FULL-FIELD INFRARED THERMOGRAPHY AT TOOL-CHIP INTERFACE THROUGH TRANSPARENT CUTTING TOOL WHILE MACHINING TI-6AL-4V

A Thesis by

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FULL-FIELD INFRARED THERMOGRAPHY AT TOOL-CHIP INTERFACE THROUGH TRANSPARENT CUTTING TOOL WHILE MACHINING Ti-6Al-4V

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Industrial Engineering.

______________________________
Viswanatha Madhavan, Committee Chair

______________________________
Krishna K. Krishnan, Committee Member

______________________________
Ramazan Asmatulu, Committee Member
DEDICATION

To my beloved God, my parents, my sister, and my dear friends
The power of knowledge, put it to task,
No barrier will be able to hold you back,
   It will support you even in flight!
It cannot be your Creator’s desire
To chain his finest in the muck and the mire,
   To eternally deny you flight!

- Otto Lilienthal
ACKNOWLEDGEMENTS

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ABSTRACT

This experimental study is aimed at obtaining the temperature distribution along the tool-chip interface in the steady state orthogonal machining of Ti-6Al-4V with a high level of accuracy. Yttrium Aluminum Garnet (YAG) is identified as a new transparent tool material which could successfully machine this ‘difficult-to-machine’ alloy. A unique fixture is developed to hold this transparent tool using which cameras sensitive to visible and infrared radiation observed the machining process in-situ and image, at a high speed, the radiation emitted from the tool-chip interface in a field less than 1 mm wide. The radiation intensity is converted to local temperature through a calibration process performed by imaging a blackbody in place of the chip at the tool-chip interface for the range of expected temperatures.

The time averaged temperature maps show a hot region adjacent and parallel to the cutting edge. The temperature is uniform in the direction along the cutting edge, but decrease near the side boundaries of the chip. The time averaged temperature profiles show an increase of temperature with distance from cutting edge in the direction of chip flow. The temperature peaks 900 °C to 1050 °C at half of the contact length and then decreases. The uncertainty for reported values in maps is 10 K and that in profiles is 6 K. Time resolved temperatures are obtained using visible and IR camera systems using very low exposure times and the evolution of rake face temperature with respect to time is predicted. High resolution visible wavelength photography is used to obtain the chip velocity field along the interface. Shear stress of the deforming material is determined from predicted temperatures by imposing sticking friction.
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<td>BB</td>
<td>Blackbody</td>
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<tr>
<td>CCD</td>
<td>Charge-coupled Device</td>
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<td>CNC</td>
<td>Computer Numeric Control</td>
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<td>EMF</td>
<td>Electromotive Force</td>
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<td>FPA</td>
<td>Focal Plane Array</td>
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<td>IR</td>
<td>Infrared</td>
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<tr>
<td>MADMACS</td>
<td>MANufacturing Deformation MAcro videography System</td>
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<tr>
<td>NA</td>
<td>Numerical Aperture</td>
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<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<td>YAG</td>
<td>Yttrium Aluminum Garnet</td>
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LIST OF SYMBOLS

\( \varepsilon \)  Emissivity

\( \lambda \)  Wavelength of radiation

\( \sigma \)  Stephan-Boltzmann constant
CHAPTER 1

INTRODUCTION

1.1 Machining - a Remarkable Process

Machining is the removal of excess material from a workpiece by deforming it with a hard tool in the shape of a wedge. It is undoubtedly the most widely used of all manufacturing processes. The manufacture of most of the items used today involves machining, at least in some degree. For this reason, machining has been researched ever since man started to produce goods of utility.

The practical machining process is often complicated which prevents the advance and accurate prediction of how the material behaves. For this reason, machining is still not well understood. Figure 1.1 shows a simplified model called 2D orthogonal machining which is

![Schematic of 2D orthogonal machining](image-url)

Figure 1.1. Schematic of 2D orthogonal machining
always used to explain the basics of a machining process. The cutting tool is made to advance into the workpiece perpendicular to the cutting edge. This causes a shearing action where the workpiece material deforms along the shear plane and results in a chip. This region along the shear plane is called the Primary Shear Zone. The chip slides on top of the tool rake face where friction between the chip underside and the rake face causes secondary deformation. The region where this occurs is called the Secondary Shear Zone. Over the period of use of the tool, a new surface forms on the tool flank face near the cutting edge which is called tertiary shear zone.

Jaspers and Dautzenberg (2002) summarized the findings of Alexander (1985) and Kalpakjian (1997) and compared the deformation mechanics of various common manufacturing processes. This is listed in Table 1.1 which shows that the conditions involved in machining are very different from those in the other conventional processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Strain</th>
<th>Strain rate (s(^{-1}))</th>
<th>(T_{\text{homologous}} = T/T_{\text{melt}})</th>
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<td>Extrusion</td>
<td>2-5</td>
<td>(10^{-1}-10^3)</td>
<td>0.16-0.7</td>
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<tr>
<td>Forging/rolling</td>
<td>0.1-0.5</td>
<td>(10^0-10^3)</td>
<td>0.16-0.7</td>
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<td>Sheet-metal forming</td>
<td>0.1-0.5</td>
<td>(10^0-10^2)</td>
<td>0.16-0.7</td>
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<td>1-10</td>
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<td>0.16-0.9</td>
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</table>
1.2 Heat Generation and Need for Temperature Prediction

The mechanical energy used in the deformation of material in the primary and secondary shear zones is dissipated as heat (Shaw, 1984). This heat is parted between tool, workpiece and chip which raise their temperature. The heat partition is dependent on the cutting variables such as speed, depth of cut and geometry of tool. Temperature affects the deformation characteristics and machinability of the workpiece by affecting its mechanical properties like yield strength. The high temperature along the tool-chip interface softens the tool causing it to wear faster. Thus temperature influences rate of tool wear and in effect the life of the tool (Takeyama, 1963), tool performance and dimensional accuracy of the workpiece.

The competitiveness of an industry is largely dependent on the volume and quality of produced items. The rate of material removal has increased tremendously over the years leading to reduced costs of production. This is achieved by increasing the cutting speed and feed resulting in higher temperatures which can reach close to the melting point temperatures as given in Table 1.1. Therefore, in order to meet the required specifications of tolerance and surface finish, there is a pertinent need for optimization of power and accuracy.

Machining models and simulation can aid in designing the process better and thus reduce the time and costs. But, there is a big scope for improving and refining these models. This can be done only using well quantified values of process parameters which are still largely determined empirically from past experience and by trial-and-error methods. One of the most important amongst them is temperature at the tool-chip interface. The knowledge of cutting temperature helps to determine the best conditions to increase tool life, reduce workpiece damage and integrity, and increase machining precision.
1.3 Ti-6Al-4V - A Difficult-to-Machine Material

The majority of materials used in machining are metals and alloys. Titanium alloys are widely used in the aerospace industry where strength-to-weight ratio and corrosion resistance are of chief importance. Titanium has the highest strength to weight ratio of any metal and thus is exclusively used in the aerospace industry, often mixed with aluminum. It is used in the most important strength bearing parts of a plane. Titanium alloys are famously called the “difficult-to-machine” materials due to their poor machinability. This is due to their low thermal conductivity and high chemical reactivity with many materials used as cutting tools. In effect, the generated heat is mostly conducted into the tool causing thermal stresses leading to tool failure. Furthermore, the deformed work material adheres onto the tool at the tool-chip interface. Therefore, temperature is one of the major concerns in the manufacturing of these advanced materials (Klocke et al., 2002).

