The International Journal of Advanced Manufacturing Technology (2022) 122:3957–3968
https://doi.org/10.1007/s00170-022-10093-7

ORIGINAL ARTICLE

Ineffectiveness of flood cooling in reducing cutting temperatures during continuous machining

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Received: 10 May 2022 / Accepted: 5 September 2022 / Published online: 19 September 2022

Abstract

Water-based metalworking fluids are applied in the form of a liquid jet to flood the entire cutting zone and increase the tool life. The objective of this study is to investigate the effectiveness of flood cooling in reducing the tool chip interface temperatures during continuous cutting. An instrumented smart cutting tool with a thin film temperature sensor was fabricated to accurately measure the real-time cutting temperatures from 1.3 µm below the tool chip interface in orthogonal turning of AISI 4140 steel under dry and flood cooling conditions. The cutting process was simulated in Deform 2D with the Johnson–Cook material model to present the transient temperature distributions on the coated cutting insert. The heat flux into the cutting tool was also estimated analytically and then three-dimensional finite element heat transfer simulations were performed to determine the maximum convective heat transfer of the cutting fluid in steady state. The measurements with the embedded thermocouple showed that flood cooling with a water-based cutting fluid slightly lowers the tool chip interface temperature. Moreover, the chip color may not be a good characteristic indicator to evaluate the cutting temperature in machining of metals. It was also found that flood cooling becomes more effective at a distance of approximately 150 µm from the cutting edge where the chip does not contact the rake face of the cutting tool.

Keywords Turning · Flood cooling · Cutting temperature · Modeling · Simulation

1 Introduction

High strength and abrasion resistant steel alloys are mostly used to produce the critical parts including gears, hydraulic shafts, pumps, spindles, and collars in the automotive industry. The machining operations (e.g., turning) are performed at high cutting speeds and feeds to improve the manufacturing efficiency as a consequence of high material removal rates. However, severe plastic deformation at high strain rates and friction at the tool workpiece interface enhances the temperature rise in the cutting zone, and results in accelerated tool wear, more frequent tool change, poor surface finish, dimensional deviation, and increase in the cost per part. Active cooling strategies can be used to control the cutting temperatures in the turning operation. The most common and commercial technique is the conventional flooding of the machining area with coolant nozzles although it has several adverse effects on the operators' health as well as environmental pollution due to the presence of potentially dangerous chemicals in the oil-based metal working fluids [1]. Moreover, the economic impact of the flood cooling is significant. Klocke and Eisenblätter [2] reported that the cost of the coolants can be as high as 17% of the total manufacturing cost. This percentage is even several times higher than the cost of tools (2–4%). Therefore, the cutting fluid must be efficiently employed in the machining operation to remove the heat from the cutting zone and enhance the process stability.

The ability of flood cooling to improve the tool life has been investigated through various methods. Seah et al. [3] performed turning experiments on two different medium carbon steels with uncoated tungsten carbide inserts to study the effects of water-soluble cutting fluids on the crater and flank wear. Contrary to what is commonly believed, the experiments showed that the application of flood cooling increases the magnitude of both wear mechanisms at the cutting speeds of 130–190 m/min. The wear rate with coolant was also greater at the first stages of the cutting when compared to the dry machining. Avila and Abrao [4]

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investigated the performance of flood cooling with emulsion and synthetic cutting fluids over dry condition in continuous machining of hardened AISI 4340 with alumina-based mixed cutting tools. The longest tool life was obtained when using emulsion cutting fluids without mineral oils. The tool wear with the synthetic and emulsion cutting fluids including mineral oil was larger than the one in dry machining. Moreover, reducing the concentration of the fluid from 5 to 3% increased the tool life at the cutting speed of 400 m/min while it did not affect the tool wear rate at 200 m/min. Jayal and Balaji [5] studied the influence of the metalworking fluid applications including the conventional flood cooling on the tool wear in cutting of AISI 1045 steel with various tool surface modifications (e.g., coating, chip breaker). It was observed that the crater wear on the PVD-coated cutting tools was larger in dry machining with flat-rake cutting tools, and the tools with chip breakers increased the magnitude of it under dry and flood cooling conditions. At the moderate and high cutting speeds, the flank wear was always smaller under conventional flood cooling conditions when using flat-faced multi-layer CVD-coated tools. However, Khrais and Lin [6] reported that the conventional flood cooling has an adverse effect on the tool life in machining of AISI 4140 steel with titanium aluminum nitride (TiAlN)-coated cutting inserts. A similar trend was also observed in cutting of a duplex stainless steel with the titanium carbon nitride-coated cutting tools [7]. Revuru et al. [8] conducted cutting experiments with coated tools on a medium carbon steel and the statistical analysis clearly showed that the average tool wears are similar during dry machining and conventional cooling.

Various studies were also conducted to investigate the influence of the flood cooling on the roughness of the machined surface. Paul et al. [9] studied the role of different cooling approaches on the surface finish in turning of AISI 1060 steel with two different chip breaker geometries. During the machining tests under conventional flood cooling, the surface roughness increased at a higher rate than the dry machining in both type of cutting inserts. Dhar et al. [10] observed that conventionally applied cutting fluid negatively affects the surface roughness in turning of AISI 4340 steel with carbide inserts and the growth rate increases with the machining time when compared to the dry cutting. No significant improvement in the surface roughness was obtained in turning of AISI 4140 steel with a vegetable oil-based cutting fluid [8] while emulsion based flood cooling could reduce the surface roughness by 15% in machining of a stainless steel [11]. Although the flood cooling could improve the surface finish at low cutting speeds and feeds in cutting of C45 steel with TiAlN coated tools [12], the results of the mean and peak to valley surface roughness were also similar when turning of AISI 4140 steel with ceramic tools [13]. This could be due the electrochemical interaction between the cutting tool and workpiece material under flood cooling conditions.

Tribological effects of the cutting fluid have also been investigated to explore the possibility of reduction in the friction coefficient during turning operations. Cutting and thrust forces were measured in machining of AISI 1045 steel with flat and grooved cutting tools [5], and it was found that all the types and applications of the cutting fluid used in the experiments could not decrease the friction at the tool and workpiece interface. Tangential, radial and feed forces in turning of AISI 1045 steel with PVD-coated cutting inserts were analyzed at various cutting speeds and feeds under dry and flood cooling conditions [12]. It was observed that the cutting fluid did not provide any significant improvement on the resultant forces within the range of the cutting parameters used in the machining tests. Orthogonal turning experiments were also conducted on the AISI 4130 steel under flood cooling [14], and machining force components were measured to study the performance of the cutting fluid in the machining process. The results showed that the cutting force was not significantly influenced by the conventional flood cooling while noticeable reduction was obtained in the thrust force at low feed rates. Rajaguru and Arunachalam [15] observed that the application of a water miscible oil in turning of a super duplex stainless steel can cause an increase in the axial and tangential forces by approximately 2 and 5%, respectively, in comparison to dry machining.

