Infrared Measurement of the Temperature at the Tool-Chip Interface While Machining Ti-6Al-4V

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Abstract

The challenges associated with machining titanium alloys (e.g., Ti-6Al-4V) are directly related to high cutting tool temperatures due to the low thermal conductivity of these alloys and the heat generated in the primary shear zone and at the tool-chip interface. Transparent yttrium aluminum garnet (YAG) tools are used in the current study to orthogonally machine a Ti-6Al-4V disk. Although YAG tools are not industrially relevant, they permit the temperature on the tool-chip interface to be measured. These measurements are relevant because they can be used to validate cutting models, which are in-turn used by industry to improve cutting processes. An infrared camera, using a high frame rate (700 Hz) and a large field of view (20 mm²), observes the tool-chip interface through these tools and measures the temperature distribution and records the chip curl and breakage while cutting with a feed rate of 50 $\mu\text{m}/\text{rev}$ and cutting speeds between 20 m/min and 100 m/min. In addition to the temperature measurements, cutting forces are recorded and the chip formation is documented

[☆]Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose. This publication was prepared by United States Government employees as part of their official duties and is, therefore, a work of the U.S. Government and not subject to copyright.

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using a high-speed (3 kHz) visible-light camera. Results show that radiant temperature increases with speed while the cutting and thrust forces show no significant trend. Analysis of the temperature distribution from one edge of the chip to the other reveals differences from 6 % to 21 %, indicating that caution must be used when performing thermographic measurements of chip temperatures from the side of the cutting zone. Finally, post process measurements are performed using a scanning white-light interferometer to investigate any correlation between the tool condition and cutting temperature. Although the qualitative analysis of some cases appears to reveal a correlation between the condition of the YAG tool and the measured temperature distribution, no conclusions can be drawn from this study.

Keywords: Metal cutting, titanium, infrared temperature measurement, transparent tool, tool wear, model validation

1. Introduction

The light weight and high strength of titanium alloys make them ideal materials for aerospace applications. Unfortunately, they are difficult to machine because their low thermal conductivity prevents much of the heat generated at the tool tip from escaping, which according to Komanduri and Von Turkovich (1981), leads to increased tool wear and necessitates decreased cutting speeds compared to other metals. Process improvements can be realized through measurement of the tool-chip interface temperatures (Al Huda et al. (2002a)), which are influenced by the primary and secondary shear zones as well as the friction at the tool-chip contact. Unfortunately, measuring these effects is a challenging prospect that Davies et al. (2007) discussed in great length.

Information about the temperature at the tool-chip interface has been acquired through measurements using thermocouples. For instance, Hong and Ding (2001) embedded a thermocouple flush with the insert rake face to validate their cutting model and to investigate the impact of cryogenic cooling. Similarly, Arriola et al. (2011) embedded several thermocouples into the insert

flank to measure temperatures in conjunction with cutting forces to assess the machinability of different grades of steel. Unfortunately, in both of these studies the placement of the thermocouple relative to the tool-chip interface was limited due to the need to maintain the structural integrity of the insert; therefore, direct measurement of the interface temperatures was not possible. Carvalho et al. (2006) used thermocouple measurements and inverse simulation to estimate the heat flux through the interface. Although this approach enables the temperature distribution in the tooling to be numerically calculated, its accuracy is inherently dependent on the model and the boundary assumptions. The tool-work thermocouple method indicates the temperature at the interface, though as Stephenson (1993) concluded, this method only measures the average thermal electromotive force at the interface and is sensitive to the response linearity and the temperature distribution at the interface.

The ability to optically measure temperatures near the shear zone and the tool-chip interface was first demonstrated by Boothroyd (1961). The side of the tool, chip, and workpiece was exposed to an infrared photographic plate for 15 s to acquire a single image during an orthogonal turning operation. Though the long exposure time prevented the discernment of any temporal fluctuations, this approach has been improved over the years by other researchers and important observations have been made about the process. Miller et al. (2003) used an infrared camera to image the side of the tool at a rate of 30 Hz while cutting American Iron and Steel Institute (AISI) 1025 steel and found the peak temperature on the side of the tool to be away from the cutting edge and behind the rake face. Davies et al. (2003) measured temperature distribution on the sides of the tool, the AISI 1045 steel workpiece, and the resulting chips made with various feedrates and compared the results to those from finite element analysis (FEA). This comparison revealed that cutting temperatures increased with feed and that FEA could capture this trend. Focusing only on the side of the chip and not the tool, Sutter et al. (2003) found the maximum temperature to be near the rake surface, approximately two thirds the uncut chip thickness away from the cutting edge. Heigel et al. (2008) observed orthogonal cutting