1.4 Temperature Measurement Techniques

Understanding the criticality of temperature prediction in high speed cutting, researchers have come up with many different methods. Temperatures do not reach steady state in most cases of high speed machining as it finishes in a short duration. Therefore, the various time resolved temperature measurement techniques can be broadly classified into conduction and radiation types. The former type primarily consists of inserted thermocouples, tool-work thermocouples, temperature sensitive paints, thermographic phosphors etc., while infrared (IR) pyrometers and cameras constitute the well-known radiation type measurement techniques. Bacci da Silva and Wallbank (1997), Komanduri and Hou (2001), Longbottom and
Lanham (2005), and Davies et al. (2007) provide a comprehensive review of the most widely used temperature measurement methods.

1.4.1 Thermocouple Methods

When certain dissimilar metals are joined, a difference in temperature across their junctions can result in a measurable change in voltage. This is called the Seebeck effect and is the guiding principle for these methods. Such pairs of metals are called thermocouples. The junction which is at the higher temperature is called the hot junction and the other is called the cold junction. A thermocouple can be inserted into holes drilled on the tool when tool is stationary, or on the workpiece when workpiece is stationary. Authors who used this technique in temperature measurement of difficult-to-machine materials include Usui et al. (1978) El-Wardany et al. (1996) and Kitagawa et al. (1997) who studied the influence of temperature on tool wear during high speed milling of difficult-to-machine materials including Ti-6Al-4V alloy. Though thermocouples are relatively inexpensive and versatile, thermocouple system is still complex due to unknown contact conditions. Also, there are limitations on how close the holes can be to the area of interest and on the minimum time resolution possible.

Tool-work thermocouple is a common method used to measure cutting temperatures since the 1920s. This was thought to be a successful method by many like Shore (1925), Herbert (1926), Shaw (1984), Lezanski and Shaw (1990), Stephenson (1992) and Ivester et al. (2000). In this method, the tool-work contact forms the hot junction, as shown in Figure 1.2, while remote sections of the tool and workpiece form the cold junction and the average thermo-electric emf at the tool-workpiece interface is measured. This will equal the actual interfacial temperature only if that emf is uniform and the temperature-emf relation for the
tool-workpiece combination is linear. This method poses several implementation issues like the need to isolate the tool-work circuit due to extraneous emf and secondary junctions.

### 1.4.2 Radiation Methods

When a body is heated, it emits radiation, the energy of which can be related to its thermodynamic temperature. This is the guiding principle for these methods. A perfect radiator is called a blackbody, which absorbs all the incident radiation in all wavelengths and directions, and emits it completely, independent of direction. Plank’s law governs the functional dependence of the blackbody’s spectral emissive power on temperature and wavelength as given in equation (1.1).

\[
E_{\lambda,b}(T) = \frac{2hc^2}{\lambda^5(e^{\frac{hc}{\lambda T}} - 1)}
\]  

where \(E_{\lambda,b}\) is the spectral emissive power of the blackbody, \(T\) is the thermodynamic temperature of blackbody, and \(\lambda\) is the wavelength of emitted radiation, \(h\) is Planck’s constant,
c is speed of light in vacuum and \( k \) is Boltzmann’s constant. Integrating this spectral power in all directions and wavelengths gives the Stefan-Boltzmann Law as given in equation (1.2).

\[
E_b = \sigma T^4
\]

(1.2)

where \( E_b \) is the total emitted power of blackbody and \( \sigma \) is called the Stephan-Boltzmann constant. A non-blackbody emits only a portion of this power, the ratio of which with respect to \( E_b \) is called emissivity (\( \varepsilon < 1 \)).

IR pyrometers collect some or all of the emissions from the cut surface and predict the point temperatures. Unlike the conduction methods, these have very fast response times and are the most used techniques for cutting temperature measurement (Longbottom and Lanham, 2005; Davies et al., 2007). Schwerd (1933) was the first to conduct pyrometric measurements by focusing the radiation on to a detector in the form of a thermocouple. Lin et al. (1992) used fiber optic along with IR pyrometry and measured the temperatures at several locations on the rake face. The largest source of error in these measurements is from uncertainty in the value of emissivity which changes along with material surface, view angle, temperature and wavelength. In order to overcome this, researchers like Kottenstette (1986), Ueda et al. (1999) and Muller and Renz (2001) have developed a ratio technique which is also called dual-wavelength pyrometry. As long as the greybody assumption that emissivity is independent of wavelength is valid, the ratio of radiance in two different wavelengths can be related to temperature. The greybody assumption is not valid in most cases and this leads to significant errors. Hijazi et al. (2011) developed a non-greybody compensation factor, but the dual and single wavelength measurements did not match. The error in this factor gets amplified in temperature as compared to single wavelength method where it decreases.
An advancement of pyrometry is IR thermography using a camera which can provide the temperature distribution in the form of a map. Boothroyd (1961) was the first to use this technique to obtain a full-field measurement of cutting temperatures using an IR film which was soon followed by Salmon et al. (1968). This technology has improved tremendously over the last decades due to the development of Charge-coupled Devices (CCD) and Focal Plane Arrays (FPA) with low noise and high spatial resolution. Recent attempts have been made by many like Jaspers and Dautzenberg (2002), M’Saoubi et al. (2002), Davies et al. (2003), Sutter et al. (2003) and Ivester (2011), but they were not successful in obtaining a 2D temperature distribution of the tool-chip interface.

1.5 Transparent Cutting Tools

Providing optical access to the tool-chip interface is the only way to observe the cutting process in-situ and obtain the 2D temperature map. Muller-Hummel and Lahres (1997) measured the tool-chip interface temperature using a diamond coated tool and a thermographic camera. They provided optical access through a small diamond window in a hole on the tool rake face and their innovative tool holder had a mirror to guide the radiation from cutting to an IR camera. The disadvantage of this configuration is that the hole and diamond affects the temperature field. The calibration process is a very crucial step in these types of measurements, the details of which are vague in the above work.

A more direct way of providing optical access to the tool-chip interface is the use of transparent materials, like glass, sapphire etc., as cutting tools. Nakayama (1959) was the first to make use of transparent cutting tools which has been used recently in the works of Ackroyd et al. (2001), Narayanan et al. (2001) and Madhavan et al. (2002). Both visible and infrared
range of wavelengths can be used to image the tool-chip interface. The cutting configuration involving these tools is much simpler as compared to earlier setups. The most important advantage of obtaining such temperature distributions directly from the tool-chip interface is that they can be used to compare, validate and refine simulation models.

1.6 Objective of Current Work

Cutting temperature research is a very active field of study from the time of Taylor’s experimental study in 1907 which showed that increasing cutting speed reduces tool life. With the industry pushing for higher and higher cutting speeds, temperature is becoming more and more important. Many machining models have been developed and proposed over the years, but only a few comparisons have been reported between predicted temperatures and measured values with less uncertainty. Many researchers have made attempts at this task through different methods, but have not been able to predict temperature distributions with high accuracy while cutting difficult-to-machine materials.

