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Tool–Chip Interface Temperature Measurement in Interrupted and Continuous Oblique Cutting

Sinan Kesriklioglu
Department of Mechanical Engineering,
University of Wisconsin-Madison,
Madison, WI 53706

Justin D. Morrow
Department of Mechanical Engineering,
University of Wisconsin-Madison,
Madison, WI 53706

Frank E. Pfefferkorn[1]
Department of Mechanical Engineering,
University of Wisconsin-Madison,
Madison, WI 53706
e-mail: frank.pfefferkorn@wisc.edu

The objective of this work is to fabricate instrumented cutting tools with embedded thermocouples to accurately measure the tool–chip interface temperature in interrupted and continuous turning. Thin-film thermocouples were sputtered directly onto the flat rake face of a commercially available tungsten carbide cutting insert using micromachined stencils and the measurement junction was coated with a protective layer to obtain temperature data 1.3 μm below the tool–chip interface. Oblique interrupted cutting tests on AISI 12L14 steel were performed to observe the influence of varying cutting speeds and cooling intervals on tool–chip interface temperature. An additional cutting experiment was conducted to monitor the interface temperature change between interrupted and continuous cuts. [DOI: 10.1115/1.4038140]

Keywords: cutting, temperature, interrupted cutting, thermocouple

Introduction

The development of smart cutting tools and machining strategies requires better understanding of the thermal damage of the cutting tool due to temperature change at the tool–chip interface in machining of interrupted cuts. This is of interest when turning parts with cross-drilled holes, lubrication channels, key slots, and splines [1]. The heat generated from the primary and secondary shear zones often lead to rapid tool wear and occasionally unpredictable catastrophic tool failures [2]. Thus, real-time sensing of thermomechanical phenomena is essential for further advancements in machining processes.

Numerous attempts have been made over the years to develop analytical and numerical models to predict the cutting edge temperature during continuous and interrupted cutting [3,4]. A great amount of research was also performed to validate the models using infrared cameras. However, it is difficult to obtain a clear line of sight between the camera and the cutting zone, and the high temperature gradient during machining makes a local temperature measurement at the cutting interface difficult to extrapolate. Garcia-Gonzalez et al. [5] used an optically transparent yttrium aluminum garnet cutting tool that provides an optical path to the tool–chip interface. They imaged the interface with a low noise camera mounted on a stereomicroscope to measure the rake face temperature distribution. However, this method requires image processing and interface temperatures might be different in machining with standard cutting tools due to their different thermal properties. Therefore, direct temperature measurement of the cutting interface with thin-film thermocouples embedded in a standard tool coating is important for accurately characterizing the tool–chip interface temperature.

Basti et al. [6] deposited a built-in thin-film thermocouple directly on the rake face of a ceramic cutting insert using sputtering and photolithography technique, and measured the cutting temperature 0.3 and 0.5 mm away from the cutting edge, resulting in measurement near but not beneath the tool–chip contact area. A type-C microthin-film thermocouple was fabricated by Werschmoeller et al. [7] and diffusion bonded between two polycrystalline cubic boron nitride pieces to obtain thermal data from the close vicinity (70–700 μm) of the tool–chip interface. Recently, Sugita et al. [8] used a tungsten carbide insert (WC-Co) itself as one trace of the thermocouple in order to make a micro-WC-Co and chromium temperature sensor in the trench ablated by a femtosecond laser. This study focuses on fabricating a thin-film thermocouple inside a conventional coating system, located under the tool-chip contact area, on a commercially available WC-Co cutting insert, without the need to modify the insert in any way. Thin-film thermocouples were sputtered directly onto the insert's rake face and coated with aluminum titanium nitride (AlTiN) to protect the temperature sensor and represent a typical cutting surface and coating system. This paper presents the design, fabrication, and cutting tests of the sputtered thin-film thermocouples to examine the adhesion of the coated layers, and obtain temperature data in the close vicinity of the tool–chip interface in oblique machining of 12L14 steel.