of AISI 1045 steel using visible and infrared cameras simultaneously and found that peak temperature at the side of the tool-chip interface was directly related to cutting speed but inversely related to the cutting forces.

Despite the wealth of data that can be acquired from thermal measurements made from the side of the cutting process, this approach does have its limitations. First, Heigel and Whitenton (2009) demonstrated that the rapid temporal and spatial temperature fluctuations experienced in segmented chips can lead to significant measurement errors if the integration time and the camera magnification are not sufficient. Although the error introduced by these effects is more pronounced in the shear band than it is near the tool-chip interface, a follow up study by Heigel and Whitenton (2010) found that a significant error could occur in both the shear band and the interface due to variations in the chip and tool emissivity as well as the point spread function of the camera. Finally, temperatures measured on the side surfaces of the cutting processes may not be indicative of the temperatures in the middle of the interface. As part of their study, M'Saoubi and Chandrasekaran (2004) estimated that the difference in temperature between their infrared measurements of the side plane of the tool and the middle plane was approximately only 1%. However, no direct measurements of the center of the tool-chip interface could be performed to confirm this calculation. A greater error was found by Soler et al. (2015) using numerical and experimental means. Their results demonstrated that that relying on the temperatures on the side of the tool could lead to errors of 30 % or more.

The temperature in the middle of the tool-chip interface can only be measured optically if the tool is modified. For instance, Müller-Hummel and Lahres (1995) used an infrared camera to measure the temperature distribution on the tool-chip interface through a hole through the tool that was capped with a diamond window. Results showed that Ti-6Al-4V cutting temperatures increased with both speed and feed. Although this method provides a glimpse at the tool-chip interface, the dissimilarities between the conductivity of the underlying diamond window ($2200 \text{ W m}^{-1} \text{ K}^{-1}$) and the insert ($110 \text{ W m}^{-1} \text{ K}^{-1}$)

for tungsten carbide) could influence the results. In a similar effort, Al Huda et al. (2002b) used a single-point, two-color pyrometer to measure the cutting temperatures through a fiber aimed at the rake surface through a bored hole that terminated 1 mm from the rake surface. The authors also embedded their fiber into a steel workpiece to measure the temperature during a milling process. Al Huda et al. (2002a) also inserted an optical fiber into a hole that granted access to the rake surface of the chip and measured its temperature using a two-color pyrometer. Although single-point, two-color pyrometers enable the true temperature to be measured without knowing the target's emissivity, they integrate over a single finite area and therefore cannot reveal the true maximum temperature (which was estimated by Al Huda et al. (2002a) to be 4 % higher than the measurement) or the temperature distribution. In addition, these holes that allow optical access to the tool-chip interface cannot be placed too close to the cutting edge without significantly weakening the tool and therefore they are unable to measure the temperature near the cutting edge. Finally, the field of view is limited by the diameter of the access hole.

Instead of modifying tooling to provide small windows into the tool-chip interface, some researchers have replaced conventional tooling with ones made of transparent materials. Although this approach produces results that are not directly relevant to industry, it does enable the tool-chip interface to be directly measured, improving the fundamental understanding of metal cutting and providing data to validate cutting models. For instance, Madhavan et al. (2002) investigated the material flow along the tool-chip interface while machining various pure metals using transparent glass and sapphire tools. Later work by Menon and Madhavan (2014) measured the temperature distribution on the tool-chip interface. An experimental setup consisting of a transparent yttrium aluminum garnet (YAG) tool, an infrared camera, and a reflecting mirror was used for the measurement while machining Ti-6Al-4V. For a cutting speed of 60 m/min, their results show a time averaged maximum temperature of 906 °C that occurs approximately at the midpoint of the tool-chip contact length. Garcia-Gonzalez et al. (2016b) used the same setup to measure the temperatures

while cutting Ti-6Al-4V and nickel alloy 718 and found negligible differences in the peak temperatures of the two materials. Additional work applied a thin coating to the YAG tool to investigate the effects of friction (Garcia-Gonzalez et al. (2016a)), but the fragility of the coating made the results inconclusive. As informative as these works are, they are limited by the low frame rate of the camera (approximately 20 frames per second) and the relatively long integration times (40 ms to 80 ms). These slow speeds did not allow the observation of any temporal fluctuations in temperature.