The first part of this work, performed in the Advanced Manufacturing Laboratory at Wichita State University, improves upon the research done over the past decade in IR thermography using transparent cutting tools. It focuses on high accuracy visible and near IR thermographic measurements at the tool-chip interface while cutting Ti-6Al-4V using YAG as the transparent cutting tool in a very simple and innovative design of tool holder. This study is the first successful effort of this kind, yielding results for steady state 2D orthogonal machining with very high resolution and accuracy. The work is presented in the form of a paper, along with author’s advisor Dr. Vis Madhavan, which is being submitted to International Journal of Machine Tools and Manufacture.
The second part of this work, most of which is currently being undertaken in the Manufacturing Engineering Laboratory at National Institute of Standards and Technology, makes use of IR thermography in longer wavelengths using the same transparent tool design to study time variations of temperature. This effort is aimed at finding a steady state for the rake face temperatures in addition to repeating the experiments of previous work for higher speeds. The work will also attempt to determine shear stress for the work material on the tool rake face from these temperature maps.
CHAPTER 2

HIGH ACCURACY FULL-FIELD INFRARED THERMOGRAPHY OF THE CHIP-TOOL INTERFACE THROUGH TRANSPARENT CUTTING TOOLS WHILE MACHINING Ti-6Al-4V

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2.1 Abstract

The development of an improved design of transparent cutting tools and the choice of YAG as a new tool material have together enabled in-situ observation of the chip-tool interface while machining Ti-6Al-4V. Low-noise cameras sensitive to visible and near IR radiation have been used to image the radiation emitted by the hot chip-tool interface. The image intensity is related to the local temperature of the object points by a calibration process wherein a blackbody source is imaged through the transparent tool. Emissivity values found in the literature are compensated for emission into YAG, and the reflectivity of YAG during calibration is accounted for. The temperature is found to increase with distance from the cutting edge along the chip flow direction, reaching a maximum at about one-half the length of contact. For the cutting conditions used, peak temperatures of 900 °C to 1000 °C are observed. The expanded ($k = 2$) uncertainty in temperature is less than 10 K for most of the data in the field maps reported and is less than 6 K for the average temperature profiles reported.

This is a paper which is being submitted to International Journal of Machine Tools and Manufacture.
2.2 Introduction

Material removal processes are the default finishing processes used to achieve the tolerances and surface finish required for most mechanical parts to meet design requirements. The efficiency and productivity of these processes is a key component of industries’ manufacturing competitiveness. Model based process optimization is a way to offset the high cost of labor and digital manufacturing, via accurate simulations, is an increasingly significant component of developed nations’ plan to sustain and enhance the competitiveness of their manufacturing industries. Accurate knowledge of key inputs — friction models, constitutive models, thermal properties, etc. — is a prerequisite for machining models to be valid. However, to date, most machining models are validated with not much more than the measured cutting forces and chip thickness. Since the peak tool temperature is the most important output of interest, it will be good if this can actually be measured and verified against the predictions of these models. The peak tool temperature is known to occur along the chip tool interface and a novel experimental capability for the measurement of the temperature fields along the normally inaccessible chip-tool interface can make a significant contribution to verifying the outputs of the simulations, and towards improving the accuracy of the material and friction models used in simulations.

Compared to other methods of sensing temperature using sensors such as thermocouples which perturb the temperature field being measured, IR thermography is a non-contact technique carried out using array detectors that can be used to measure the temperature distribution over a surface without perturbing it. However, this technique requires optical access to the surface of interest. This is achieved in the case of the normally
inaccessible chip-tool interface by making the tool out of a transparent material and viewing
the chip-tool interface through the tool while the tool is cutting the work material. The present
study is the first successful effort in which the distribution of temperature at the chip-tool
interface has been measured with high spatial resolution and with a well characterized and
unprecedentedly low expanded uncertainty of less than 10 K. For the purpose of validating
material models used in FEA, the fact that the tool material is not used commercially is not
important. So long as the tool is strong enough to cut the work material without deformation
or wear and the thermal properties of the tool material are accurately known, temperature
measurements made through these transparent tools can be used to refine the material model
for the work piece and the friction model used for the interface till the predicted values
coinde with the measured values. While the friction model to be used for other tool materials
and coatings will be different, the material model developed for the workpiece can be used
with confidence for all other simulations involving this work material.

2.3 Background

The temperature distribution along contact surfaces has long been a subject of intense
interest. This is because the temperature is a major factor in the observed wear rate of the
surfaces. The real contact area at which two bodies in contact typically touch each other is only
across their asperities. As the contact load increases, these asperities deform plastically to
increase the area of contact as well as to bring other asperities into contact. Junction growth is
the phenomenon of additional plastic deformation and contact area increase that occurs when
a sliding force is applied to one of the bodies in contact (Bowden and Tabor, 1950). As the body
begins to slide over the other, the contacts at asperities are formed and broken at a rapid rate
and the rapid plastic deformation causes very high temperatures called flash temperatures at the asperities in contact. The heat diffuses over the entire surface with time resulting in an average contact temperature over which the flash temperature is superimposed (Blok, 1963). While observations from the side are sensitive to the average contact temperature, one of the counterfaces has to be transparent and observations need to be made through this surface to obtain the average as well as the flash temperatures. There is an excellent body of work on average contact temperatures and flash temperatures (Bair et al., 1991; Chung, 1992; Tian and Kennedy, 1995; Enthoven and Spikes, 1996).

In metal cutting, it is well known that the normal pressure along the contact between the tool and the chip material is high enough that the work material conforms to the tool surface over most of the nominal area of contact. This is commonly referred to as the sticking friction regime (Trent, 1988). Yet, according to direct observations (Ackroyd et al., 2001; Madhavan et al., 2002) as well as slip-line field models (Challen and Oxley, 1984; Childs et al., 2000), the work material slides over the tool rake face in what is referred to as a retarded flow zone. The friction and sub-surface secondary shear deformation lead to rapid heating of the material, superimposed on the temperature rise due to the shear plane and the cutting edge. The high temperature that results, in addition to causing changes in the strength of the workpiece material and friction at the chip-tool interface, accelerates tool wear which limits productivity.

Since the development of the tool-work thermocouple (intrinsic thermocouple) technique by Shore (1925) and Herbert (1926) to measure the average temperature at the chip-tool interface, many researchers have measured cutting temperatures. The techniques used
include the tool-work (intrinsic) thermocouple technique (Trent, 1984; Leshock and Shin, 1997), embedded thermocouple technique (Usui et al., 1978; Han et al., 2008), radiation techniques such as IR pyrometry and thermography (Boothroyd, 1963; Kottenstette, 1986; Muller-Hummel and Lahres, 1994; Jaspers et al., 1998; Yoon et al., 2000; Narayanan et al., 2001, Miller et al., 2003, Muller et al., 2004), metallographic techniques (Wright and Trent, 1974) and metallography with specially added inclusions (Lo Casto et al., 1989). Metallographic techniques can yield an estimate of the temperature distribution; however, they are not applicable to commonly used carbide cutting tools without additional defined melting point inclusions, their spatial resolution is coarse, and they have not been applied to estimate the temperature over the rake face but only along interior sections of the cutting tool. It is much harder to obtain the temperature distribution using other single point measurement techniques such as pyrometry or extrinsic thermocouples. Usui et al. (1978) used the extrinsic tool work thermocouple technique to map the temperature distribution under one cutting condition through a painstaking series of experiments. Such a study is very expensive to carry out on a routine basis, for instance for optimization of tool coatings.