Due to the intense contact between the tool and workpiece in the machining process, the cutting fluid cannot provide a desired penetration through the interface, and the cooling effect of it become more important than the lubrication in continuous machining [16–18]. Therefore, the research has tended to focus on evaluating the performance of the cutting fluids in terms of cutting temperatures. An IR thermographic image was used to measure the cutting temperatures in turning of AISI 4140 steel under dry and cooling conditions [19]. It was found that the flood cooling can provide a temperature drop by 49% at a cutting speed of 100 m/min. Sivaiah and Chakradhar [11] observed that the flood cooling reduces the temperature by 45% in machining of 17–4 PH stainless steel when compared to the dry machining conditions. However, as the authors reported that the low temperatures measured by the infrared thermometer may not show the actual cutting temperatures since the chips and cutting fluid block the IR radiation. Ji et al. [14] placed a standard thermocouple wire below the cutting insert and used a thermal camera to study the effect of cooling on cutting temperature, and the measurement results with dry condition in orthogonal turning of AISI 4130 steel were compared. As expected, the temperature measurements with the thermocouple were much lower than the thermal camera measurements because it was located far away from the cutting interface and caused a temperature decrease due to the conduction heat transfer. However, significant reduction in the cutting temperature was observed with flood cooling in both measurement methods. Hoyne et al. [20] drilled a 0.7 mm diameter hole with electrical discharge machining to insert the thermocouples for the measurement of cutting temperatures in turning of Ti-6Al-4 V workpiece. A fiber optic two-color pyrometer with a diameter of 0.5 mm was also placed into the blind hole machined under the rake face to investigate the influence of the coolant pressure and flow rate on the cutting temperature during machining of aerospace materials [21]. This measurement technique was also used by Liu et al. [22] in cutting of AISI 1045 steel. There was no noticeable difference in the machining temperature under dry and wet cutting conditions at a cutting speed of 150 m/min and uncut chip thickness of 300 µm. Moreover, flood cooling increased the cutting temperatures at lower speed or feed. In these methods, the temperatures can be easily measured using the standard temperature sensors, but the machined holes weaken the strength of the cutting tools and cause chipping during the turning process. Moreover, the size of the thermocouple bead is much larger than the uncut chip thickness and contact length used in the turning operations. Since steep temperature gradients exist in the cutting zone [23], the results of conventional flooding may not reveal the actual trend of cutting temperatures when the measurement junction of the sensors is exposed to the impingement of cooling jet. Therefore, the temperature at the tool chip interface is needed to be obtained accurately and characterized for better understanding of the cooling mechanism of conventional flooding.

The tool work thermocouple technique [24] has been utilized to measure the mean tool chip interface temperature in continuous machining operations. Kurimoto et al. [18] investigated the effect of aqueous fluids on the cutting temperature in the turning operation. The temperature measurements by the tool work thermocouple method concluded that the cooling ability of the cutting fluids is inversely proportional to the concentration ratio. The temperature drop was lower at high cutting speeds and feed. Dhar and Kamruzzaman [25] also used this technique to study the effect of cooling condition on the average tool chip interface temperature in turning of AISI-4037 steel with coated carbide inserts. The measurement results showed that the conventional flood cooling enabled to decrease the cutting temperatures by approximately 7%. In turning of AISI 9310 steel with uncoated carbide tools, the reduction was by 40 °C at a cutting speed of 250 m/min [26]. Although these studies show the coolant performance of the conventional flood cooling to some extent, the uncertainty in the calibration of the tool work thermocouples has not been clarified yet. Since the temperature gradients changes with the cutting parameters through the coated layers of the cutting, the contribution rate of each coating layer to the net electromotive force (emf) will be different. The secondary thermocouple junction will also exist when the chip contacts to the tool material at different location than the interface and it will cause a variation in the thermal emf generation. Moreover, since the water-based metalworking fluids are electrically conductive, it could influence the seebeck coefficient obtained during the calibration.

The objective of this work is, thus, to accurately determine the temperatures in the cutting zone during orthogonal turning of AISI 4140 steel and evaluate the cooling effect of conventional flood cooling beyond the dry machining. Previous studies [23, 27] proved the ability of the instrumented cutting tool with an embedded thin film thermocouple to measure the tool chip interface temperatures in turning of alloy steels. By following the recipe developed in the previous research [27], the thin film temperature sensor was deposited on the rake face of a standard carbide tool, and the entire cutting tool was electrically isolated to measure the cutting temperatures under flood cooling and dry condition. The transient and steady-state cutting temperatures were also predicted for the coated cutting tools to assess the cooling ability of the cutting fluid.

2 Methodology

This section briefly provides a temperature measurement technique to determine the tool chip interface temperatures during the machining process under dry cutting and flood cooling conditions. A two-dimensional finite element software was used to simulate the transient cutting process under dry machining and convection cooling. Three-dimensional thermal analysis was also performed to compare the performance of conventional flood cooling over dry machining at the steady-state conditions. As the effects of conventional flood cooling on the tool wear (flank and crater), surface roughness and cutting forces have been studied extensively and high cutting temperatures lead to rapid tool wear, this work focused on investigating the influence of flood cooling on the tool chip interface temperature. Since the thin film thermocouple is located 1.3 um below the interface and in the vicinity of the cutting edge, evaluating the performance of flood cooling with respect to tool life is not within the scope of this study.

2.1 Experimental setup

An instrumented cutting tool was fabricated by following the recipe developed in an earlier study [27]. In this method, an alumina layer was first deposited onto the surfaces of the square shape uncoated carbide insert to electrically isolate the cutting tool. Then, the nickel/chromium thermocouple traces were sputtered on the rake face of cutting tool using the micro machined aluminum stencils. It was followed by depositing another dielectric layer to prevent the short circuit between the thermocouple junction and workpiece. The thin film thermocouple was also protected by an aluminum titanium nitride layer because it is subjected to high compressive and shear stresses during the cutting operation. With this instrumented cutting tool, the cutting temperatures can be measured only 1.3 µm below the tool chip interface.

A tool holder with a rake of 0 degree was designed and machined in a five-axis mill-turn center (Mori Seiki NT1000W). Since the cutting tests are also performed under flood cooling, a cover was designed and manufactured with 3D printing to protect the contact pad connections against the cutting fluid as shown in Fig. 1a. As shown in Fig. 1b, custom-made spring-loaded pogo pins were used to make the electrical connections between the thin film thermocouple contact pads and extension wires. A thermocouple signal conditioning circuit was used to raise the analog temperature signals in millivolts to the measurable noise-free levels and apply the cold junction compensation based on the room temperature. The temperature signals were then acquired at a sampling rate of 25 kHz with the National Instruments 9205 module. The accuracy of the temperature measurement and data acquisition system is ± 1.5% with a resolution of 0.23 °C.