Fabrication of Thermocouple Traces

The design and fabrication of the instrumented cutting inserts focus on accurate measurement of the tool–chip interface temperature during machining of metal alloys, achieving a fast enough response time that the temperature sensor can capture the thermomechanical data in interrupted cutting with small cooling intervals. The fabrication method must result in functioning thermocouple junctions that do not delaminate when machining steels of low to moderate hardness at a speed range beyond which built-up edge forms. Therefore, deposited layers must be compatible with commercially available tungsten carbide cutting inserts and minimize thermal resistance between the thin film thermocouple and the tool–chip interface. The instrumented inserts must also be designed to fit into a standard tool holder and be secured by a mounting screw.

For this initial phase of the research, a relatively large thermocouple junction was chosen (100 μm × 100 μm), because it could be produced with sputtering through masks. The required masks can be fabricated with micro-end milling. This approach does not require the more complicated series of processes required for micro-electro-mechanical systems manufacturing (e.g., spinning photoresist, exposing, developing, etching). In this way, the focus could be on developing the cleaning and sputtering parameters to achieve coatings with sufficient adhesion to survive metal cutting experiments.

A commercially available uncoated WC-Co cutting insert (Sandvik SPGN 120308 H13A) with a flat rake face and clearance angle on its flanks was used to sputter the thin-film

[1]Corresponding author.

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thermocouples. The rake face of the cutting insert, on which the thin-film thermocouples were fabricated is 12.7 mm (0.5 in) square. The clearance angle enables it to be used for positive rake angle cuts. These cutting inserts are electrically conductive and made of WC with 6–12 wt % cobalt that is located at the WC grain boundaries. The surface roughness of these cutting inserts is approximately 350 nm S_a and 5.3 μm S_z. Since the commercially available inserts have relatively high surface roughness for thin film deposition, they were polished using standard mechanical polishing techniques to produce a scratch free surface.

The polished WC-Co cutting inserts are cleaned from surface contaminations (e.g., cutting/polishing fluids, debris, and residues) by ultrasonication in a series of solvent baths (acetone/methanol/isopropanol) for approximately 10 min each and subsequently rinsed with de-ionized water and then dried with low velocity air for 1 min using a sweeping motion while working from one edge of the insert to the opposite edge. It should be noted that the insert must be rinsed with methanol immediately after acetone cleaning, because the acetone can leave a white residue if allowed to dry, which can reduce adhesion and lead to delamination of coatings. Argon plasma cleaning is then applied to the inserts in the sputtering system to remove metal oxides and activate the surface for thin film deposition.

Mask-Substrate Holder Design and Fabrication. The sensor layouts were designed with 100 μm critical dimensions. The distance of the junction from the cutting edge was set to less than 150 μm so that the thin-film thermocouple is located under the tool–chip interface (assumes a tool–chip contact length of at least 0.2 mm). The 0.8-mm-thick 6061-T6 aluminum masks for thin film thermocouple deposition (sputtering) on the rake face of the cutting insert were fabricated using a three-axis computer numerical control mill (HAAS TM-1) with a high-speed spindle (NSK HES-810) secured in the computer numerical control mill spindle to provide the required spindle speed for micromachining (60,000 rpm). Rough machining was done with a 1-mm-diameter tungsten carbide micro-end mill and finish machining, including the slots for thermocouple traces, was done with a 100-μm-diameter tool as shown in Fig. 1.

The masks were aligned consistently to ensure proper junction placement by designing a custom substrate holder. The holder was designed in SOLIDWORKS, path planning (G-code) was created in ESPRIT CAM software, and a five-axis mill-turn center (Mori Seiki NT1000W) was used to create the holder from 6061-T6 aluminum. The fabricated holder for cutting insert and masks is shown in Fig. 2.

Sensor Fabrication. The fabrication procedure of embedding the thin-film thermocouples consists of sputtering a single layer of Alumel–Chromel thermocouple traces between dielectric layers. After sputtering, the insert is coated with AlTiN as demonstrated in Fig. 3. All the layers were deposited by a research grade sputter deposition system (Denton Discovery 24) having one radio frequency (RF) and three DC magnetron stations. Deposition was performed on a rotating stage (15 rpm), with a distance to substrate of approximately 200 mm (8 in), and a vacuum pressure of approximately 2×10^{-6} Torr. The sputtering targets were made from high-purity (99.9%) elemental metals and 75 mm (3 in) in diameter.

