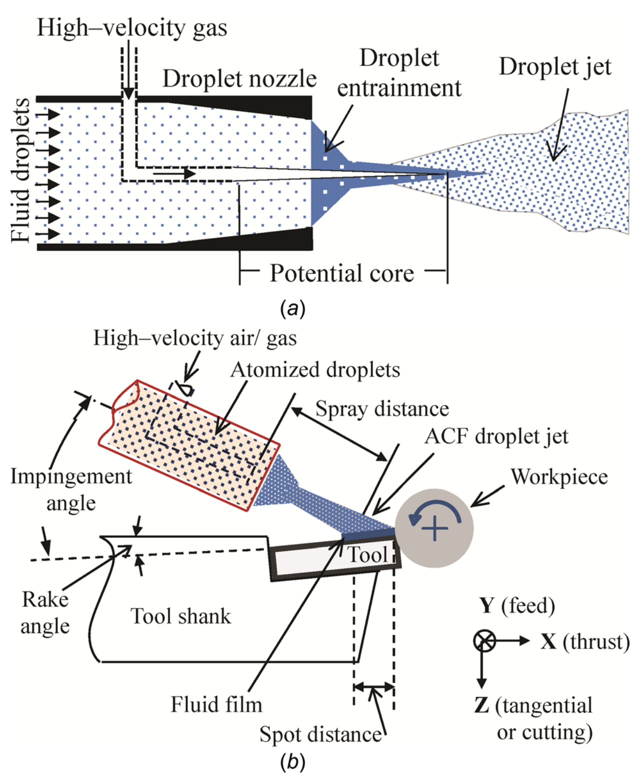


Fig. 5 (*a*) Schematic of the ACF spray system [21] and (*b*) ACF spray parameters in turning setup [2]

2.3 Experimental Design. Titanium turning experiments were conducted on the Mori Seiki Frontier–I CNC lathe. Figure 6 depicts the experimental setup with the ACF spray system. A Ti–6Al–4 V workpiece was turned using fresh Kennametal K313 inserts at four combinations of feed rate (i.e., 0.15 and 0.2 mm/rev) and cutting speed (80 and 110 m/min). The depth of cut was set as 1.5 mm in all tests. The tool inserts were set such that the principle cutting edge angle (φ_o) and the orthogonal rake angle (γ_o) are 60 deg and 5 deg, respectively. The cutting conditions were chosen to reflect those commonly used in industry for high productivity [1].

Machining experiments for dry cutting and flood cooling were also conducted for comparison to the ACF spray system in terms of cooling and lubrication effectiveness. Flood cooling experiments were conducted at a flow rate and pressure of about 1500 ml/min and 60 psi, respectively. The ACF spray system was set with an impingement angle of 35 deg, a spray distance of 35 mm, a spot distance of 7 mm, a high-velocity gas pressure of 150 psi, and a flow rate of 20 ml/min (refer Figs. 5(*b*) and 6). Water-soluble cutting fluid S-1001 at 10 vol. % dilution in water was used in this study [2,22]. The thermophysical properties of this fluid concentration at room temperature were measured as follows: density 1000 kg/m^3, surface tension 32.2 mN/m, viscosity 1.68 cP, and thermal conductivity 0.506 W/m K [22].