The objective of this work is to measure the temperature distribution on the tool-chip interface while cutting Ti-6Al-4V over a wide range of cutting speeds and to provide these results to the modeling community to validate cutting models. The radiant temperature is measured using a high frame rate and large field of view. A transparent YAG tool is used to cut the workpiece and allow the infrared emission from the chip to be measured by a high speed infrared camera, similar to the strategy used by Menon and Madhavan (2014). The current work differs from that study by measuring a range of cutting speeds using a shorter wavelength ($3.9 \mu\text{m} \pm 0.1 \mu\text{m}$) at a higher frame rate of 700 Hz, a quicker integration time of 10 μs , and larger field of view of approximately 5.3 mm wide and 4 mm tall. Simultaneously, a high speed visible light camera observes the cutting process from a different viewing angle so that any phenomena occurring in the infrared through-the-tool measurements can be verified. In addition to measuring the infrared emissions, the cutting forces are measured using a 3-axis dynamometer. Finally, the condition of each cutting surface is characterized post process using a scanning white light interferometer and compared to the measured radiant temperature distribution.

2. Experimental Procedure

Figure 1(a) presents the measurement setup used in this study. An infrared camera is used to observe the radiant temperature of the tool-chip interface during two dimensional (2D) orthogonal cutting. A rotating Ti-6Al-4V disk,

with an approximate diameter of 100 mm and an approximate thickness of 1 mm, is fed into a transparent YAG tool. The tool is cube shaped, with each side 6.1 mm wide, and is mounted into a holder and fixture that imposes a -4° rake angle and a 4° clearance angle. The fixture is attached to a 3-axis dynamometer so that the cutting forces can be measured along with the radiant temperature. A first-surface-silvered acrylic mirror is used to enable the camera to be placed out of the cutting plane and still observe the tool-chip interface, as illustrated in Figure 1(b). In addition to the thermal camera, a high speed visible light camera (3 kHz frame rate, 333 ns integration time) is used to observe the chip formation process. It is positioned to have the same approximate point of view as in Figure 1(b), where its field of view is identified by the dashed rectangle.

The infrared camera records images at a rate of 700 Hz using an integration time of 10 μ s. A bandpass filter is used to restrict the measurable wavelengths to $3.9 \mu\text{m} \pm 0.1 \mu\text{m}$. With the chosen frame rate and optics, the field of view (FOV) is 5.28 mm wide (160 pixels) and 3.96 mm tall (120 pixels). As in all thermography, the camera does not directly measure temperature; instead it measures radiation and the temperature is calculated from the measured signal based on a calibration with a black body reference. In this study, a black body is used to calibrate the infrared camera between 225 $^\circ\text{C}$ and 750 $^\circ\text{C}$ so that radiant temperature can be calculated. The true temperature of the interface cannot be calculated without knowing or assuming the interface emissivity. During the calibration, the camera is pointed directly at the black body cavity and focused on the plane of the opening. The YAG tool and acrylic mirror are not included in the optical train during the calibration and therefore, their impact on the measurement are not known. Because of this and the fact that the emissivity of the chips while in contact with the tool is not known, the true temperature cannot be calculated in this work. However, relative difference or changes in radiant temperature may accurately represent changes in true temperature if the emissivities, transmittance, and reflections along the optics path remain consistent. These effects are assumed to be consistent in this study.

(a) The measurement setup

(b) Zoomed in

Figure 1: The experiment setup used to measure the radiant temperature of the tool-chip interface.