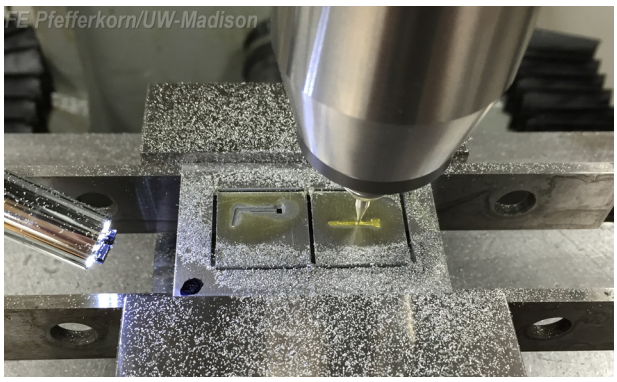


Fig. 1 Mask fabrication for thin-film thermocouple sputtering

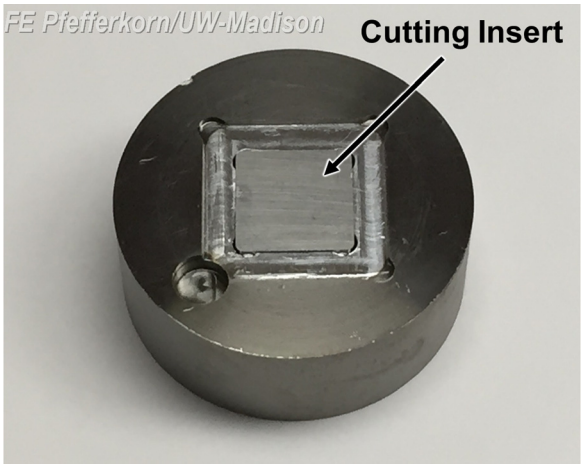


Fig. 2 Holder for the cutting insert and masks

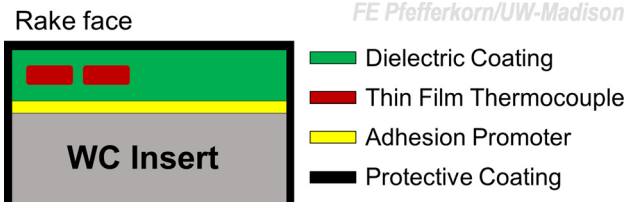


Fig. 3 Sputtered layers

Good adhesion of the coated layers to the cutting insert is essential, since they must endure significant compression (cutting) and shear (chip friction) forces. Therefore, ultrasonically cleaned inserts are first heated up to 300 °C and then Argon plasma cleaned for 20 min with a RF bias power of 500W. A 100-nm-thick layer of chromium (adhesion promoter) is sputtered on the rake and flank faces of the insert to form a compatible interface between the WC-Co cutting tool and dielectric coating. Aluminum oxide (Al_2O_3) was selected as the dielectric layer to minimize the mismatch between thermal expansion coefficients of the coating layers and the WC-Co insert. Cutting edges of the inserts were aligned with the Al_2O_3 sputtering target by rotating the table in vacuum, and stagnant deposition was applied to increase the very low deposition rate of the Al_2O_3 coatings. A 435-nm-thick Al_2O_3 layer was deposited on top of chromium layer with a RF power of 140 W for 4 h.