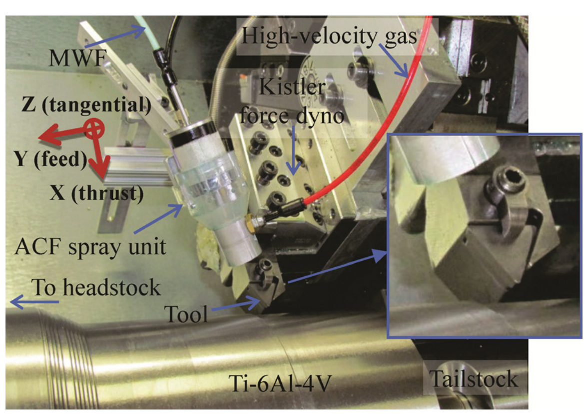


Fig. 6 Photograph of the setup with the ACF spray system in the CNC lathe

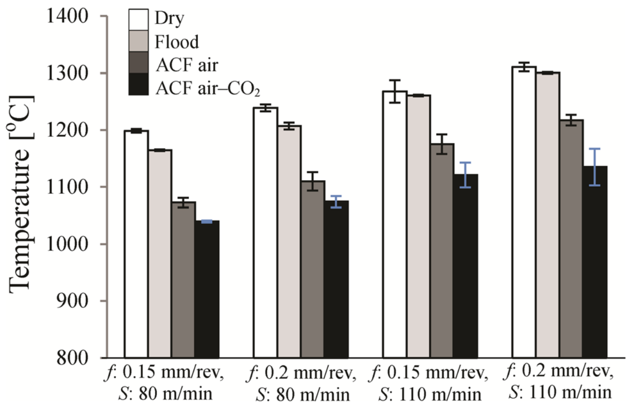


Fig. 7 Tool–work thermocouple temperature measurements

The cutting temperatures are collected for two repeated experiments of 15 s of cutting for each combination of feed rate and cutting speed using both the tool–work and the inserted thermocouple techniques to gather the mean cutting temperature and the temperature gradient inside the tool–chip interface, respectively. In order to calculate the tool–chip interface friction coefficients, the cutting forces are also obtained in each trial using a Kistler three-component force dynamometer (type 9121) sampled at a frequency of 1 kHz through a National Instruments data acquisition system (SCB-68) integrated with the LabVIEW software.

3 Cutting Temperature Results

3.1 Tool–Work Thermocouple Results. The thermoelectric voltage generated within the cutting interface during the machining experiments is measured using the tool–work thermocouple technique, and is converted to temperature using the calibration equation shown in Fig. 4. Figure 7 shows the averages of the cutting temperature measurements from the two repeated tests conducted with fresh tool in each test. The error bars represent one standard deviation of measurement values. It is seen in Fig. 7 that the ACF spray system more effectively reduces the mean cutting temperature compared with dry cutting and flood cooling regardless of the type of the high-velocity gas or the cutting condition. While comparing the high-velocity gases of the ACF spray system, it is evident that the air–CO_2 mixture far more effectively reduces the cutting temperature than air alone.

The ACF spray system is also able to maintain large cutting temperature reductions across the range of cutting conditions investigated. Table 2 shows the percent reduction in average cutting temperature for the three cutting fluid application methods in comparison to dry machining at the same cutting conditions. The percent reduction in cutting temperature for flood cooling is between 1–3%, while the ACF spray system maintains 7–13% reduction in cutting temperature across all cutting speeds and feeds investigated.

Table 2 Percent reduction in cutting temperature from dry cutting

Cutting conditions	Cutting fluid application method: Flood (%)	ACF air (%)	ACF air–CO_2 (%)
f: 0.15 mm/rev, *S*: 80 m/min	2.8	10.5	13.3
f: 0.2 mm/rev, *S*: 80 m/min	2.6	10.4	13.3
f: 0.15 mm/rev, *S*: 110 m/min	0.6	7.3	11.6
f: 0.2 mm/rev, *S*: 110 m/min	0.7	7.1	13.4

3.2 Inserted Thermocouple Results. Although the temperature measurements from the tool–work thermocouple experiments indicate that the ACF spray system can lower the cutting temperature by a greater amount compared with flood cooling, the temperature reduction mechanism (i.e., tool–chip interface fluid penetration) is not fully explained without an understanding of the temperature gradient inside the tool–chip interface. Unlike the tool–work thermocouple technique, the inserted thermocouple technique allows for the measurement of cutting temperature at different locations of the tool–chip interface. The tool–chip contact length is first measured in order to ensure the thermocouples are placed at desired locations of the tool–chip interface. Fresh tools are used to turn Ti–6Al–4 V at each of the four cutting conditions investigated. The rubbing marks left on the tool for each cutting condition are measured to determine the tool–chip (T–C) contact length (see Fig. 8). The lower feed of about 0.15 mm/rev has a tool–chip contact length of about 0.26 mm, while the higher feed of 0.2 mm/rev has a longer tool–chip contact length of about 0.33 mm. Thermocouples are positioned both outside and inside the tool–chip interface (i.e., 0.45, 0.35, 0.25, and 0.15 mm to cutting edge) to understand the temperature gradient within the tool–chip interface during titanium machining.