Turning tests were conducted under dry cutting and conventional flood cooling on an annealed, cold-drawn AISI 4140 steel with a measured hardness of 186 HB. A 2 mm wide rib was first machined to have a constant width of cut in the orthogonal cutting tests. Since the farthest edge of the thin film thermocouple is approximately 70 µm away from the cutting edge, the instrumented cutting tool was then tested at various cutting parameters so that the measurement junction is located under the chip flow zone in both cutting conditions. This is because the thin film thermocouples measure the average temperatures [28] through the junction, and the measurements with the instrumented cutting tool would be misleading where the tool chip contact length is much greater or smaller than this value. Therefore, a constant surface speed of 200 m/min and feed of 0.050 mm/rev was determined to study the effect of cutting fluid on cutting temperatures. The deionized water and mineral oil (Hocut 795-D) were mixed at room temperature to form a clear emulsion with 6% running concentration, and it was applied through the nozzle with a diameter of 2.87 mm at a flow rate of 5 L/min and a pressure of 3.5 bar to flood the cutting zone.

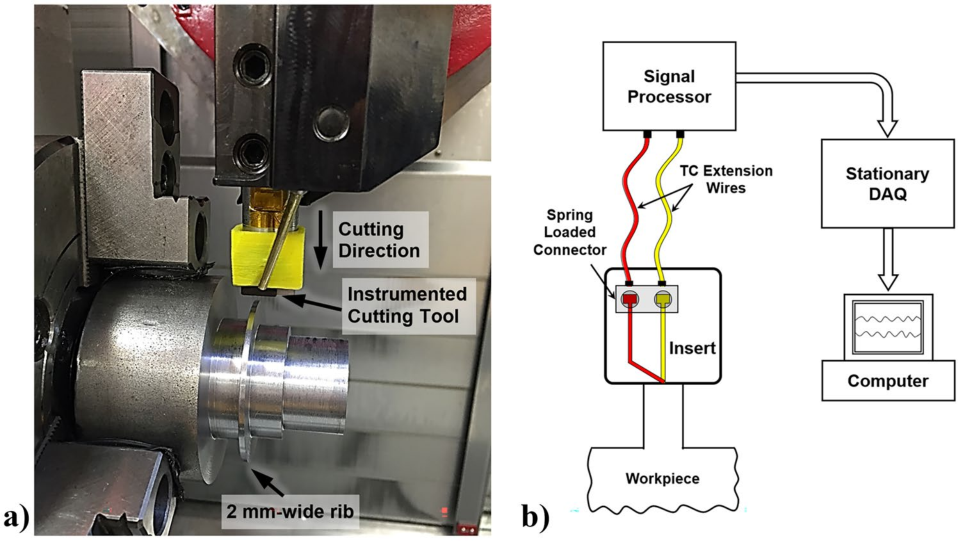
2.2 Finite element modeling

The turning operation of the instrumented smart cutting tool was also simulated to better understand the temperature distribution through the cutting tool and workpiece. Since the machining process was orthogonal, two-dimensional transient finite element modeling was first used to show the effectiveness of the flood cooling, and compare the predicted tool chip interface temperatures with the measurements of the cutting insert with thin film thermocouples. Three-dimensional steady-state heat transfer analysis was also performed to present the maximum temperature reduction of the cutting fluid in the continuous machining operations with coated cutting tools.

2.3 Transient analysis

A commercially available finite element software (DEFORM 2D) was used to simulate the orthogonal cutting of AISI 4140 steels. It is based on the updated Lagrangian formulation which couples the thermo-mechanical phenomena at large strain rates. In this FEM software,

Fig. 1 **a** Workpiece, tool, and **b** temperature measurement setup



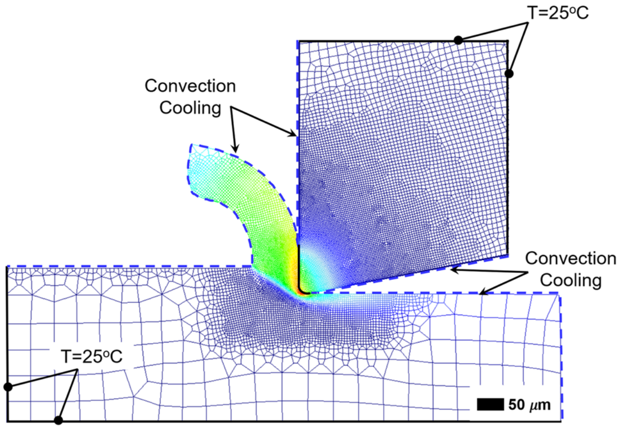


Fig. 2 Finite element mesh and boundary conditions

automatic remeshing was used to concentrate the meshes near the cutting region (i.e., primary shear and secondary deformation zones) so that the high temperature and strain gradients occurring during the machining process are calculated accurately (Fig. 2). The meshes were also coarsen away from the machining zone to reduce the computational time significantly, and simulate the continuous chip formation per tool advance within a relatively short time [29]. In this study, 35 elements were specified through the uncut chip thickness to simulate the transient cutting operation with a minimum element size of less than 1.5 µm. The total simulation time was 16 h on a 64-bit computer configured with Intel(R) Xeon(R), 3.6 GHz processor and 64 GB RAM.

The AISI 4140 steel workpiece was defined as elastic–plastic, and the cutting tool was considered a rigid body. Since the flow stress is strongly influenced by the temperature, strains and strain rates in the machining operation, the original form of the Johnson–Cook material model [30] was used to describe the material behavior and chip formation during the orthogonal cutting process. The flow stress in this model is expressed as

$$\sigma = (A + B\varepsilon^n)\left(1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right)\left(1 - \left(\frac{T - T_o}{T_m - T_o}\right)^m\right) \quad (1)$$

where A is the yield strength, B is the hardening modulus, n is the strain-hardening exponent, C is the strain rate sensitivity, m is the thermal sensitivity, T_m, is the melting temperature, $\dot{\varepsilon}$ is the strain rate, and T_o is the ambient temperature. The reference strain rate ($\dot{\varepsilon}_o$) of the workpiece material was taken as 1.0 s^{-1}. All the other parameters were compiled from [31] and listed in Table 1. A constant shear friction model with a coefficient of 0.577 [32] was employed to define the interaction between the cutting tool and workpiece material at the interface.

Table 1 Johnson–Cook model parameters for AISI 4140 steel [31]

A	595 [MPa]
B	580 [MPa]
C	0.023 [-]
n	0.133 [-]
m	1.03 [-]
T_o	1793 [K]
T_m	300 [K]

Since the fabricated instrumented cutting tool has coating layers for electrical isolation and protection, aluminum oxide and aluminum titanium nitride layers with a total thickness of 2 µm were defined on the rake and flank faces of the uncoated tungsten carbide cutting tool material. The nodal velocities at the bottom of the workpiece material were specified as 0 and the tool was moved from right to left at the rate of cutting speed. The rake and flank faces of the cutting tool as well as the top and left sides of the workpiece are exposed to the natural and forced convection heat transfer, respectively, at a constant fluid temperature of 25 °C under dry and flood cooling conditions. As the FEM software remeshes the elements automatically during the deformation, the heat was also removed from the chip surface by convection at the same rate. Table 2 shows all the physical, thermal and mechanical properties of the workpiece and tool materials used in the simulations. Temperature-dependent thermal properties were also used for the workpiece material to accurately simulate the cutting process.