To measure a large range of tool–chip interface temperatures that are expected to occur under various cooling conditions (e.g., cryogenic cooling, water-based flood cooling, dry machining), K-type thermocouples were deposited by pairing Alumel (95% nickel, 2% manganese, 2% aluminum, and 1% silicon) with Chromel (90% nickel and 10% chromium) as shown in Fig. 4. Pairing these materials allows temperature measurements in the range of −200 to 1260 °C with a sensitivity of 41 μV/°C. The chamber was pumped down to a pressure of less than 2×10^{-6} Torr, and then a 200-nm-thick Alumel trace was sputtered on the Al_2O_3 dielectric layer, followed by deposition of a 200-nm-thick Chromel layer. The farthest edge of the thin-film thermocouple junction was positioned 120 μm away from the cutting edge of the insert. Thus, the thin-film thermocouple can be used to measure tool–chip interface temperature during orthogonal and oblique turning operations.

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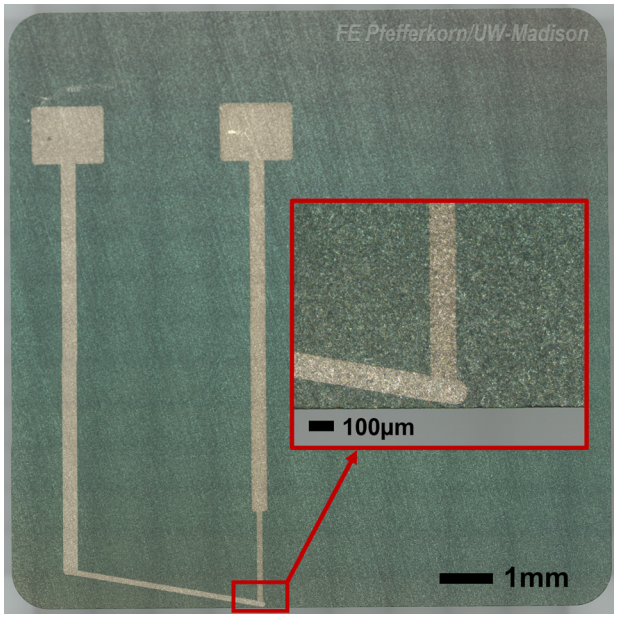


Fig. 4 Fabricated thermocouple before protective coating

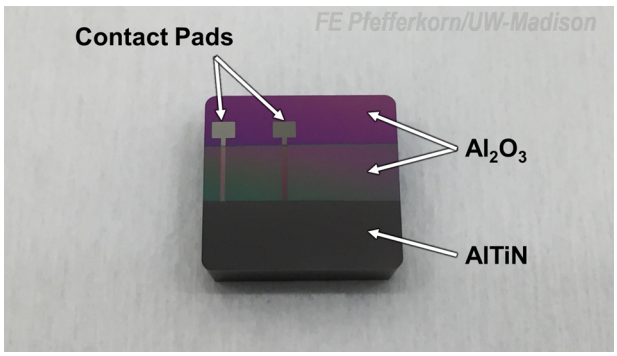


Fig. 5 Instrumented cutting insert

The thin-film thermocouple fabrication process was followed by coating the thermocouple traces, except for the contact pads, with a 550-nm-thick layer of Al_2O_3. The target to substrate distance was decreased from 200 mm to 100 mm to further increase the deposition rate of Al_2O_3. A 700-nm-thick protective layer of AlTiN was then sputtered over the rake and flank faces of the instrumented cutting tools using a high purity AlTiN alloy target, composed of 32% Al, 18% Ti, and 50% N with an RF power of 140 W. Figure 5 shows the final fabricated insert: the dielectric layers below and above the thermocouple traces, the thermocouple contact pads, and the AlTiN coating are visible. The same sputtering setup was used for AlTiN coatings due to the similar deposition rate to Al_2O_3. The reason behind selecting this type of