As discussed in Sec. 2.1, K-type thermocouples inserted into blind holes with varying depths relative to the cutting edge (see dimension "*a*" Fig. 1) measure temperature at different locations of the interface to build a map of temperature profile. The resulting temperatures for different cooling and cutting conditions are shown in Fig. 9. The error bars represent one standard deviation of measurement from two repeated tests conducted with fresh tool. The temperature measurements demonstrate that while cutting temperatures are relatively constant outside the tool–chip interface, there is a severe increase in temperature within the cutting interface as distance from the cutting edge decreases. The increasing trend in cutting temperature is present for every cutting condition and cutting fluid application method investigated.

Comparing temperature results across a range of cutting conditions (see Fig. 9) re-enforces the observations made by the tool–work thermocouple technique that flood cooling becomes less effective in reducing cutting temperature at higher cutting speeds and feeds in comparison to the ACF spray system. For the least aggressive cutting condition (i.e., $f = 0.15$ mm/rev and $S = 80$ m/min), only the ACF spray system with air–CO_2 mixture outperforms flood cooling in terms of temperature reduction inside the tool–chip interface. However, for the most aggressive cutting condition (i.e., $f = 0.2$ mm/rev and $S = 110$ m/min), the ACF spray system outperforms flood cooling in terms of cutting

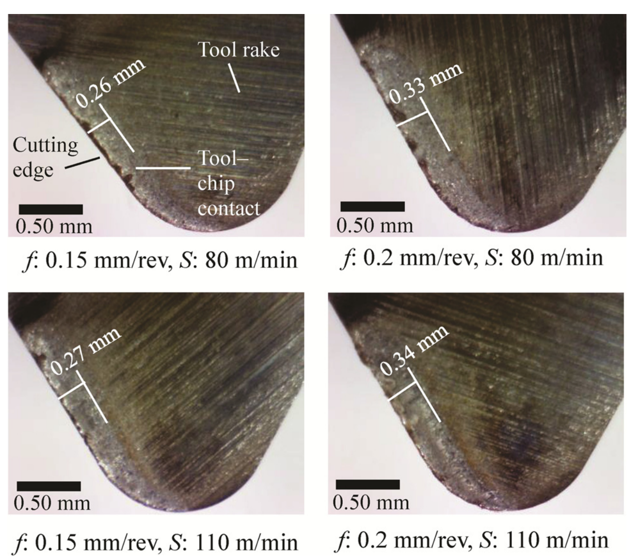


Fig. 8 Tool–chip contact length measurements

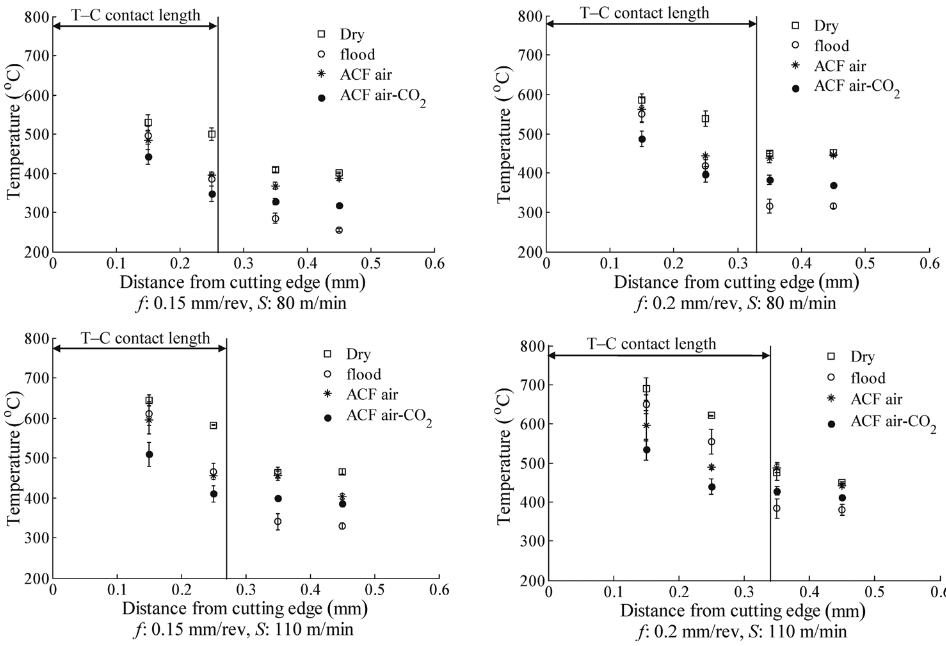


Fig. 9 Inserted thermocouple temperature measurements

temperature reduction regardless of the type of the high-velocity gas used. Although the temperature for flood cooling is found to be lower outside the tool–chip interface, the ACF spray system more effectively reduces cutting temperatures within the tool–chip interface where heat removal is the most critical to suppress tool wear. Note that the ACF spray system consumes a very small amount of cutting fluid (10–20 ml/min) as compared to flood cooling (1–10 l/min) and, therefore, the fluid film cannot conduct heat away from the tool outside the tool–chip interface.