2.4 Steady-state analysis

Three-dimensional steady-state thermal analysis was performed in Ansys software to present the changes in the temperature distribution with and without conventional flood cooling. The CAD file of the square shape cutting insert was downloaded for the manufacturer's website [33], and aluminum oxide and aluminum titanium nitride layers were added on the entire surface of the tool because they act as thermal barriers and significantly affect the heat dissipation during the machining operation. The total heat flux into the cutting tool was assumed constant and estimated using the modified form of Loewen and Shaw's orthogonal cutting model [34] with the temperature-dependent thermal and physical properties of the AISI 4140 steel alloy. Since the chip is in contact with the cutting tool perfectly at the interface, convection heat transfer was applied on the entire flank and rake faces except for the contact region. As the thermal analysis is performed at steady-state conditions, it cannot be assumed that the back and bottom sides of the cutting insert are at a constant temperature. Therefore, heat transfer coefficients on these surfaces were calculated based on the conduction resistance through the tool holder, and defined

Table 2 Properties of workpiece and tool materials and conditions

Property	AISI 4140	WC-6%Co	Al_2O_3	AlTiN
Thermal conductivity [W/m K]	f(T), 41.7–34.1	94 [33]	37	5
Density [g/cm^3]	7.85	14.85 [33]	3.89	5.22
Specific Heat [J/kg K]	f(T), 254–610	250 [33]	342	150
Thermal expansion coefficient [µm/m K]	f(T), 10.8–14.9	5	8.4	9.2
Poisson's ratio [-]	0.3	0.25	0.22	0.23
Shear friction coefficient [-]	0.577 [32]			
Convection heat transfer coefficient [W/m^2 K]	20 (dry)–60,465 (flood cooling) [34]			
Interface heat transfer coefficient [W/m^2 K]	100,000 [35]			

in Ansys FEM software. A high density of tetrahedron mesh structure was also defined around the contact zone and coating layers since steep temperature gradients are expected in these regions and the accuracy of the finite element models are directly related to the element size.

3 Results and discussions

This section provides the tool chip interface temperatures measured by the instrumented smart cutting tool with thin film thermocouples. The chips obtained during the machining process under dry cutting and flood cooling were also collected to study the influence of the chip formation on the cutting temperatures. The transient and steady-state temperature distributions through the cutting tool are also presented to show the effect of cutting fluid in removing the heat from the cutting tool during the turning operation of AISI 4140 steel.

Since the previous researches [23, 27] showed the capability of the embedded thermocouples in measuring the transient temperatures in oblique turning of low and medium carbon steels at various cutting parameters, a higher cutting speed (200 m/min) was selected in this work to have a significant change in the color of the metal chips, and investigate the effect of conventional flood cooling on the tool chip interface temperatures. The feed was kept constant at 0.050 mm/rev to concentrate the heat input in a relatively small area for the cutting process while the width of cut was 2 mm in the orthogonal cutting tests. A CNC program was written to perform the orthogonal turning process at a constant surface speed under dry cutting condition. As shown in Fig. 3, the turning operation was initially carried out under dry cutting conditions. The first part of the subsequent cutting process was also machined in dry cutting condition to show the repeatability of the temperature measurements by the instrumented cutting tool. Since activating the coolant pump and delivering the cutting fluid into the machining zone take time before the wet cutting, a transition (dwell) time was also defined in dry cutting to avoid the temperature rise due to the heat accumulation. Figure 3 shows the temperature measurement results with and without the metalworking fluids.

As shown in Fig. 3, the cutting tool with the embedded thin film thermocouple measured the maximum temperature of approximately 750 °C in both dry and wet machining. The mean temperatures are 680 °C and 651 °C under dry machining and flood cooling, respectively. Since the temperature of 29 °C is within the fluctuation of measurements which could be obtained due to the sticking and sliding friction of the chips, it is concluded that the change in the tool chip interface temperature was negligible under conventional flood cooling. After the machining operation, the tool temperature decreases rapidly as the cooling jet could touch the chip flow region where the measurement junction of the thermocouple is located.

Since the color of metal chips has been used to evaluate the level of the chip temperatures in machining of steel alloys [36–39], the chip formations were also qualitatively characterized in terms of the color and radius of curvature to investigate the effect of these parameters on the cutting temperature. As shown in Fig. 4, the chips were formed ribbon widthwise and continuously, and the color of the metal chip was dark blue in dry machining while it was silverly white under flood cooling. Since the measurements showed that cutting temperatures are almost same in both conditions, the water-based metalworking fluid most likely protected the steel metal chips against the oxidation at high temperatures. Therefore, the color of chips is not a good indicator in the comparison of the tool chip interface temperatures in machining of steel alloys. It was also observed that the radius of the chips became smaller when applying the cutting fluid onto the machining zone. The coolant could reduce the temperatures much greater than the natural convection on the rough side of the chips, create higher thermal contractions in that region, and cause a reduction in the radius of curvature. Since the junction of the thin film thermocouple was located very close to the cutting edge, it did not affect the temperature measurements during the machining operation. Otherwise, significant temperature decrease could be observed due to the large size and/or wrong location of the sensing device, and it would not give an accurate assessment.

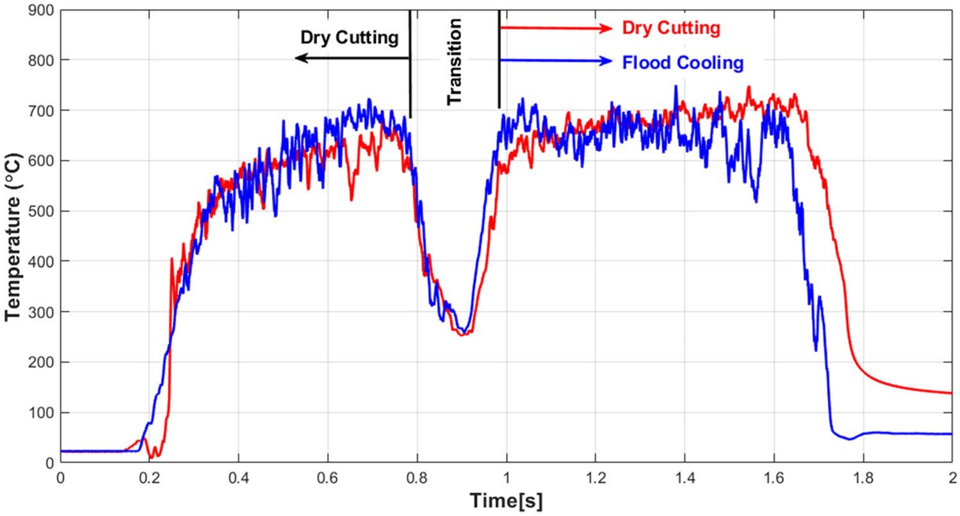


Fig. 3 Tool chip interface temperatures measured by the instrumented cutting tool under dry machining and flood cooling