Five different cases, numbered 1 through 5, with cutting speeds increasing in speed from 20 m/min to 100 m/min in 20 m/min increments are investigated. In each case, the feed rate is 50 $\mu\text{m}/\text{rev}$ and 0.8 m of material is cut. This necessitates approximately 2.5 revolutions after which the disk is held stationary while the tool removes residual runout for another 2.5 revolutions before retraction. Each cut is performed with a new cutting edge. This is achieved by either rotating the cutting tool, since it is a cube, or replacing it entirely. Unfortunately, YAG tools are considerably more frail than commercial cutting tools and can catastrophically fail if the process is not perfect. This fact, and the limited number of YAG tools available at the time, limited the number of cases and replications that could be performed. Each rake surface corresponding to a successful measurement is characterized post-process using a scanning white-light interferometer to explore a possible correlation between the measured temperature distribution and the final condition of the YAG tool. The interferometer is used to measure an approximate 2 mm² area of the rake face with a lateral resolution of approximately 1 μm and a vertical resolution of approximately 60 nm.

3. Results and Discussion

The following sections first present the infrared images and how to interpret them, then introduce the method used to analyze the measurements, and finally discuss the similarities and differences between each case.

3.1. *Interpreting the videos and analyzing the data*

Figure 2 shows example frames from the thermal and visible cameras, as well as an analysis of the thermal data acquired during the steady-state portion of the cut. In the thermal frame presented in Figure 2(a), the horizontal dashed blue line represents the approximate location of the cutting edge. The chip flows down from the cutting edge and curls away from the rake face, slightly to the right, exposing its free surface. After the curl, the chip is broken (in this

instance) and can be seen folded down further in the background, though it has moved out of focus. The additional markings in Figure 2(a) will be discussed shortly. The observations made of the chip formation in the thermal frame are confirmed in the corresponding high speed visible camera frame shown in Figure 2(b). In this image the disk is located along the top edge of the frame, and the YAG tool is slightly right of center with its edges outlined in blue.

Before the additional markings in Figure 2(a) are discussed, it must first be noted that although the free surface of the chip appears to be hotter than the rake surface of the chip, it is almost certainly not. Heat generated while cutting Ti-6Al-4V is attributed to the primary and secondary shear zones as well as the friction at the tool-chip interface, though Komanduri and Von Turkovich (1981) observed that the secondary shear zone is insignificant when cutting Ti-6Al-4V. These heat generation mechanisms occur relatively near the cutting edge and not near the free surface of the chip. Despite this, the free surface appears hotter in this study for two reasons. First, the free surface of the chip is rougher than the rake surface, which can appear polished from rubbing against the tool. Rougher surfaces tend to have higher emissivity than smoother surfaces, making the free surface appear hotter as demonstrated by Vollmer and Möllmann (2010). Second, radiation emitted from the hottest part of the chip near the primary shear zone can reflect off the curled chip back towards the camera, as illustrated in Figure 3. Since the chip curls slightly to the side, it and those reflections are visible to the camera and make the surface appear hotter than it is. Similarly, radiation emitted from other hot areas can reflect off the free surface as it curls away from the rake surface, artificially increasing its radiant temperature.

The occurrence of spots that artificially appear to be hotter than in the tool-chip interface necessitates caution when analyzing the data. The additional markings in Figure 2(a) indicate the region over which the radiant temperature is analyzed. The two vertical dashed gray lines indicate the sides of the chip if it were to travel from the cutting edge straight down the rake surface. All of the analysis in this study is constrained to the region between these lines. The two vertical green lines and the single horizontal dashed green line further constrain

(a) A single infrared image acquired using an integration time of $10\ \mu\text{s}$

(b) A single visible light image acquired using an integration time of $333\ \text{ns}$

Figure 2: Example images from (a) thermal and (b) visible cameras. These images were obtained during Case 5 (100 m/min) at a process time of 0.478 s.

Figure 3: An illustration of how reflections on the free surface of the chip can make it appear artificially hotter. This illustration is inspired by the chip formation displayed in Figure 2(a).

the analysis and create the region of interest (ROI). Seventy five percent of the chip width is found between those vertical green lines, while the dashed green line is located 20 pixels below the first detectable temperatures within those bounds. The ROI serves two purposes. First, the average radiant temperature of the tool-chip interface is calculated from the ROI because, as it will be demonstrated shortly, there is a significant drop in temperature near the sides of the chip. Second, the ROI excludes erroneously higher radiant temperatures that can occur due to reflections off the curled chip, as discussed earlier.