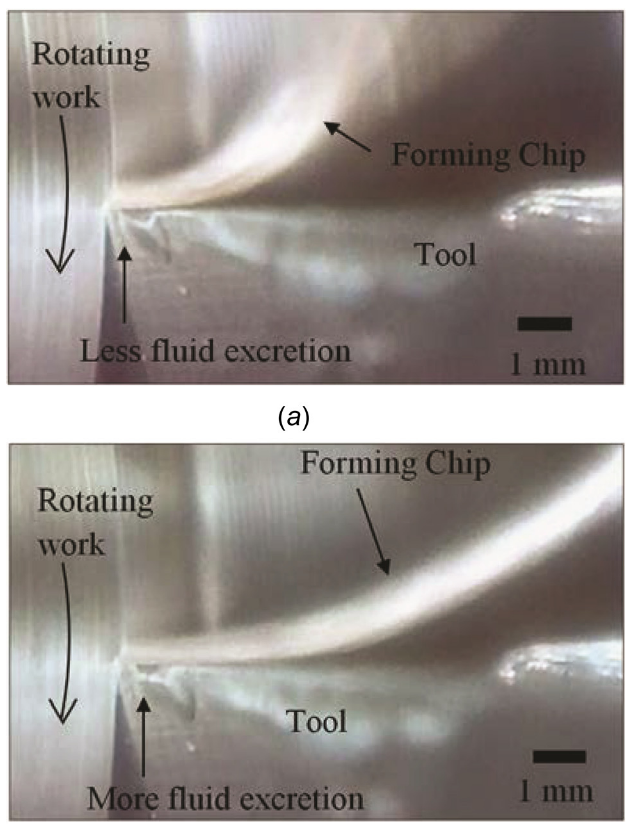
The significantly lower temperatures at the tool–chip interface measured by the inserted thermocouple technique indicate that the ACF spray system actively penetrates cutting fluid in the form of a thin fluid film (microscale) into the tool–chip interface to extend tool life. This finding is in agreement with the recent study by the authors [21], in which the thin fluid film produced by the ACF spray system is characterized and modeled. The forming chip lifting and falling during titanium machining was imaged. As seen in Fig. 10(*a*), when the chip lifts, the fluid film of the ACF spray system can easily penetrate into the tool–chip interface. The successive frame indicates that when the chip falls back to the rake face of the tool, cutting fluid is excreted out from the tool–chip interface at the cutting edge onto the minor flank of the tool (see Fig. 10(*b*)). This means that the velocity of the thin fluid film was fast enough to wet the entire interface in each chip lifting–falling cycle. The physics-based fluid film model developed in Ref. [21] also shows that the velocity of this fluid film is about 20 times greater than what is necessary for complete fluid progression and penetration (with its high dynamic pressure) of the cutting interface for the same set of ACF spray conditions.

The presence of cutting fluid at the interface that reduces cutting temperature can also be supported from the tool–chip friction coefficient. Additional machining experiments using flood coolant and the cutting conditions as a feed rate of 0.15 mm/rev, a speed of 80 m/min, and a depth of cut of 1 mm were conducted and cutting force data were collected. The friction coefficient was estimated using the following relationship:

$$\mu = \frac{F_z \sin\varphi_o \sin\gamma_o + F_y \cos\gamma_o}{F_z \sin\varphi_o \cos\gamma_o - F_y \sin\gamma_o} \quad (1)$$

where μ is the friction coefficient between the tool and the workpiece, F_y is the feed force, F_z is the tangential cutting force, φ_o is the principle cutting edge angle, and γ_o is the orthogonal rake angle [23].