IR thermography has been used to study the temperature distribution over the cutting tool (Miller et al., 2003; M’Saoubi and Chandrasekaran, 2004), the workpiece (Boothroyd, 1963), the chip side face (Sutter et al., 2003; Hijazi et al., 2011), the free surface of the chip (the back surface, Jaspers et al., 1998), and the interface (Davies et al., 2003), by imaging the side faces of the tool and the workpiece. Typically, it is found that uncertainty in these measurements is dominated by the uncertainty in emissivity and correct estimates for uncertainty are of the order of 50 °C for a 15 % uncertainty in the emissivity, over a baseline
value of 0.14 (Davies et al., 2003). In such studies, only the side faces of the interface are visible and at best, the 1D temperature distribution along the intersection of the tool rake face and the side planes of the workpiece and tool can be obtained. However, material near the side faces of the workpiece deforms in plane stress and the temperatures along the side face are significantly lower than the temperatures along inner planes along which material deforms in plane strain. The temperatures predicted by plane strain FEA simulations of 2D orthogonal cutting are up to 200 °C higher than values measured experimentally. 3D FEA simulations showed that there could indeed be a significant drop in temperature of the order of 200 °C from the high temperatures that exist along the interface over most of the width of the cutting edge to those along the side face of the cutting tool.

Only the studies by Muller-Hummel and Lahres (1994 and 1995), Muller-Hummel et al. (1997) and Narayanan et al. (2001) have attempted to measure the 2D distribution of temperature over the chip-tool interface by providing optical access to the chip tool interface and carrying out IR thermography. Both these studies required the development of many novel techniques. Muller-Hummel and Lahres used an innovative design of the tool and the tool holder comprising of a 0.5 mm thick diamond window fitted into a hole in the rake face of the tool and a mirror beneath it to provide optical access to the rake face. The tool and the optical window were both over coated with a 5 μm thick layer of CVD diamond to prevent the chip material from sticking to the gaps. An IR camera was used to measure the intensity of radiation emitted by different points on the chip surface, in the 8 μm to 12 μm wavelength range. While the details of the calibration are vague, it involved use of a blackbody to calibrate the optical system, measuring the spectral transmittance of the diamond window and an emissivity.
measurement step to estimate the emissivity of the chip by heating it in a nitrogen atmosphere. The aim of their work was to identify the maximum feeds and speeds that could be used for machining aluminum and titanium alloys with CVD diamond coated tools, prior to the onset of excessive oxidative wear of the coating brought on by high temperatures. The perturbation of the temperature field by the hole beneath the diamond window and by the outstanding thermal conductivity of diamond is causes for concern. These perturbations and the fact that a 3D cutting geometry has been used (rather than orthogonal cutting) makes it very hard to use this data to validate machining simulations. Additionally, the closest the window gets to the cutting edge is 100 µm and so the temperature distribution from the cutting edge to this distance cannot be measured. Additionally, they do not seem to have factored into account the reduced numerical aperture of the optics near the edges of the window by blockage of part of the cone of rays by the walls of the hole. Yet another concern is that temperatures significantly greater than the melting point of the work material are reported and the uncertainty in the measurements is not quantified. This approach also requires painstaking preparation of these complicated cutting tools for each test and it may be hard to coat materials other than diamond over the diamond window.

Narayanan et al. (2001) used a different approach of using cutting tools made of sapphire which is transparent in the near and mid-IR wavelengths. Preparation and use of these transparent cutting tools is much simpler than preparation of the tools with the diamond windows used by Muller-Hummel and Lahres. In addition, it is possible to directly compare results along the middle of the chip with results of 2D plane strain FEA. They imaged the radiation emitted by the chip along the chip-tool interface and estimated the temperature
using the dual wavelength ratio technique to handle the unknown emissivity of the chip face. The emissivity of the chip face was thought to be higher in regions where the chip material deposited on (i.e. got stuck to) the rake face of the tool. The deposition was found to occur on three of the four borders of the rectangular boundary of the contact region, except along the cutting edge. The ratio technique results showed that the regions of deposits also had higher temperatures. Thus this study showed that the temperature along the side faces may actually be higher than the temperature in the plane strain regions in cases where the chip material seizes to the tool along the side faces.

Efforts made by the present group to continue and improve upon this research over the past decade had been stymied by various hurdles such as the inability to cut harder materials in a robust manner, the expense of the tools, problems with calibration for converting the IR measurements into temperature, etc. One source of uncertainty is that, if the two bands of radiation chosen are widely spaced, in order to cause the ratio to change faster with temperature, it cannot be assumed that the emissivity remains the same in the two wavelengths. Hijazi et al. (2011) found that non-greybody behavior of low emissivity surfaces can lead to significant systematic error in dual-wavelength IR thermometry and developed procedures to measure the non-grey body compensation factor (NGCF). It was found that the NGCF depended on the surface finish for the aluminum alloy used. When these methods were applied to estimate temperatures from IR images of the chip-tool interface through transparent cutting tools, it was observed that dual-wave and single wave measurements did not yield consistent results due to unknown effects of internal reflections during calibration for each of the wavelengths. It was also found that any error in NGCF would be amplified in the
temperature measurements, whereas, the error in emissivity in single wavelength thermography gets reduced by the exponent relating the temperature to intensity. Additionally, interference fringe patterns formed beyond the end of the length of contact, where the chips curled out of contact with the tool, also caused spurious peaks in the data for dual wavelength measurements. This occurs because the fringes occur nearer to the cutting edge for the lower wavelengths, thereby artificially increasing and then decreasing the ratio of radiation in the lower to higher wavelength ranges. For these reasons it was concluded that single wavelength thermography can result in more accurate measurements especially if temperatures are high enough that near IR thermography can be carried out (for which the exponent relating the intensity to temperature is very high) and if the emissivity is uniform (without variations caused by sticking) and is reasonably well bracketed based on measurements or literature values.

Based on the above, it can be noted that there is a critical need for high accuracy measurements of the temperature distribution along the chip tool interface especially in the case of hard to machine materials. The chip-tool interface is the surface over which the temperature distribution is of most interest since the distribution of tool wear rate is directly related to temperatures here. However, this interface is normally a “hidden” surface and it is known from simulations that the temperature of this hidden surface is significantly different (of the order of 200 °C for commercial cutting conditions for Ti 6-4) from the temperatures measured on the side face of the tools or on the side face of the workpiece and chip. For this reason, IR thermography has been carried out through a new design of the cutting tool with simplified mechanical and optical design.
2.4 Methods

2.4.1 Overall Approach

Single wavelength thermography through transparent cutting tools, while cutting is ongoing, is used to image the radiation emitted by the hot chip surface while it is sliding over the tool rake face. This image of the radiation emitted by the chip is converted to a temperature map by relating the intensity at each pixel of the image to the temperature of the local point of the chip through a calibration process. Single wavelength thermography is used as it can make the temperature estimation much more robust in the face of uncertainty in emissivity in the red or IR radiation band used in this study. It is known that the surface finish of the chip in contact with the tool will assume a highly polished appearance due to the high contact pressure between the chip and the polished faces of the transparent crystal. So this method is better suited to materials which exhibit high emissivity even in the polished condition.

Orthogonal cutting is chosen, as this is the simplest condition for verifying simulations or analytical models with experimental observations and is achieved by end-turning of tubes as shown in Figure 2.1. The main failure mode of the tool is known from experience to be chipping, both at microscopic and macroscopic scales. To mitigate this, the material has been changed to YAG from sapphire and a strong 90° wedge is chosen. YAG has higher hardness and strength than sapphire at high temperatures (Mah and Parthasarathy, 1997) and is completely transparent from 0.4 μm to 4 μm, without any absorption. The 90° wedge angle of each cutting edge also increases the strength of the edge with the only drawback being that positive rake angles cannot be studied. To increase the number of cutting edges available for use in each tool, a cubic geometry is chosen, thereby giving 12 cutting edges on each tool. The simplified
cubic geometry has also simplified the optical arrangement and the estimation of the effect of internal reflections which are found to be negligible. The tools are further annealed to heal pre-existing cracks and improve the resistance to fracture. A quick change fixture has been developed (Figure 2.1) using which the tool cutting edge can be quickly changed without disturbing the optical arrangement used for viewing.