The quick integration time and high frame rate used in this study enables details of the chip formation to be observed that would not be evident using the slower speeds in the earlier study by Menon and Madhavan (2014). For instance, in addition to observing the chip curl behavior, temperature fluctuations within the tool-chip interface can also be observed. Because the emissivity of the interface is expected to remain constant during each cut and consistent between cases, the fluctuations in radiant temperature will be indicative of the true temperature fluctuations. These fluctuations may occur for a variety of reasons including shear banding, built up edge formation, and degradation of the cutting edge. Although the frame rate is not sufficiently fast to observe the

periodic shear banding that occurs when cutting titanium, the integration time is quick enough that the increase in temperature resulting from individual non-consecutive shear bands may be measured.

Figure 4 demonstrates the temperature profiles that are extracted from the average radiant temperature distribution during steady-state and from the individual frame presented earlier in Figure 2(a). The solid lines represent the steady-state (SS) profiles while the dashed lines denote the profiles from the individual frame. The red lines represent the maximum radiant temperature in each row within the horizontal bounds of the ROI. The black lines are the averages of those rows within the same horizontal constraints. Error bars representing 2 standard deviations are added to the steady-state average profile to illustrate the temperature fluctuation during that period. It is typical that the steady-state maximum profile and the individual frame average are within or near the extremes of these error bars. However, in all cases the individual frame maxima frequently exceeds these error bars as hot spots on the interface develop and fade away. Finally, the blue curves present the radiant temperature profile along the side of the chip closest to the camera, which is in all cases below the error bars. This indicates that chip temperature measurement from the side of the tool-chip interface, similar to the method used by Heigel et al. (2008), does not accurately represent the temperature at the middle of the interface.

Figure 5 presents the history of the cutting and thrust forces and the peak temperature within the ROI during the entire cutting process. Peak radiant temperatures below 225 °C are not shown because that is the minimum temperature of the calibration. The steady-state portion of the cut is indicated by the gray shaded region, approximately between 0.3 s and 0.6 s in this example. The general trends displayed here are typical of each case. During the ramp-in period before steady-state, the forces and peak radiant temperature steadily increase. In some cases, the forces and temperature overshoot before settling to their steady-state values. This overshoot is likely due to the machine controller or due to the YAG tool shifting slightly in the holder. During steady state, these values remain fairly constant, though some deviation occurs. The steady state

Figure 4: Example of the temperature profiles along the chip rake surface. These results correlate to the thermal data presented in Figure 2(a) (Case 5 which is performed at 100 m/min).

average peak temperature of 493 °C and 2 standard deviations (2σ) of 26 °C are highlighted by the horizontal solid and dashed white lines, respectively. There are several possible causes for the observed fluctuations in temperature during steady state. For instance, shear banding has been shown by Heigel et al. (2008) to cause significant fluctuations in temperature measurements near the rake surface. In addition, the measured temperature could be affected by built up edges and other material that has been shown by (Madhavan et al., 2002) to periodically stick to the rake surface. It's also possible that degradation of the tool could impact the temperature, as will be discussed later. After steady state, the forces and radiant temperature decrease steadily, though these values do not reach zero right away because the disk and YAG tool continue to rub and briefly re-engage. This is potentially due to the disk not being cut perfectly round because the tool has a tendency to shift slightly during the cut.

Although the high frame rate provides a wealth of data during steady state (10^2 frames to 10^3 frames), the data can be overwhelming and difficult to make

Figure 5: Example cutting and thrust forces and the peak temperature in the region of interest (Case 5).

comparisons with the results from measurements performed using slower camera speeds. Therefore, it is advantageous to simplify this data. Figure 6(a) presents an averaging of all the thermal video frames acquired during the steady-state portion of a cut. This is analogous to data that would be acquired using a long integration time. For the purposes of the current study, it enables the average distribution of the radiant temperature to be studied. To assist the reader's interpretation of the data, the same markings have been added as were initially presented in Figure 2(a). In addition, a dotted horizontal line has been added through the location of the peak temperature. It is over this line that the temperature profile across the chip width is extracted and the difference between the radiant temperature at the side of the chip and the peak in the center is compared.