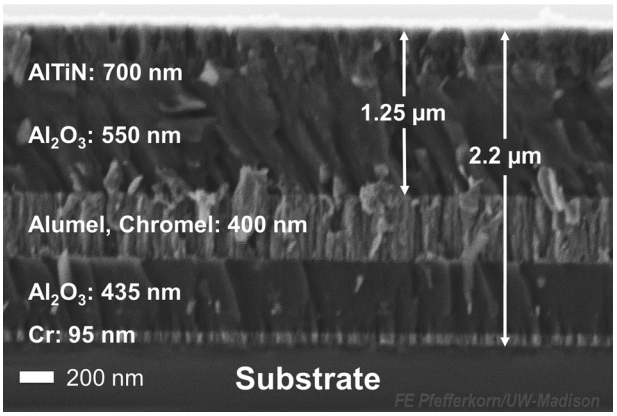


Fig. 6 Cross section of the coating layers

aluminum-containing nitride coating was that it produces a continuous, thin but dense aluminum oxide layer at elevated temperatures during the machining of particularly abrasive and difficult to cut materials (e.g., titanium alloys). The deposition parameters used for thin-film thermocouple fabrication are summarized in Table 1.

The cross-sectional scanning electron micrograph of the coating layers, deposited on a silicon wafer, is shown in Fig. 6. A distinct borderline was not observed between the Alumel and Chromel layers. It might be because of their similar elemental compositions (95 wt % Ni and 90 wt % Ni, respectively). The instrumented insert has its thermocouple junction located approximately 1.25 μm beneath the tool–chip interface (rake face), hence should be able to accurately measure that temperature. The total thickness of the sputtered layers is approximately 2.2 μm.

The maximum heat flux at the tool–chip interface is estimated to be 225 W/mm^2 for dry, orthogonal, cutting of carbon steel at 200 m/min. Assuming steady-state conditions, this heat flux is uniformly distributed across the tool–chip interface, and the layer thicknesses measured in Fig. 6, the temperature drop from the cutting interface to the top of thin-film thermocouple is approximately 9 °C. The temperature drop is proportional to the heat flux into the cutting tool. Hence, smaller heat fluxes will result in smaller temperature drops.

The compositional analysis of the thin-film thermocouple traces and protective layer are significant because the change in the material compositions affects the electrical behavior of the thin-film thermocouple and wear resistance of the coatings. The 100-nm-thick Alumel, Chromel, and AlTiN layers are sputtered on a single crystal Silicon wafer using the parameters in Table 1, and the elemental compositions of each layer were measured using X-ray photoelectron spectroscopy (XPS). The composition of the sputtered layers is given in Table 2. Based on the XPS results, the compositions of the thermocouple traces are only altered to a very limited extent from their nominal values, therefore, sputtered temperature sensor characteristics (e.g., sensitivity, linearity) are not expect to deviate significantly from standard K-Type thermocouples.

Table 1 Sputtering parameters for tool coating with embedded thermocouples

WC → Layer	1	2	3	4	5	6
Parameter	Cr	Al_2O_3	Alumel	Chromel	Al_2O_3	AlTiN
Power (W)	420	140	350	350	140	140
Cathode	DC	RF	DC	DC	RF	RF
Press. (mTorr)	12	3	10	10	3	5
Ar flow (sccm)	20	20	20	20	20	20
Distance to substrate (mm)	200	200	200	200	100	100
Dep. Time (min)	3.5	240	35	25	150	150

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Table 2 Composition of the thin-film thermocouple traces and protective layer (measured by XPS)

Material	Alumel	Chromel	AlTiN
Composition (wt %)	Ni:93.40 Mn:2.24 Al:2.77 Si:1.58	Ni:90.16 Cr:9.84	Al:42.45 Ti:22.65 N:34.90

Oblique Cutting Tests

The response of the instrumented tool, and adhesion of coating layers were investigated by a set of (dry) interrupted and continuous turning experiments. Cutting tests were conducted on a five-axis mill-turn center (Mori Seiki NT1000W) to measure the tool–chip interface temperature at two different cutting speeds (60 m/min and 200 m/min) and various cooling intervals during which the cutting tool does not engage the workpiece. The feed and depth of cut were held constant at 0.05 mm/rev and 2 mm, respectively, for all three experiments. The workpiece material was 12L14 free machining steel with a measured hardness of 42 HRA. The instrumented cutting tool has a positive rake angle of 5 deg. Oblique cutting with an inclination angle of 4.5 deg was chosen to prevent the chip from ricocheting off the workpiece and touching the thermocouple contact pads. Five and two interruptions per revolutions were made to have different lengths of ribs and cooling slots as shown in Figs. 7(*a*) and 7(*b*), respectively.