Hard to machine materials are chosen, as they are the materials that are of most interest from an economic perspective. In addition, materials such as Ti and Inconel also exhibit an inherently high emissivity, even in the polished condition. Furthermore, they also
result in very high temperatures, which minimize the relative impact of many sources of error such as background radiation, making it easier to measure the temperature.

2.4.2 Experimental Setup

The tube turning experiments are carried out on a custom built high rigidity, high speed lathe in which the cutting tool is held stationary while rotating tubes are fed into the tool, as shown in Figure 2.1. Tubes of 25.4 mm (1 in) OD and 1.2 mm wall thickness are prepared from solid rods of solution treated and annealed Ti-6Al-4V and held in a collet on the spindle of the lathe. The solid rod is drilled and bored in 25.4 mm (1 in) increments to permit secure holding of the workpiece with minimal runout. The loop stiffness of the lathe in each degree of freedom is of the order of 100 N/µm. The spindle is capable of delivering up to 30 kW at cutting speeds up to 50 m/s.

The cutting tool is held within a specially designed tool holder that presents the tool at a -5° rake angle, as shown in Figure 2.2. The fixture contains locating faces that support the cubical cutting tool block on three orthogonal faces that react the cutting forces generated. A clamp is used on the side face to keep the tool in position. Clamps are not needed along the rake and flank faces on account of the cutting forces themselves acting to clamp the tool against the support faces. The tool holder is mounted on a Kistler 9367B tri-axial dynamometer that measures the cutting and thrust forces.

Out of the 12 edges of each cubic YAG tool, four were rounded to 100 µm, four to 200 µm and the rest retained the original 45° chamfer about 40 µm to 45 µm wide (i.e. measuring ~30 µm on the adjacent faces, which can be considered to be their equivalent edge radius) that
they were supplied with. The rounding was performed on a surface polishing machine using 1 μm PolyLube diamond suspension on Magercloth (rayon fabric) at 300 r/min.

The tool holder has a small pocket which accommodates a front-surface mirror that reflects the radiation emitted by the surface of the chip in contact with the tool towards the viewing direction, as shown in Figure 2.2. The radiation is imaged by a LaVision Imager Intense (branded version of PCO’s SensiCam QE) cooled low noise camera that is mounted on a Leica MZ16 stereomicroscope (Hijazi and Madhavan, 2008). Figure 2.3 shows a zoomed-in view of the cutting arrangement from the point of view of the camera, and Figure 2.4 shows an actual in-situ image recorded by the camera. In Figure 2.4, it can be seen that both a direct image of
the rake face, as well as a reflected image are formed with mirror symmetry about the cutting edge with the chip flowing away from the cutting edge towards the end of chip-tool contact.

A 1x plan apochromatic objective (NA 0.14) and a 1.5x coupler are used along with an 8x optical zoom to achieve an effective magnification of 12x on the 1376 × 1040 CCD array. Each 6.45 μm square pixel thus images an approximately 0.56 μm square region of the tool surface and the total field of view is 770 μm × 570 μm. By imaging a calibration plate containing small circles on a 100 μm square grid, it was found that each pixel corresponds to 0.56 μm and that the focus could be adjusted so that a 500 μm × 200 μm region covering most of the chip-tool

Figure 2.3. Close-up view of tube turning and viewing arrangement from the point of view of camera
contact region could be imaged in good focus. The point spread function was not calculated, but it was observed that the 25 µm diameter circles on the grid were resolved as 25 µm to 35 µm wide ellipses, depending on the extent of defocus. Thus the intensity of each pixel of the image is a convolution over a 0 µm to 5 µm region of the object plane (the chip-tool interface). If the mirror had been oriented with a single 45° angle with respect to the rake face so that the rake face is perpendicular to the viewing direction, then it would have been possible to image the entire rake face in sharp focus. However only a half-cone of rays from each of the points on the object plane would have been imaged and internal reflections may cause some blurring.

Figure 2.4. In-situ image of the chip-tool interface at 1 m/s speed and 50 µm feed for a 30 µm edge radius
The camera has a 12 bit dynamic range (4095 counts), with readout noise less than 2.5 counts rms, dark noise less than 1 count, nonlinearity less than 1 % and non-uniformity less than 0.6 %. The lab is darkened and the background images at room temperature, of typically about 40 counts are obtained prior to each cutting experiment, averaged, and subtracted pixel-by-pixel from the in-situ images recorded.

The cutting experiment is begun by initiating the acquisition of a sequence of images with the camera. The programmable timing unit that triggers the camera also issues a trigger signal that begins the feed motion at the set rate, with the offset distance established in such a manner that the second full revolution of cutting at steady state is recorded as one frame of the sequence. The data acquisition hardware also records the camera trigger signals as a fourth channel so that the cutting forces can be used to verify that the second full revolution of cutting at steady state has indeed been recorded, as shown in Figure 2.5.

2.4.3 Calibration

The calibration process includes the steps shown in the flowchart in Figure 2.6, to relate the radiant intensity distribution over the image of the front surface of the chip to its temperature. In the first step, the radiation emitted by a miniature blackbody source (Electro-Optical Industries, Model 19708-51) placed over the cutting tool is imaged through the transparent tool. Figure 2.7 shows a schematic ray diagram of the optical arrangement, indicating the position and orientation of the blackbody cavity with respect to the cubical tool and the mirror. The conical cavity of the BB source is the heated region and the cylindrical aperture is made through an insulating material. Thus the BB is not a Lambertian source and there is some directionality to the output beam (Scopatz et al.). For this reason, the blackbody
axis needs to be aligned with respect to the viewing direction for the images to be uniform. The viewing direction was determined by viewing a metallic pin kept on the rake face through the tool and orienting it such that the side faces could not be observed. The viewing direction $AO$ is at an angle of $31^\circ$ with respect to the rake face in the $X$-$Y$ plane as shown in Figure 2.7 and at an angle of $11^\circ$ with respect to the $Y$ axis along the $Y$-$Z$ plane. The blackbody is oriented along the viewing direction and brought as close as possible to the tool rake face, till the front face of the BB touches one corner of the cubical block.

Figure 2.5. Example plots of thrust and cutting forces, along with exposure time, obtained from an experiment at 1 m/s speed and 50 $\mu$m feed with a 30 $\mu$m cutting edge radius (45 $\mu$m chamfer)
By focusing the camera on a sheet of paper stuck to the front face of the BB, it was determined that the distance from this to the rake face of the tool is 0.28 mm. Due to absorption by the walls of the cylinder, there is a slight change in the radiant intensity of the beam as the plane of focus shifts from the end of the cone to the front face of the BB, and beyond to outside the BB.
The ratio of the intensity at the entrance to the conical cavity, which is 3.94 mm inside the front face of the BB, to that at a plane 0.28 mm outside the front face of the blackbody was found to be a nearly constant value of 1.15, independent of temperature, as shown in Table 2.1. The output hole diameter is 3.18 mm, which permits focusing of objectives of semi-cone angles up to 22° (NA 0.37) on the plane at the entrance to the conical cavity without obscurcation.