The temporal fluctuation of the radiant temperature is represented in Figure 6(b). This figure presents the standard deviation of the thermal frames acquired during steady state over a period of 0.3 s. This data shows that within the ROI and the sides of the chip, the temperature fluctuation during steady state is relatively small. This indicates that longer integration times can be used

to measure the temperature without significantly affecting the average result. In contrast, the radiant temperature fluctuation is large away from the tool-chip interface because the chip periodically curls into view.

Figure 7 present an example of the rake face analysis performed after each test. In this example (Case 3 performed at 60 m/min), there are notches along the cutting edge that coincide with the sides of the chip. The approximate depth of these notches is 35 μm . In between these notches, some crater wear has begun that measures approximately 8 μm deep. In the 2D image in Figure 7(a) white streaks appear on the rake surface extending from the left notch. Since these do not appear in the 3D measurement in Figure 7(b), they are deemed superficial and are not considered when quantifying the tool wear. This example presents all the features observed in the difference cases.

Figure 7: Examples of the post process tool characterization. These images are of the tool from Case 3 (60 m/min).

3.2. Comparison of the Results

The cumulative results of the analysis are presented in Table 1. Post-process measurements of the chips created during steady state are used to determine the chip width in the videos and to calculate the normalized cutting and thrust forces by dividing the average of each force by the measured width. This calculation enables a more appropriate comparison between cases of forces since the disk width is not consistent. In contrast, the variation in disk width is not accounted

for when reporting radiant temperature because, as it will be shown in later figures, the temperature within the middle portion of the chip is fairly consistent. The normalized forces and radiant temperatures reported in the table are calculated by averaging those values during the steady state portion of each cut. The average radiant temperature of the sides of the tool-chip interface is extracted from the horizontal line through the average peak as discussed earlier and shown in Figure 6. The percent difference between these two temperatures, calculated by first converting into Kelvin, quantifies the error that may occur when measuring the chip temperature near the interface from the side.

Table 1: Steady state analysis results.

Case	Speed (m/min)	Rep.	Chip width (mm)	Normalized cutting force (N/mm)	Normalized thrust force (N/mm)	Average peak radiant temperature (°C)	Average side radiant temperature (°C)	Difference between side and peak (%)
1	20	1	1.02	104 +/- 15	67 +/- 13	352 +/- 16	288 +/- 55	12
1	20	2	0.95	109 +/- 15	84 +/- 17	382 +/- 16	327 +/- 54	11
2	40	1	1.47	102 +/- 16	65 +/- 13	380 +/- 29	337 +/- 54	9
2	40	2	1.50	122 +/- 24	88 +/- 20	434 +/- 33	336 +/- 57	17
3	60	1	1.22	113 +/- 19	62 +/- 15	440 +/- 18	421 +/- 38	6
4	80	1	1.32	100 +/- 18	55 +/- 13	441 +/- 41	344 +/- 58	19
4	80	2	1.32	118 +/- 25	90 +/- 18	496 +/- 24	428 +/- 34	13
5	100	1	1.37	111 +/- 21	66 +/- 14	493 +/- 27	345 +/- 72	23

The mean values of the steady-state peak radiant temperature and normalized forces are compared in Figure 8. The forces do not appear to relate to speed. Although thrust force appears to decrease slightly as speed increases, this decrease is within the scatter of the data. In contrast, the mean peak radiant temperature is directly related to the cutting speed. A red dashed line is added to the figure to help illustrate this claim. Although these temperatures are only radiant and not true, it is reasonable to assume that the effective emissivity of the chip in contact with the YAG tool is consistent among all cases. Therefore, there would also be a direct relationship between the true peak temperature and cutting speed.

Figure 9 shows the steady-state radiant temperature profile down the rake face for each case. In each case, the first replication is presented in black while the gray profile represents the second replication if one was performed. As stated earlier, the limited supply of YAG tools and their fragility limited the number of successful replications. Because of the slight deviations in the camera position

Figure 8: Comparison of the mean forces and mean peak temperature during steady state. The error bars represent 2 standard deviations of measured peak values.

between each cut, the data has been shifted so that the peak of the means line up to aid in the comparison between replications. In general, the shape of each profile is consistent, with the magnitude rising with cutting speed.