Further investigation was focused on simulating the machining operation to understand the temperature distribution and effectiveness of the flood cooling through the cutting tool. Since the cutting process is orthogonal and the machined rib is wide enough (2 mm), two-dimensional finite element analysis was performed in a commercially software (Deform 2D) to show the transient thermal response of the coated cutting tool. Natural convection heat transfer with a coefficient of 20 W/m^2 K was used through the workpiece and cutting insert for dry machining while the average heat transfer coefficient for the water-based coolant nozzle was calculated as 60,465 W/m^2 K using the analysis of the single impingement jets [34]. A heat transfer coefficient of 100,000 W/m K [35] was used between the workpiece and cutting contact. Figure 5 shows the predicted average tool chip interface temperatures as a function of time for dry and wet machining. The temperature data was extracted from the rake face of the cutting tool at a spatial resolution of 5 µm and the mean of them was calculated in Matlab for each simulation time step. The largest time interval was less than 1 µs in the simulations. The maximum average temperature was predicted to be 618 °C in dry cutting while the application of the convective cooling can reduce the cutting temperature by 5 °C. It should be noted that the transient FEM simulations underestimated the tool chip interface temperatures by 9% and 6% for dry and wet machining conditions, respectively, although the trend was similar. This could be because of the total cutting length as the temperatures quickly reach the quasi steady-state condition and increase slowly during the machining operation. Since the real cutting time was three orders of magnitude larger than the simulations, which is required to perform the analysis with an acceptable

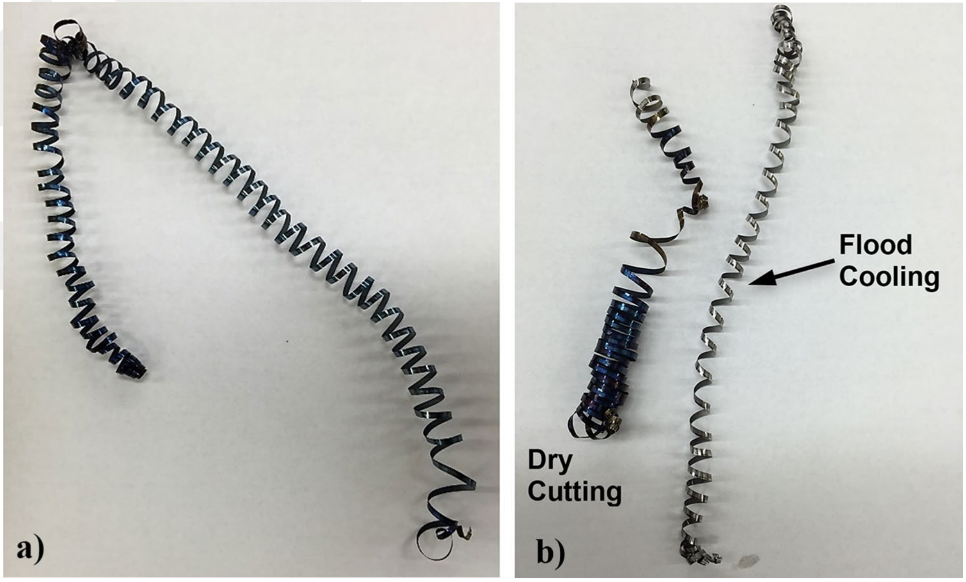


Fig. 4 Chip morphology under **a** dry machining and **b** dry and flood cooling

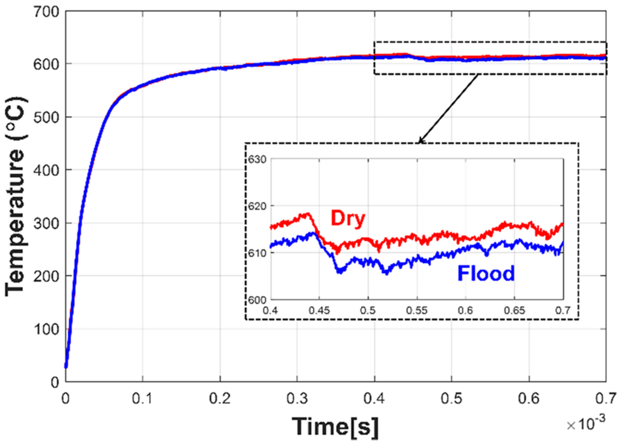


Fig. 5 Average predicted tool chip interface temperatures under dry machining and flood cooling

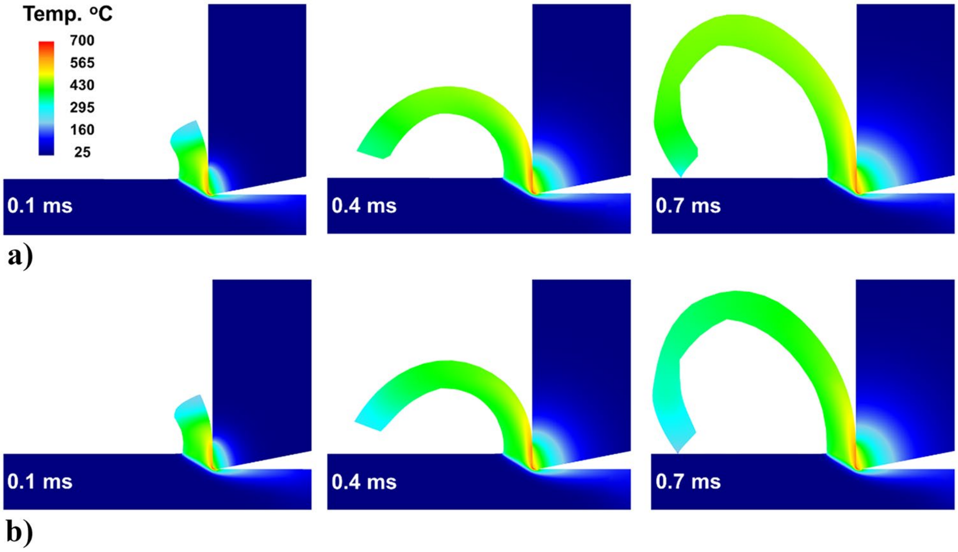
computational time, these deviations are expected for the comparisons of the experimental and predicted data.

The instantaneous temperature distributions were also presented to show the chip formation and influence of the conventional flood cooling in the machining zone. As shown in Fig. 6, continuous chip formation was obtained as observed in the machining experiments (Fig. 4). Although the convective flood cooling reduces the temperature of the chips to some degrees, the temperature at the tool chip interface is still close to the one in the dry machining because the cooling is not effective in the contact region. It should also be noted that unlike the chips obtained during the cutting tests, there is no visible difference in the chip radius between the dry and wet machining simulations. This could be due to the assumption of the uniform convective heat transfer over the entire workpiece surface including the metal chips. On the other hand, the pressure of the cooling jet may act on the chip surface and cause a decrease in the chip radius. The coolant pressure could be defined as one of the boundary conditions and the thermal analysis could be coupled with the computational fluid dynamic analysis to better understand the effect of flood cooling on the chip formation.