Silver paste (PELCO® Colloidal) was applied to provide electrical connections between the thin-film thermocouple contact pads and 80-μm-diameter thermocouple extension wires. A National Instruments 9205 module with NI cDAQ 9172 chassis was used to acquire the temperature data using LabVIEW software. A four-channel thermocouple amplifier circuit with built-in cold junction compensation (EGT-K) was used to convert the nonlinear thermocouple signals in millivolt range to 0–5 V linear analog output. It has an accuracy of $\pm 1.5\%$ and digitizes the temperature to a resolution of 0.23 °C. Though the NI 9205 module can sample at 250 kHz, the maximum sampling rate of the system is 25 kHz with one channel, due to the limitation of the thermocouple amplifier circuit. Before cutting experiments, the instrumented cutting tool was tested using boiling water. The contact pads were covered with Kapton tape and only the tip of cutting insert, where the thin-film thermocouple junction is embedded, was immersed to concentrate the major temperature gradient near the sensor. The measured temperatures were between 99 °C and 100.5 °C (within the gain error of the thermocouple amplifier circuit).

Five 6.35-mm-wide (1/4 inch) notches with the angels of 30 (A), 45 (B), 60 (C), 90 (D), and 135 (E) deg were machined into the 12L14 steel workpiece (Fig. 7(*a*)) to evaluate the performance of the embedded thin-film thermocouples at a cutting speed of 200 m/min (average rotational speed of 910 rpm). As shown in Figs. 8(*a*) and 8(*b*), the embedded temperature sensor could