Figure 11 compares the friction coefficient data using flood cooling collected in this study with the data collected earlier by the authors [24] using the ACF spray system with air–CO_2



(*a*)

(*b*)

Fig. 10 Chip lifting–falling cycle during titanium machining: (*a*) Chip lifting allows thin film to penetrate (less fluid excretes) and (*b*) chip falling causes more fluid excretion from the interface [21]

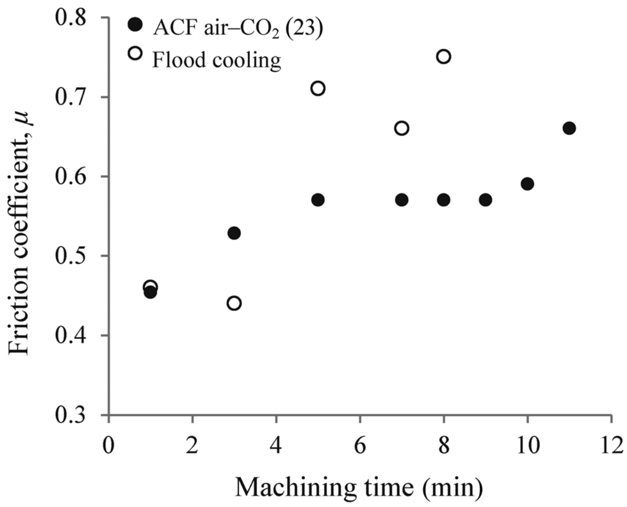


Fig. 11 Friction coefficient development over machining for flood cooling and the ACF spray system

mixture under identical machining conditions. Note that the cutting forces were collected until the tool fails, defined as 0.6 mm of maximum flank wear. Figure 11 exhibits that, for the first 4 min of machining, there is no visible difference in friction coefficient values between these two cutting fluid application methods. However, the friction coefficient for flood cooling increases rapidly to a value of about 0.7 after just 4 min of machining, while the ACF spray system with air–CO_2 mixture sustains a friction coefficient of 0.57 up to 10 min of cutting. This suggests that, with the ACF spray system, there is an effective penetration of the cutting fluid at the tool–chip interface, resulting in a prolonged tool life.

4 Conclusion

- The cutting temperature in the tool–chip contact zone is measured using the tool–work and the inserted thermocouple techniques during machining of a titanium alloy, Ti–6Al–4 V. The placement of thermocouples perpendicular to the tool flank yields cutting interface temperature measurements as close as 0.15 mm from the cutting edge.
- The tool–work thermocouple measurements indicate that the ACF spray system reduces average cutting temperatures by 7–13%, whereas flood cooling reduces it by only 1–3% as compared to dry machining.
- The temperature gradient along the tool–chip interface indicates that the ACF spray system with air–CO_2 mixture more effectively penetrates the tool–chip interface during titanium machining in comparison to flood cooling and the ACF spray system with air alone.
- Tool life experiments reveal that, after 4 min of machining, the ACF spray system with air–CO_2 mixture has a lower friction coefficient than flood cooling, and thereby enhances tool life.

Acknowledgment

The authors are thankful to the National Science Foundation (NSF) for supporting this research under the Grant No. NSF 12-33944.