Figure 2.7. Schematic ray diagram of the optical configuration used for calibration
TABLE 2.1
RESULTS OF EXPERIMENT TO STUDY EFFECT OF FOCAL PLANE LOCATION WITH RESPECT TO FRONT FACE OF BLACKBODY ON COUNTS/MS

<table>
<thead>
<tr>
<th>True Blackbody Source Temp (K)</th>
<th>Intensity (counts/ms) at Two Positions of Focal Plane</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 ms Exposure</td>
<td>80 ms Exposure</td>
<td>Average</td>
<td>Average</td>
<td>Ratio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 mm In</td>
<td>0.28 mm Out</td>
<td>4 mm In</td>
<td>0.28 mm Out</td>
<td>In</td>
<td>Out</td>
</tr>
<tr>
<td>974.65</td>
<td>0.534</td>
<td>0.454</td>
<td>0.565</td>
<td>0.496</td>
<td>0.55</td>
<td>0.475</td>
</tr>
<tr>
<td>1075.85</td>
<td>2.744</td>
<td>2.427</td>
<td>2.755</td>
<td>2.409</td>
<td>2.75</td>
<td>2.418</td>
</tr>
<tr>
<td>1275.68</td>
<td>38.126</td>
<td>33.102</td>
<td>38.474</td>
<td>33.358</td>
<td>38.3</td>
<td>33.230</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The tool, the front surface mirror and the camera are maintained in exactly the same orientation all through the calibration and cutting tests in order to maintain the light collecting efficiency of the optics unchanged. While space limitations limit the size of the pocket and the size of the front surface mirror, it was found from CAD that for the numerical aperture of 0.14 of the objective, the entire cone of light collected by the objective of semi-angle 8° consists of light reflected by the front surface mirror. However, significant deviations from the viewing location or angle could cause part of the cone to fall outside of the mirror extents and for this reason the viewing direction is maintained unchanged throughout this study.

The BB was sequentially set to seven equally spaced temperatures between 700 °C and 1000 °C in 50 °C increments, while heating up and cooling down. At each temperature setting the BB temperature was found to stabilize within a few minutes, but we waited at least 20 min for the temperature fluctuations to completely settle down before taking several images each at 40 ms and 80 ms exposure times. The images were noted to have a small gradient in the
intensity values, likely arising from the axis of the blackbody not being exactly aligned with the viewing axis. Images under the same conditions were averaged pixel-by-pixel and the average intensity within a 400 µm square box of nominally uniform intensity within the aperture of the shim was obtained. Table 2.2 shows the results from this calibration experiment wherein it can be seen that the counts/ms exposure time are nearly the same for each temperature regardless of whether the blackbody is heating up or cooling down and independent of exposure time. This demonstrates the good linearity of the camera.

**TABLE 2.2**

<table>
<thead>
<tr>
<th>True Blackbody Source Temp (K)</th>
<th>Intensity (counts/ms)</th>
<th>x 1.15</th>
<th>/0.911</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40 ms Exposure</td>
<td>80 ms Exposure</td>
<td>Average (0.28 mm in front of BB)</td>
</tr>
<tr>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
<td>Heating</td>
</tr>
<tr>
<td>974.65</td>
<td>0.308</td>
<td>0.288</td>
<td>0.288</td>
</tr>
<tr>
<td>1025.25</td>
<td>0.678</td>
<td>0.688</td>
<td>0.688</td>
</tr>
<tr>
<td>1075.85</td>
<td>1.472</td>
<td>1.408</td>
<td>1.417</td>
</tr>
<tr>
<td>1126.10</td>
<td>2.764</td>
<td>2.903</td>
<td>2.888</td>
</tr>
<tr>
<td>1176.35</td>
<td>5.426</td>
<td>5.622</td>
<td>5.621</td>
</tr>
<tr>
<td>1226.02</td>
<td>10.651</td>
<td>10.723</td>
<td>10.651</td>
</tr>
</tbody>
</table>

A power law curve gives a good fit to the temperature as a function of the measured average counts/ms (Figure 2.8), with an rms error of 1.09 K. The fit exponent of 0.0647 compares well with the exponent of 0.069 calculated using Planck’s law, the quantum efficiency of the optics and the spectral response provided by Leica for a typical objective. Any non-linearity of the average response of the camera is accounted for by this calibration process to determine the
exponent and only the non-uniformity of the response of the pixels needs to be accounted for in the uncertainty analysis. Fitting the Sakuma-Hattori equation (2.1) of the form

$$T = 1036.65 \left( \frac{S}{st} \right)^{0.0647}$$

to the calculated dependence of intensity on temperature, the constants obtained are $a_2 = 0.628$, and $a_3 = 110$. Equations given by Saunders and White (2003) are used to estimate the effective wavelength as 0.69 μm and the bandwidth as 0.09 μm, for the temperature range of interest.

Figure 2.8. Power law relation between temperature and counts/ms (S/t) obtained from corrected through-the-tool calibration data.
To study the effect of glare from internal reflections within the tool, a 0.025 mm (0.001 in) thick steel shim with a square hole of size 500 µm × 500 µm (as well as another with a square hole of size 1 mm × 1 mm) was used to limit the field that is illuminated. The aperture was placed in the middle of the field of view of the camera, in such a manner that one edge of the square was located along the cutting edge. It was observed that the size of the aperture and even the complete absence of the shim did not affect the measured intensity significantly. For 80 ms exposure and 1000 °C, the values of average intensity for a 100 µm square window with 1 mm shim, 500 µm shim and without shim were 1630 counts, 1640 counts and 1665 counts respectively. Conversely, it was also observed that the counts from the regions covered by the shim show only a small increase, showing again that scattering of light within the crystal does not affect the counts significantly – i.e. cross-talk is small at least for well-separated points. This is likely due to the simplified optical configuration of the cube (Figure 2.7), the polished surfaces which do not scatter light appreciably and the 16° average angle at which the radiation that is imaged impinges the lower surface of the tool. The internal reflection at this face BC’ is also 8.9 %, but it would take the radiation many internal reflections before it can again reach the chip-tool interface. Even after just the second internal reflection, the power in the radiation reflected back into the tool at point C’ would be less than 1 % of that emitted by the interface. The reason why even complete removal of the shim did not change the radiant intensity of the image significantly is again due to the fact that any ray that is not parallel to the axis of the blackbody will not get imaged by the camera after the first refraction and, due to the maximum refracted angle of 33°, can be imaged only after multiple reflections, each reflecting
8.9 % of the remaining light. The above analysis neglects any lensing effects caused by any of the cutting edges on the block.

As described above, the fact that the BB radiance decreases with distance from the conical cavity is accounted for by multiplying the counts measured by a factor of 1.15. There are two additional differences between the BB calibration and measurement of the radiation emitted by the chip. The first is the reflection loss from the front surface of the YAG tool as shown by ray \( AB' \) in Figure 2.7. Based on the average refractive index of \( \sim 1.83 \) for YAG over the wavelength range of interest, the reflection loss is calculated to be 8.9 % for the incident (compound) angle of 32.2°. This loss is not sustained for radiation emitted by the chip surfaces in intimate contact with the tool, directly into the tool. If the reflectivity changes significantly with wavelength, the wavelength dependent free-surface reflectivity may change the exponent of the calibration curve with respect to that obtained while staring directly into the blackbody. However, the wavelength dependence of the refractive index and the reflectivity are small for YAG with the calculated normal reflectivity changing from 8.7 % at 532 nm to 8.4 % at 1064 nm and the effect of this on the exponent is negligible.