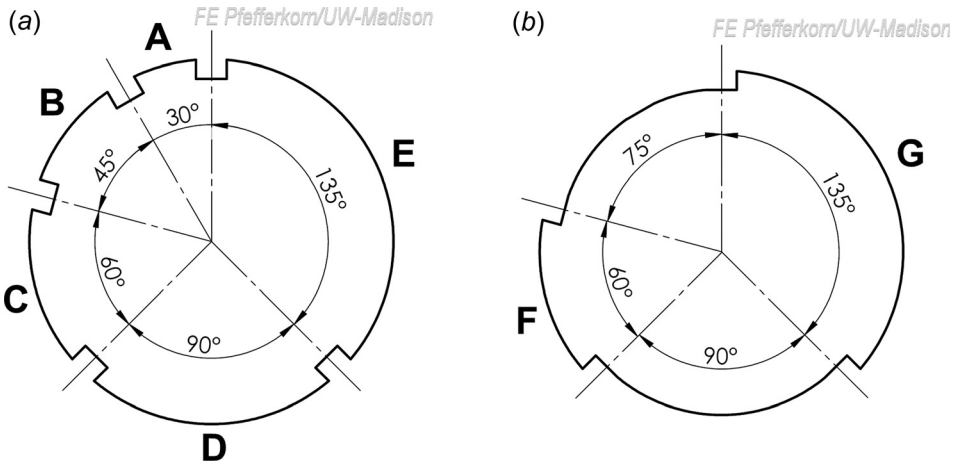


Fig. 7 Scheme of the workpiece with (*a*) five and (*b*) two interruptions

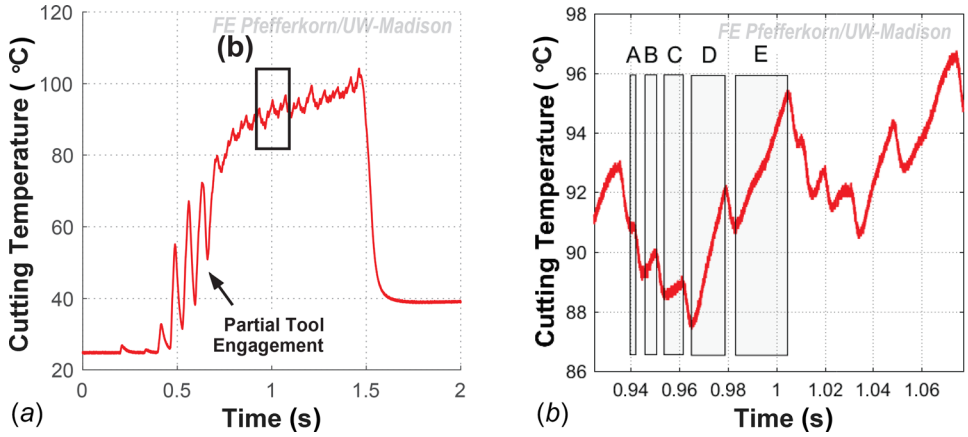


Fig. 8 (*a*) Tool chip interface temperature during interrupted cutting with five ribs at a cutting speed of 200 m/min and (*b*) temperature change in two revolutions

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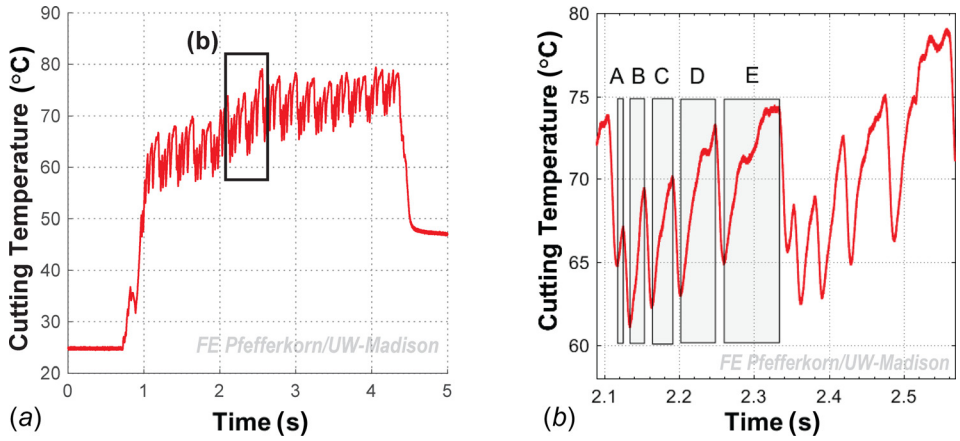


Fig. 9 (*a*) Tool chip interface temperature during interrupted cutting with five ribs at a cutting speed of 60 m/min and (*b*) temperature during two revolutions

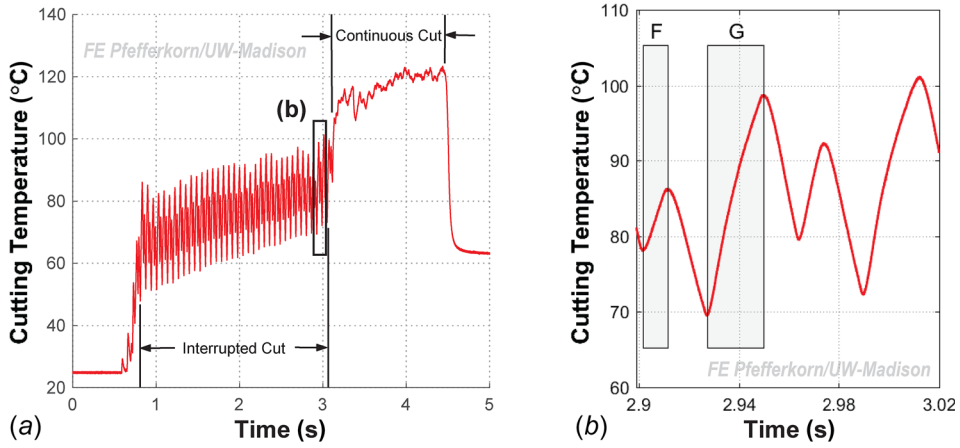


Fig. 10 (*a*) Tool chip interface temperature during interrupted and continuous cutting with two ribs at a cutting speed of 200 m/min and (*b*) temperature change in two revolutions