Figure 9: Comparisons of the temperature profiles calculated from the region of interest. The error bars represent 1σ of the frames collected during steady state for each replication. The vertical axis is in radiant temperature $^{\circ}\text{C}$

The temperature profile across the width of each chip is presented in Figure 10 and compared to the final condition of the corresponding rake face. The radiant temperature is extracted from a horizontal line that intersects the steady-state peak temperature and terminates at each side of the chip. In accordance with the earlier observations, the radiant temperature magnitude increases as the speed increases from left to right. In contrast, there is no

correlation between the increase in cutting speed and the final condition of the tool; however, the conditions are comparable within replications of the same cutting speed. For instance, both replications of Case 1 show slight crater wear and some notch wear. Both of the Case 2 replications exhibit comparable crater wear and minimal notch wear. Finally, significant gouges have been taken out of each Case 5 replication. The similarities within each case demonstrate the consistency of the experiment.

Figure 10: Comparison of the radiant temperature profile across the chip width during steady state and the final condition of the YAG tool rake face in each case. The sides of the chip are projected onto the rake surface and coincide with the sides of the temperature plots. The radiant temperature scale is in °C.

The most interesting observation that can be made from the data presented in Figure 10 is the possible relationship between the shape of each radiant temperature profile and the corresponding surface condition. In several cases, the shape of the profile seems to follow the undulations in the rake surface. This is exemplified in Case 4, where the temperature increases in the same location as the pits on the surface. It can be also be seen to a lesser extent in Case 3 and one of the Case 2 replications (bottom). If this relationship exists, one would also expect that as the tool progressively wore during the cut, the temperature

profile would evolve as well. Once again this appears to be possible considering Case 4, where the first frame of steady state, represented by the green curve, is at a lower magnitude and has less variation from side to side compared to the last frame of steady state, which is represented by the blue curve. However, if this relationship does exist, it is unclear if the temperatures in these cases are actually hotter at these pits or if the rake surface changes the emissivity of the surface. If the latter is true, it would imply that the condition of the tool must be accounted for when calculating the true temperature on the tool-chip interface.

Although some cases provide evidence to support these claims, others present conflicting evidence. For example, the profile in Case 5 is not as flat and consistent as the crater wear. Furthermore, the profile in the first frame of steady state is hotter than in the last frame. At this time, no conclusions can be drawn regarding the effect of the surface condition on the measured temperature profile. More extensive studies are required to at least determine the possible impact of the tool condition on the temperature measurement and to investigate the relationship between tool wear and the tool-chip interface temperature.

4. Conclusions

Measurement of the temperatures on the tool-chip interface has the potential to enable the machining community to overcome the significant challenges involved in cutting titanium alloys. A strategy has been implemented to measure the radiant temperature distribution on the interface using an infrared camera and transparent cutting tools. These measurements reveal that the peak temperature increases with cutting speed, and although the magnitude increases, the shape of the temperature distribution does not significantly change. In contrast, the cutting and thrust forces exhibited were unaffected by cutting speed. The versatility of the temperature measurement setup was demonstrated in the large field of view. In addition to being able to measure the radiant temperature near the cutting edge, the chip curl and breakage were also

observable in the infrared measurements and confirmed in the accompanying high-speed visible-light video. The post-process condition of each tool was characterized with a white light interferometer. This characterization revealed that the transparent tools withstood the cutting conditions, and although the wear was consistent among replications, it changed drastically with variations in cutting speed. While some cases indicate a relationship between the tool condition and the radiant temperature profile, there is not enough evidence at this time to draw any conclusions.

Future work will attempt to calculate the true temperature from the radiant temperature presented here. Although industry would not directly benefit from this calculation since YAG is not a material used for tooling, industry will indirectly benefit from the use of this data by the modeling community to improve and validate their models. In addition, the system will be used to measure the tool-chip interface temperature during cryogenic machining, providing insight into the magnitude of the effect of cryogenic coolant on the cutting temperatures. Finally, more in-depth analysis is required to understand the temporal fluctuations of the temperature data.

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