Since the temperature changes in the cutting tool cannot be seen clearly from Fig. 6, the temperatures of each node through the rake face were extracted to show the temperature gradients as a function of position for the specified time intervals. As shown in Fig. 7, the conventional flood cooling can only provide a temperature drop by 5 °C at the tool chip interface while the reduction can be approximately four times larger at a distance of 150 µm from the cutting edge where the chips are not in contact with the cutting tool. It is expected that the rate will increase with the cutting time.

Steady-state thermal analysis was also performed to provide the maximum efficiency of the conventional flood cooling in removing the heat from the cutting tool. The heat input was estimated with the analytical heat transfer model for orthogonal machining [34] which is based on the Loewen and Shaw's method [40]. By using the temperature-dependent thermophysical properties of AISI 4140 steel, the heat flux for the cutting parameters used in the experiments was calculated to be 443 W/m^2. This value is also consistent with the average heat flux of the transient machining simulations. It was assumed that the heat transfer rate into the cutting tool does not change with the tool cooling conditions as the temperature gradients through the interface were similar in the transient analysis at dry and wet cutting, and the standard deviation of the tool chip interface temperature at the last step of the transient analysis is 16.6 °C. Then, three-dimensional thermal analysis was carried out to present the steady-state response of flood cooling over the

Fig. 6 Temperature distributions under **a** dry machining and **b** flood cooling at the cutting times of 0.1, 0.4, and 0.7 ms



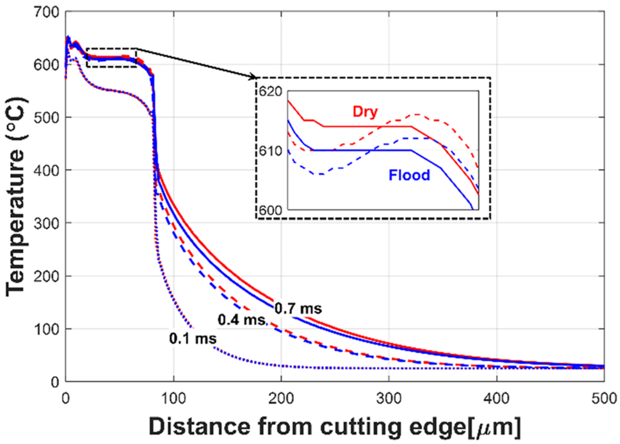


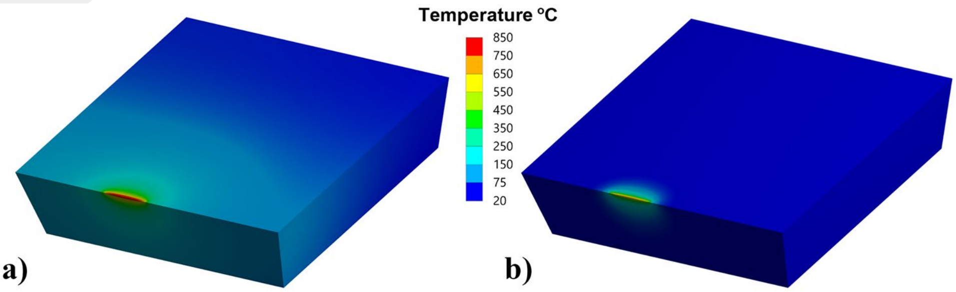
Fig. 7 Temperatures through the rake face of cutting tool under dry machining and flood cooling at the cutting times of 0.1, 0.4, and 0.7 ms

dry machining. Figure 8 shows the temperature distribution of the instrumented cutting tool with the coating layers of Al_2O_3 and AlTiN.

As can be seen in Fig. 8, the cutting fluid with conventional flooding can greatly decrease the temperature of the cutting insert except for the contact region because the heat first needs to spread out through the insert and coating materials, then it is removed by convection over the rake and flank faces of the inserts as well as conduction into the tool holder. The temperature changes through the rake and flank faces of the cutting tool are demonstrated in Fig. 9. The maximum cutting temperature was predicted as 846 °C in dry machining of AISI 4140 steels at steady-state conditions with a cutting speed of 200 m/min, feed of 0.050 mm/rev and width of 2 mm. As the heat continues to accumulate in the cutting tool after the quasi steady-state cutting condition when the temperature is measured by the instrumented cutting tool, it resulted in a predicted maximum temperature that was approximately 24% greater than the experimental measurement. On the other hand, the deviation between the steady-state simulation and thin film thermocouple measurements is only 3.5% for conventional flood cooling condition. It could be because the heat is dissipated from the cutting zone into the cutting tool which provides greater heat removal by convection. The steady-state thermal analysis was also performed when the heat transfer coefficient is halved. It was observed that the flood cooling can provide temperature reductions of 26% and 20% to the tool chip interface at the heat transfer coefficients of 60,465 W/m^2 K and 30,000 W/m^2 K while these percentage rates are approximately three times higher at only 1 mm away from the cutting edge. Therefore, the influence of the flood cooling on the cutting temperature cannot be evaluated accurately when the measurement location of the temperature sensors are not located under the interface region [20, 21]. On the other hand, the reduction difference was slightly lower through the flank face since the direction of the heat flux is perpendicular to the rake face. Decreasing the heat transfer coefficient by 50%, which can be obtained reducing the flow rate of the coolant significantly, causes a temperature increase of 48 °C at the cutting edge. It should be noted that the convection heat transfer coefficient can be further increased when using a coolant with higher specific heat and thermal conductivity. However, the sensitivity analysis of the tool chip interface temperature showed that the increase in the heat transfer coefficient of 50% can only reduce the cutting temperature by approximately 10 °C in orthogonal turning of Ti6Al4V alloy [34]. Moreover, the change in the coolant flow rate drives a small impact on the cutting temperature. On the other hand, reducing the tool chip interface friction using a cutting fluid with better lubricant capacity can significantly decrease the tool chip interface temperature, but Childs [41] stated that the lubricant can only penetrate into the contact at low cutting speeds (less than 30 m/min) and self-lubrication occurs in machining of steels at high speeds due to the local thermal softening of the chips by the frictional heat. Therefore, for the cutting parameters used in this study, the tool chip interface temperature is not expected to change significantly when flooding the machining zone with another cutting fluid having better cooling and lubricant capacity.