The second difference also arises due to the fact that the Ti-6Al-4V chip is emitting radiation directly into YAG. The environment into which a surface is emitting changes its emissivity, causing it to be higher. For a surface of refractive index \( n_2 \) (= 2.36 at \( \lambda = 0.69 \) μm for Ti-6Al-4V, from Weaver and Frederikse, 2012) and extinction coefficient \( k_2 \) (= 3.11, op. cit.), emitting into a transparent medium of index \( n_1 \), the normal emissivity is given as

\[
\varepsilon = \frac{4n_2n_1}{n_2^2 + 2n_2n_1 + n_1^2 + k_2^2}
\]  

(2.2)
(from equation 3.13 in Howell et al., 2011). Using this, the emissivity into air and into YAG is found to be 0.45 and 0.63 respectively and the ratio is found to be 1.41. The angle dependent emissivity can also be calculated using equations 3.17 (op. cit.) for an emission angle of 16° and are found to be identical to the values for normal incidence to three decimal places. This correction to the emissivity, increasing it by 41 % over values for emissivity into air or vacuum, is quite significant. These corrections change the multiplicative factor in the calibration equation and the final equation used to convert the intensity counts $S$ into temperature is

$$T = 1036.7 \left( \frac{S}{\varepsilon} \right)^{0.65}$$

(2.3)

where $\varepsilon$ is the emissivity of the surface into YAG and $t$ is the exposure time in milliseconds.

To collect a full cone of rays from the points of the rake face and to avoid interference with the machined surface, the mirror is located below and to the right of the cutting edge and oriented at a compound angle as shown in Figure 2.2. In addition, this viewing angle also permits study of the cutting edge region $EN$ of the tool for tools with finite cutting edge radii. However, the viewing direction causes the reflection of the rake face by the flank face to also be imaged as a temperature distribution on the flank face as shown in Figure 2.9. The angle at which the radiation is emitted from point $E$ for both light paths $EF$ and $EE'F'$ that are imaged is nearly the same (16°) and since internal reflection along the flank face is lossless, both the actual images of the rake face and its reflection on the flank face are expected to have the same intensity. For points along the cutting edge $EKN$, it can be seen that radiation from points between $K$ and $N$ will not have a mirror image while the portion of the edge from $E$ to $K$ will have a mirror image. The total width of the cutting edge region (sum of its widths in the directed and reflected images) in the images can be estimated using geometric optics to be
195 µm for a cutting edge radius of 100 µm. The intensity on the reflected image for the $EK$ portion of the cutting edge can be different from the direct image due to the expected non-Lambertian emission by the chip. The changes in the local tangent plane from point to point along the cutting edge radius causes the viewing angle of the direct image as well as the reflected image to change with respect to the local surface normal. Due to the partial reflection
and partial emission from each of the surface points and the convolution by the PSF of the optics, the task of fully interpreting the image from the cylindrical cutting edge region is challenging and is not undertaken here.

The other reason for the lack of exact symmetry of intensity within the reflected image as compared to the direct image, even in regions outside of the cutting edge, is that the light cone forming each pixel of the reflected image is actually made up of light emitted by different points of the rake face as shown in Figure 2.9. Three representative rays $E'F'$, $R'V'$ and $Q'U'$, that form the image at the pixel on the reflected image that corresponds to the pixel representing the image of point $E$ on the direct image, can be seen to originate from three different points $R$, $Q$ and $E$ on the rake face. In the direct image, all the rays forming the image of a point $E$ in good focus originate from that point.

The partial reflectivity of the surface being imaged does not add to the radiation emitted by points along the rake face of the tools since there is no significant source of external radiation. The ray diagram in Figure 2.7 shows that the viewing angle is such that radiation from neither the cutting edge nor the flank face can be superimposed over the radiation emitted by the chip in contact with the rake face of the tool. Only rays parallel to $DE$ that originate from the flank face at an angle of 74° can be reflected by the rake face in the viewing direction. However, noting that the critical angle for YAG is 33°, any ray originating from outside the flank face will be refracted between the normal and $DH$ and cannot be reflected parallel to the viewing direction within the first few reflections. A ray such as $DE$ that can be reflected parallel to the viewing direction can only originate from the machined surface that may be in intimate contact with the flank wear land along the flank face of the tool. For the data reported, all of
which is obtained from the first cut with a new edge, it can be noted visually from the images that there is no wear along the flank face of the tool.

2.4.4 Data Processing

From each cutting experiment, the image recorded over the second full revolution of steady cutting is processed, if it is observed to be clean without any visible macro-chipping of the tool edge as shown in Figure 2.4. The background image is subtracted and the counts $S$ at each pixel is converted into temperature using equation (2.3) using the known exposure time.

As noted above, the calculated value of emissivity for titanium using optical constants available in handbooks is 0.45 (into air). A careful survey of the results available in the literature for the emissivity of polished Ti-6Al-4V in the high temperature regime of interest to us (from 900 K to 1400 K) was carried out. Two sources in the literature list experimental data for the emissivity of polished Ti-6Al-4V in the temperature and wavelength ranges of interest for us, and have been compiled by Milosevic and Aleksic (2012, Figure 2). Sklarew and Rabenstein (1963) used highly polished surfaces of 0.05 μm (2 μin to 3 μin) heated under a perfectly held vacuum (as seen from the overlapping heating and cooling data). The emissivity is calculated from the apparent temperature measured using a spectral radiance pyrometer operating at 650 nm wavelength and that measured using a total radiation pyrometer, assuming grey body emission. The values are found to be between 0.5 and 0.55 over temperatures from 1200 K to 1450 K. Betz et al. (1957, inaccessible to us) are reported by Touloukian and DeWitt (1970) as having measured values from 0.41 to 0.5 for polished Ti-6Al-4V at 665 nm, for temperatures between 1200 K and 1650 K. However, Milosevic and Aleksic reports Betz et al. as having found an emissivity of 0.53 to 0.57 in the same temperature range.
The normal spectral reflectance data given in Figure 423A (and Table 423) of Touloukian and DeWitt also lists reflectance values between 0.45 and 0.5 for $\lambda$ between 0.6 and 0.8 which implies that emissivity is between 0.5 and 0.55.

Based upon the above, we can estimate that emissivity of polished Ti-6Al-4V into air is likely to be between 0.45 (that of pure titanium) and 0.55 (the higher end of the range for polished Ti-6Al-4V) in the effective wavelength range of the imaging system used in this study. However, since the chip is emitting into YAG, the estimated emissivity has to be increased by the factor of 1.41 to values in the range 0.64 to 0.78, with an average value of 0.71 that is substituted into equation (2.3) in the data processing. The emissivity increase into YAG has been verified by reflectivity measurements on a Ti coating deposited on one face of a polished YAG disc. Measurements of the reflectivity were carried out using a Shimadzu 1650 PC spectrometer with the Ti coating as the front surface and with the YAG crystal as the front surface. After subtraction of the 8.9% reflection from the front surface of YAG, the reflectivity from the Ti side was found to be 45% higher than the reflectivity from the YAG side.

The intensity image was converted into a temperature map using the steps shown in Figure 2.10. The background image is subtracted from the in-situ image taken during cutting. This is then converted into a temperature map applying equation (2.3) to the counts value of each pixel. As will be shown below in the uncertainty analysis, the random noise contributed by the camera is the main source of uncertainty at low temperatures. To avoid excessive noise in the temperature map, values less than a threshold noise of 25 counts were set equal to 25 counts, which is equivalent to 983 K for an exposure time of 80 ms. Thus, this is the lower bound of temperatures that can be resolved in the full-field temperature maps reported here.
Figure 2.10. Flow chart illustrating steps used to convert images of radiation intensity into full field temperature maps and profiles along chip flow direction.
The 1D temperature distribution as a function of distance along the rake face of the tool is the result of most interest for validating 2D plane strain simulations. This is obtained by rotating the background subtracted image so that the cutting edge is aligned along the Y-axis, extracting the interior region where the intensity gradient in the direction of the cutting edge is small as shown in Figure 2.10 and averaging the values in each column (357 columns over 200 µm) to get the average intensity as a function of distance along the rake face. This is then converted into the required temperature versus distance graph by applying equation (2.3) to the intensity at each pixel. Since the random noise is much reduced by the process of averaging the intensity over 357 pixels, a threshold of only one count is used in the conversion to temperature (as opposed to the 25 count threshold for the 2D map). The other modification to the intensity profile prior to conversion to temperature is to scale up by a factor of 1.1 the counts in the region where the chip has curled out of contact with the tool (which is identified as described later in the results section) to account for the reflection loss at the rake face.