Table 3 Oblique dry cutting test parameters

Run	Cutting speed (m/min)	Cooling interval (ms)	Cutting type
1	200	1.9	Interrupted
2	60	6.4	Interrupted
3	200	16.6–19.6	Interrupted and continuous

capture the periodic heat input of all five ribs after the cutting tool was fully engaged. After the longest cut (~82 mm), the cutting tool continued to cool down during the subsequent three cuts as can be seen in Fig. 8(*b*). The overall tool–chip interface temperature increased with cutting time due to heat soaking into the insert and tool holder, without sufficient time to cool down. Figure 9 shows the tool–chip interface temperature at a cutting speed of 60 m/min. The interface temperature appears to have reached a low secondary peak in cutting the fourth (*D*) and fifth (*E*) ribs, and a steady-state when cutting the fifth rib (E). It should be noted that at low cutting speeds, the unstable built-up edge forming then breaking off could induce the temperature transients due to a brief change of the tool chip contact length.

To investigate the influence of the interrupted cutting on tool–chip interface temperature, the ribs A, B, and D (Fig. 7(*a*)) were removed using an end mill to provide longer nonheating periods (Fig. 7(*b*)). In addition, the oblique cutting test was run until continuous cutting was observed. Figure 10(*a*) shows the temperature measured by the embedded sensor during interrupted and continuous cutting of 12L14 steel with a cutting speed of 200 m/min. The tool–chip interface temperature increased by 40 °C with continuous cutting under the same cutting conditions. Tool temperatures do not reach a steady-state during this cutting cycle as shown in Fig. 10(*b*).

All three cutting experiments on 12L14 steel were made using the same instrumented tool: due to the high fabrication time using a research-grade sputtering system. The low carbon (0.15 wt %) and lead (0.15–0.35 wt %) content of 12L14 steel result in a relatively low-strength and self-lubricating material. Hence, relatively low cutting temperatures are expected when cutting at low and moderate cutting speeds as shown in Figs. 8–10. Further evidence of low cutting temperatures is the fact that no chip color change was observed during all cutting experiments. The cutting speeds and cooling intervals of the dry cutting tests with run orders are listed in Table 3.

Figure 11 shows the rake face of the instrumented tool after all three oblique cutting tests. No spalling or delamination was

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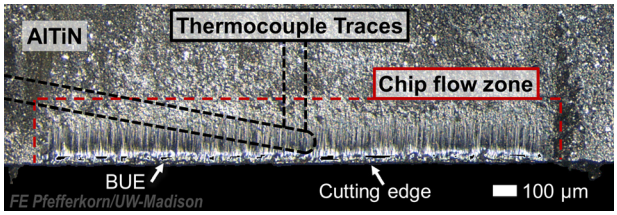


Fig. 11 Rake face of the instrumented cutting insert after all experiments

observed at the cutting zone although the deposited AlTiN coating exhibits a different composition (Table 2) than nominal. However, a built-up edge was formed due to the low cutting speed (60 m/min).

The resistance of the thin-film thermocouple traces was measured before and after the cutting tests to check the temperature sensor since thin-film thermocouple damage would result in resistance change and inaccurate temperature measurement. No measurable change in resistance was detected. The thin-film thermocouple junction was under the chip flow zone as can be seen in Fig. 11.

Conclusion

This work provides a fabrication routine for creating embedded K-Type thin-film thermocouples on commercially available tungsten carbide inserts. It is shown that this method can create a thermocouple junction within 20 μm lateral position of the cutting edge and within 2 μm of the rake face. Cutting tests show that this location is sufficiently close to the cutting zone to monitor transient temperature changes during interrupted turning tests with a relatively small cooling interval of 1.9 ms at a cutting speed of 200 m/min. It was observed that the measured tool–chip interface temperature in interrupted cutting was lower than for continuous cutting, which agrees with the expectation that the noncutting periods will decrease the overall heat input and allow the tool to dissipate heat through conduction, convection, and radiation.

The temperature measurement capabilities presented will allow further study into temperatures during milling, temperature related tool wear, and effects of cooling strategies on the interface temperature.

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