It should be noted that the time to reach the steady-state condition of the cutting insert is much larger than the continuous

Fig. 8 Steady-state temperature distributions of the cutting insert under **a** dry machining and **b** flood cooling with the heat transfer coefficient of 60,465 W/m^2 K



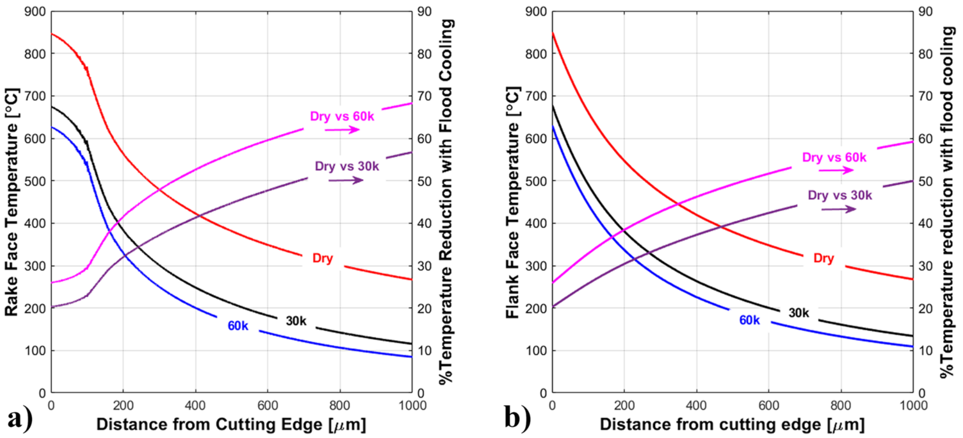


Fig. 9 Steady-state temperatures through the a rake and b flank face of cutting insert under dry machining and flood cooling with heat transfer coefficients of 30,000 and 60,465 W/m^2 K

machining time used for the practical applications of turning operation. Therefore, the real-time temperature measurements and transient analysis should be used to evaluate the performance of the cutting fluids as the interface temperature can reach about 700 °C within less than a second (Fig. 3). Moreover, the effectiveness of the flood cooling will become worse when the cutting tool has a thicker coating. In this study, the total thickness of coated layers is approximately 2 µm. However, the coating thickness of the commercial inserts can be up to 9.5 µm [42] to improve the wear resistance of the cutting tool in machining of steels alloys. Since the thermal conductivities of the most protective coating materials are much lower than the tungsten carbide cutting tools (Table 1), these layers will increase the magnitude of the spreading and conduction resistances and significantly reduce the heat removal capability of the cutting fluids. The hard coating materials with high thermal conductivities such as diamond-like carbon (DLC) can be used to increase the cooling performance of the flood cooling as the thermal conductivity of DLC coating layer is in the range of 400 to 1000 W/m K [43]. Moreover, internal cooling strategies [44] can be preferred and/or the chip formation should be interrupted [45] to provide an effective cooling for the turning operations. As shown in all the temperature measurements and simulations, the conventional flood cooling is not effective in the turning operation due to the continuous chip blockage. Therefore, this type of cooling should be used in milling [46] and vibration or modulation-assisted machining [47] so that the jet of cutting fluid enters into the cutting zone to provide the desired cooling and lubrication. However, although the overall cutting edge temperatures can be reduced with flood cooling in these operations, it will increase the temperature difference between the active and no active period of cutting, and the greater thermal cycling load could adversely influence the tool life.

4 Conclusion

This paper presents the tool chip interface temperature measurements and predictions in orthogonal turning of AISI 4140 steels under dry cutting and conventional flood cooling. The cutting temperatures were measured by an instrumented cutting tool with embedded thin film thermocouples located 1.3 µm below the tool chip contact zone. The real-time measurement results showed that the flood cooling with water-based metalworking fluids decreased the average interface temperature by only 4% although it significantly reduced the radius of the curvature of the continuous ribbon chip. Moreover, it was found that cutting chips of steel alloys cannot be used for the performance comparison of the flood cooling with respect to the tool chip interface temperature reduction in the continuous machining operation. Johnson–Cook material model was also employed on a commercial FEM software to study the transient temperature distribution through the cutting zone under dry and wet cutting conditions. The FEM simulations also showed that the convective cooling is most effective where the chips are not in contact with the cutting insert, and 4 times greater cooling can be obtained on the rake face farther away from the tool chip contact area. Three-dimensional steady-state thermal analysis was performed on the coated cutting tool to show the maximum possible cooling capacity of the cutting fluid in the continuous machining operations. It was concluded that the conventional flood cooling can achieve significant temperature reductions on the cutting tool, except for the tool chip interface, and using a fluid with 50% lower cooling ability could lead to a temperature rise by only 7% at the cutting edge of the coated insert. Therefore, this type of cooling should be used in interrupted cutting operations (i.e., milling, vibration, or modulation-assisted machining) to decrease the overall cutting temperatures in thermal cycling.

Acknowledgements The author gratefully acknowledges Professor Frank E. Pfefferkorn and the Machine Tool Technology Research Foundation (MTTRF) for the availability of the Mori Seiki NT1000/W mill-turn center.

Author contribution The author is solely responsible for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Funding This work was partially supported by the Department of Mechanical Engineering at the Mus Alparslan University.

Availability of data and material The data obtained in the framework of this study are available to the journal upon request.

Code availability The codes are available to the journal upon request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication The author has consented to publish the research article in the journal.

Conflict of interest Not applicable.