References

[1] Ezugwu, E. O., and Wang, Z. M., 1997, "Titanium Alloys and Their Machinability—A Review," J. Mater. Process. Technol., **68**(3), pp. 262–274.
[2] Nath, C., Kapoor, S. G., DeVor, R., Srivastava, A., and Iverson, J., 2012, "Design and Evaluation of an Atomization-Based Cutting Fluid Spray System in Turning of Titanium Alloy," J. Manuf. Processes, **14**(4), pp. 452–459.
[3] Davies, M. A., Ueda, T., M'Saoubi, R., Mullany, B., and Cooke, A. L., 2007, "On the Measurement of Temperature in Material Removal Processes," CIRP Ann. - Manuf. Technol., **56**(2), pp. 581–604.
[4] Longbottom, J. M., and Lanham, J. D., 2005, "Cutting Temperature Measurement While Machining—A Review," Aircr. Eng. Aerosp. Technol., **77**(2), pp.122–130.
[5] Stephenson, D. A., and Agapiou, J. S., 2006, *Metal Cutting Theory and Practice*, Taylor & Francis, New York.
[6] Herbert, E. G., 1926, "The Measurement of Cutting Temperatures," Proc. Inst. Mech. Eng., **1**, pp. 289–329.
[7] Boothroyd, G., 1961, "Photographic Technique for the Determination of Metal Cutting Temperatures," Br. J. Appl. Phys., **12**(5), pp. 238–242.
[8] Werschmoeller, D., and Li, X., 2011, "Measurement of Tool Internal Temperatures in the Tool–Chip Contact Region by Embedded Micro Thin Film Thermocouples," J. Manuf. Processes, **13**(2), pp. 147–152.
[9] El–Wardany, T. I., Mohammed, E., and Elbestawi, M. A., 1996, "Cutting Temperature of Ceramic Tools in High Speed Machining of Difficult-To-Cut Materials," Int. J. Mach. Tools Manuf., **36**(5), pp. 611–634.
[10] Kitagawa, T., Kubo, A., and Maekawa, K., 1997, "Temperature and Wear of Cutting Tools in High-Speed Machining of Inconel 718 and Ti–6Al–6V–2Sn," Wear, **202**(2), pp. 142–148.
[11] Klocke, F., Kramer, A., Sangermann, H., and Lung, D., 2012, "Thermo-Mechanical Tool Loading During High-Performance Cutting of Hard-To-Cut Materials," Procedia CIRP, **1**, pp. 295–300.
[12] Sato, M., Tamura, N., and Tanaka, H., 2011, "Temperature Variation in the Cutting Tool in End Milling," ASME J. Manuf. Sci. Eng., **133**(2), p. 021005.
[13] Li, L., Chang, H., Wang, M., Zuo, D. W., and He, L., 2004, "Temperature Measurement in High Speed Milling Ti6Al4V," Key Eng. Mater., **259–260**, pp. 804–808.
[14] Anagonye, A., and Stephenson, D. A., 2002, "Modeling Cutting Temperature for Turning Inserts With Various Tool Geometries and Materials," ASME J. Manuf. Sci. Eng., **124**(3), pp. 544–552.
[15] Li, R., and Shih, A. J., 2006, "Finite Element Modeling of 3D Turning of Titanium," Int. J. Adv. Manuf. Technol., **29**(3–4), pp. 253–261.
[16] Karpat, Y., 2011, "Temperature Dependent Flow Softening of Titanium Alloy TI6Al4V: An Investigation Using Finite Element Simulation of Machining," J. Mater. Process. Technol., **211**(4), pp. 737–749.
[17] Sima, M., and Ozel, T., 2010, "Modified Material Constitutive Models for Serrated Chip Formation Simulations and Experimental Validation in Machining of Titanium Alloy Ti–6Al–4V," Int. J. Mach. Tools Manuf., **50**(11), pp. 943–960.
[18] Ozel, T., Sima, M., Srivastara, A. K., and Kaftanoglu, B., 2010, "Investigations on the Effects of Multi-Layered Coated Inserts in Machining Ti-6Al-4V Alloy With Experiments and Finite Element Simulations," CIRP Ann. - Manuf. Technol., **59**(1), pp. 77–82.
[19] Stephenson, D. A., 1993, "Tool-Work Thermocouple Temperature Measurements—Theory and Implementation Issues," J. Eng. Ind., **115**(4), pp. 432–437.
[20] Jun, M., Suhas, S., DeVor, R., and Kapoor, S. G., 2008, "An Experimental Evaluation of an Atomization Based Cutting Fluid Application System for Micromachining," ASME J. Manuf. Sci. Eng., **130**(3), p. 031118.
[21] Hoyne, A. C., Nath, C., and Kapoor, S. G., 2013, "Characterization of Fluid Film Produced by an Atomization-Based Cutting Fluid (ACF) Spray System During Machining," ASME J. Manuf. Sci. Eng., **135**(5), p. 051006.
[22] Nath, C., Kapoor, S. G., Srivastava, A. K., and Iverson, J., 2013, "Effect of Fluid Concentration in Titanium Machining With an Atomization-Based Cutting Fluid (ACF) Spray System," J. Manuf. Processes, **15**(4), pp. 419–425.
[23] Nandy, A. K., Gowrishankar, M. C., and Paul, S., 2009, "Some Studies on High-Pressure Cooling in Turning of TI–6Al–4V Alloy With High Pressure Coolant Supplies," Int. J. Mach. Tools Manuf., **49**(6), pp. 182–198.
[24] Nath, C., Kapoor, S. G., Srivastava, A. K., and Iverson, J., 2014, "Study of Droplet Spray Behavior of an Atomization-Based Cutting Fluid (ACF) System for Machining Titanium Alloys," ASME J. Manuf. Sci. Eng., **136**(2), p. 021004.