References

1. Bennett EO (1983) Water based cutting fluids and human health. Tribol Int. https://doi.org/10.1016/0301-679X(83)90055-5
2. Klocke F, Eisenblaetter G (1997) Dry cutting. CIRP Ann 46:519–526. https://doi.org/10.1016/S0007-8506(07)60877-4
3. Seah KHW, Li X, Lee KS (1995) The effect of applying coolant on tool wear in metal machining. J Mater Process Tech. https://doi.org/10.1016/0924-0136(94)01688-W
4. Ávila RF, Abrão AM (2001) The effect of cutting fluids on the machining of hardened AISI 4340 steel. J Mater Process Technol. https://doi.org/10.1016/S0924-0136(01)00891-3
5. Jayal AD, Balaji AK (2009) Effects of cutting fluid application on tool wear in machining: Interactions with tool-coatings and tool surface features. Wear. https://doi.org/10.1016/j.wear.2009.06.032
6. Khrais SK, Lin YJ (2007) Wear mechanisms and tool performance of TiAlN PVD coated inserts during machining of AISI 4140 steel. Wear. https://doi.org/10.1016/j.wear.2006.03.052
7. Krolczyk GM, Nieslony P, Maruda RW, Wojciechowski S (2017) Dry cutting effect in turning of a duplex stainless steel as a key factor in clean production. J Clean Prod. https://doi.org/10.1016/j.jclepro.2016.10.136
8. Revuru RS, Zhang JZ, Posinasetti NR (2020) Comparative performance studies of turning 4140 steel with TiC/TiCN/TiN-coated carbide inserts using MQL, flooding with vegetable cutting fluids, and dry machining. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-020-05378-8
9. Paul S, Dhar NR, Chattopadhyay AB (2001) Beneficial effects of cryogenic cooling over dry and wet machining on tool wear and surface finish in turning AISI 1060 steel. J Mater Process Technol. https://doi.org/10.1016/S0924-0136(01)00839-1
10. Ranjan Dhar N, Islam S, Kamruzzaman M (2007) Effect of minimum quantity lubrication (MQL) on tool wear, surface roughness and dimensional deviation in turning AISI-4340 steel
11. Sivaiah P, Chakradhar D (2018) Effect of cryogenic coolant on turning performance characteristics during machining of 17–4 PH stainless steel: a comparison with MQL, wet, dry machining. CIRP J Manuf Sci Technol. https://doi.org/10.1016/j.cirpj.2018.02.004
12. Leppert T (2011) Effect of cooling and lubrication conditions on surface topography and turning process of C45 steel. Int J Mach Tools Manuf. https://doi.org/10.1016/j.ijmachtools.2010.11.001
13. Elbah M, Laouici H, Benlahmidi S et al (2019) Comparative assessment of machining environments (dry, wet and MQL) in hard turning of AISI 4140 steel with CC6050 tools. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-019-04403-9
14. Ji X, Li B, Zhang X, Liang SY (2014) The effects of minimum quantity lubrication (MQL) on machining force, temperature, and residual stress. Int J Precis Eng Manuf. https://doi.org/10.1007/s12541-014-0612-6
15. Rajaguru J, Arunachalam N (2020) A comprehensive investigation on the effect of flood and MQL coolant on the machinability and stress corrosion cracking of super duplex stainless steel. J Mater Process Technol. https://doi.org/10.1016/j.jmatprotec.2019.116417
16. Sales WF, Diniz AE, Machado AR (2001) Application of cutting fluids machining processes. Rev Bras Ciencias Mec Brazilian Soc Mech Sci. https://doi.org/10.1590/S0100-73862001000200009
17. Ezugwu EO, Bonney J, Yamane Y (2003) An overview of the machinability of aeroengine alloys. J Mater Process Technol. https://doi.org/10.1016/S0924-0136(02)01042-7
18. Kurimoto T, Barrow G, Davies BJ (1982) The influence of aqueous fluids on the wear characteristics and life of carbide cutting tools. CIRP Ann - Manuf Technol. https://doi.org/10.1016/S0007-8506(07)63261-2
19. Roy S, Ghosh A (2014) High-speed turning of AISI 4140 steel by multi-layered TiN top-coated insert with minimum quantity lubrication technology and assessment of near tool-tip temperature using infrared thermography. Proc Inst Mech Eng Part B J Eng Manuf. https://doi.org/10.1177/0954405413514570
20. Hoyne AC, Nath C, Kapoor SG (2015) On cutting temperature measurement during titanium machining with an atomization-based cutting fluid spray system. J Manuf Sci Eng Trans ASME. https://doi.org/10.1115/1.4028898
21. Klocke F, Krämer A, Sangermann H, Lung D (2012) Thermo-mechanical tool load during high performance cutting of hard-to-cut materials. In: Procedia CIRP
22. Liu H, Meurer M, Schraknepper D, Bergs T (2022) Investigation of the cutting fluid's flow and its thermomechanical effect on the cutting zone based on fluid–structure interaction (FSI) simulation. Int J Adv Manuf Technol 121:267–281. https://doi.org/10.1007/S00170-022-09266-1
23. Kesriklioglu S, Arthur C, Morrow JD, Pfefferkorn FE (2019) Characterization of tool–chip interface temperature measurement with thermocouple fabricated directly on the rake face. J Manuf Sci Eng. https://doi.org/10.1115/1.4044035
24. Stephenson DA (1993) Tool-work thermocouple temperature measurements—theory and implementation issues. J Manuf Sci Eng Trans ASME. https://doi.org/10.1115/1.2901786
25. Dhar NR, Kamruzzaman M (2007) Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition. Int J Mach Tools Manuf. https://doi.org/10.1016/j.ijmachtools.2006.09.018
26. Khan MMA, Mithu MAH, Dhar NR (2009) Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using

vegetable oil-based cutting fluid. J Mater Process Technol. https://doi.org/10.1016/j.jmatprotec.2009.05.014

27. Kesriklioglu S, Morrow JD, Pfefferkorn FE (2018) Tool-chip interface temperature measurement in interrupted and continuous oblique cutting. J Manuf Sci Eng Trans ASME. https://doi.org/10.1115/1.4038140
28. Heigel JC, Ivester RW, Whitenton EP (2008) Cutting temperature measurements of segmented chips using dual-spectrum high-speed microvideography. In: Transactions of the North American Manufacturing Research Institution of SME
29. Özel T (2006) The influence of friction models on finite element simulations of machining. Int J Mach Tools Manuf. https://doi.org/10.1016/j.ijmachtools.2005.07.001
30. Johnson GR, Cook WH (1983) A constitutive model and data from metals subjected to large strains, high strain rates and high temperatures. In: Proc. 7th Int. Symp. on Ballistics, The Hague, Netherlands
31. Pantalé O, Bacaria JL, Dalverny O et al (2004) 2D and 3D numerical models of metal cutting with damage effects. Comput Methods Appl Mech Eng. https://doi.org/10.1016/j.cma.2003.12.062
32. Astakhov VP (2006) Tribology of metal cutting. Elsevier
33. Understanding cemented carbide. https://www.sandvik.coromant.com/en-us/knowledge/materials/pages/cutting-tool-materials.aspx. Accessed 8 Mar 2022
34. Kesriklioglu S, Pfefferkorn FE (2019) Prediction of tool-chip interface temperature in cryogenic machining of ti-6al-4v: analytical modeling and sensitivity analysis. J Therm Sci Eng Appl. https://doi.org/10.1115/1.4040990
35. Iqbal SA, Mativenga PT, Sheikh MA (2008) An investigative study of the interface heat transfer coefficient for finite element modelling of high-speed machining. Proc Inst Mech Eng Part B J Eng Manuf. https://doi.org/10.1243/09544054JEM1179
36. Ning Y, Rahman M, Wong YS (2001) Investigation of chip formation in high speed end milling. In: J Mater Process Technol
37. Su G, Xiao X, Du J et al (2020) On cutting temperatures in high and ultrahigh-speed machining. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-020-05054-x
38. Chen SH, Luo ZR (2020) Study of using cutting chip color to the tool wear prediction. Int J Adv Manuf Technol. https://doi.org/10.1007/s00170-020-05354-2
39. Li B, Zhang S, Wang R, Fang Y (2019) Toward understanding of metallurgical behaviours in dry machining of hardened steel: phase transformation and surface oxidation. J Mater Res Technol. https://doi.org/10.1016/j.jmrt.2019.06.042
40. Loewen EG, Shaw MC (1954) On the analysis of cutting-tool temperatures. ASME Trans 76:217–225
41. Childs THC (2006) Friction modelling in metal cutting. Wear. https://doi.org/10.1016/j.wear.2005.01.052
42. Platit. https://www.platit.com/media/filer/2020/compendium_en61.pdf. Accessed 21 Apr 2022
43. Roy M (2017) Protective hard coatings for tribological applications. In: Materials under extreme conditions: recent trends and future prospects
44. Rozzi JC, Sanders JK, Chen W (2011) The experimental and theoretical evaluation of an indirect cooling system for machining. J Heat Transfer. https://doi.org/10.1115/1.4002446
45. Mann JB, Guo Y, Saldana C et al (2011) Modulation-assisted machining: a new paradigm in material removal processes. In: Adv Mat Res
46. Karaguzel U, Budak E (2018) Investigating effects of milling conditions on cutting temperatures through analytical and experimental methods. J Mater Process Technol. https://doi.org/10.1016/j.jmatprotec.2018.07.024
47. Gao Y, Mann JB, Chandrasekar S et al (2017) Modelling of tool temperature in modulation-assisted machining. In: Procedia CIRP