2.4.5 Uncertainty Analysis

The three sources of uncertainty in temperature are uncertainty due to emissivity of the surface, uncertainty in the measured signal from a variety of sources during the calibration and during the measurement processes, and uncertainty in the blackbody temperature. The uncertainty due to emissivity can be obtained by taking the product of the derivative of the measurement equation (2.3) with respect to the emissivity and the uncertainty in emissivity

\[
\frac{dT}{d\varepsilon} = u(T) u(\varepsilon)
\]

where

\[
\frac{dT}{d\varepsilon} = -\frac{67.04}{\varepsilon} \left( \frac{S}{\varepsilon T} \right)^{0.065} = -\frac{0.065T}{\varepsilon}
\]
which can be rearranged as

\[
\frac{dT}{T} = -\frac{0.065u(\varepsilon)}{\varepsilon}
\]

(2.6)

It is clear that the relative uncertainty in temperature is only a fifteenth of the relative uncertainty in emissivity. The uncertainty in emissivity can be estimated from the known range for it, as

\[
u(\varepsilon) = \frac{0.78-0.64}{6} = 0.023
\]

(2.7)

The emissivity component of uncertainty in temperature \(u_e\) is independent of temperature and is found to decrease slightly with temperature, from 2 K at 900 K to less than 3 K at 1400 K, as shown in Figure 2.11.

The uncertainty in temperature due to uncertainty in the signal can be written as

\[
u_s = \frac{dT}{dS} u(S)
\]

(2.8)

where

\[
\frac{dT}{dS} = \frac{67.04}{S} \left( \frac{S}{\varepsilon T} \right)^{0.065} = \frac{0.065T}{S}
\]

(2.9)

which can be rearranged as

\[
\frac{dT}{T} = \frac{0.065u(S)}{S}
\]

(2.10)

Again, the relative uncertainty in temperature due to a given uncertainty in signal counts is reduced by a factor of fifteen. The power law fit makes it easy to understand the reason for the reduction in uncertainty due to emissivity and signal uncertainty and this is the motivation for choosing this over the Sakuma-Hattori equation, though the rms error in fit with the latter is smaller (0.11 K vs. 1.09 K).
In addition to sources of uncertainty arising from the characteristics of the camera, there are two other sources of uncertainties in the signal during the calibration process, namely, uncertainty due to variation in signal with depth of the focal plane below the front face of the blackbody, and uncertainty due to variation in signal with tilt between the axis of the blackbody and the viewing direction. The camera specifications (PCO-Tech Inc., 2008) state an rms readout noise of 2.5 counts, a dark signal non-uniformity of 1 count, and brightness non-uniformity of 0.6% (of the total counts $S_T$, prior to background subtraction).

$$u(c) = \sqrt{2.5^2 + 1^2 + (0.006S_T)^2}$$  \hspace{1cm} (2.11)

Figure 2.11. Variation of combined uncertainty in temperature and its major components with respect to interface temperature.
The signal counts when imaging the blackbody increase with increase in depth of the focal plane inside the front aperture, as shown in Figure 2.12. Due to this variation, the signal measured at the entrance to the conical cavity at the depth of 4 mm may be different from the signal that truly corresponds to the blackbody temperature at the set temperature. By considering the variation between 4 mm and 4.5 mm into the aperture to correspond to twice the standard deviation and assuming that this will scale with the average counts, the uncertainty can be estimated to be

\[ u(\text{depth}) = \frac{3090 - 3060}{2} \frac{S}{3060} = 0.005S \quad (2.12) \]
In the process of studying the dependence of intensity (counts) on the depth of the focal plane, it was noted that if the viewing axis of the camera were not collinear with the axis of the blackbody, then the intensity exhibited a gradient. Corresponding to this, the average intensity was also noted to decrease. When the focal plane was 4 mm inside the blackbody cavity, images were taken at 1000 °C for the cases of coarse and fine angular adjustments of blackbody axis with respect to the viewing direction. The fine adjustment resulted in a very uniform image with a normalized gradient (gradient / average counts) of 2.1E-5 (counts/μm)/count. The coarse adjustment, which was off from the fine adjustment configuration by a maximum of 5°, resulted in a normalized gradient of 22.1E-5/μm. Corresponding to this 10× increase in gradient, the average intensity of the image was found to decrease by 6.6 %.

Images taken through the tool, at 1000 °C for two exposure times of 40 ms and 80 ms, showed normalized gradients that were close to 7.86E-5/μm. Based on this it can be estimated that the tilt is 7.86 / 22.16 = 0.3547× the tilt between the coarse and fine adjustments in the calibration process. Therefore it may be estimated that, if the blackbody had been oriented exactly along the viewing direction in the through the tool calibration step, the average intensity could have been higher by 6.63 × 0.3547 = 2.35 %. Noting that the increase in average will scale with the measured average value, and assuming that 2.35 % corresponds to 3× the standard deviation in uncertainty, the uncertainty due to tilt can be estimated as

\[ u(\text{tilt}) = \frac{0.0235}{3}S = 0.0078S \]  

(2.13)

The signal component of uncertainty \( u_s \) decreases with increase in temperature from about 8 K at 950 K for 40 ms exposure to less than 2 K for higher temperatures (above 1190 K for \( t = 40 \) ms and above 1128 K for \( t = 80 \) ms), as shown in Figure 2.11. It is found that almost
all of this uncertainty is due to the camera (of which most of it is due to the read noise) and the uncertainties due to tilt and depth are less than 0.8 K and 0.45 K respectively. This small magnitude of the effect of the tilt is the reason why this bias is neglected and left uncorrected.

The uncertainty in blackbody temperature $u_{bb}$ is known from the blackbody calibration carried out by the manufacturer a week prior to the calibrations here, to be less than 2.5 K. The fact that this is much more than the rms error in the power law fit is one more reason why the power law fit is chosen over the Sakuma-Hattori equation. Including the blackbody temperature uncertainty, the combined uncertainty can be written as

$$u_c = \sqrt{u_e^2 + u_s^2 + u_{bb}^2}$$

From Figure 2.11, it can be seen that this is less than 9 K for all signal values greater than 25 counts, which corresponds to 983 K for $t = 80$ ms (and to 1028 K for $t = 40$ ms). The combined uncertainty is dominated by the camera noise at lower temperatures. In comparison, the components due to emissivity uncertainty and due to blackbody temperature uncertainty are nearly constant, between 2 K and 3 K.

For the profiles obtained by averaging the temperatures over 357 rows of data, the camera component of uncertainty is much reduced and this ensures that the combined uncertainty is less than 9 K for all values of signal greater than 1 count (which corresponds to 800 K), as also shown in Figure 2.11. Based on the above, it can be concluded that, for 40 ms and 80 ms exposure times used in this study, the range of temperatures that can be measured is from 983 K (710 °C) to 1423 K (1150 °C).
Other sources of error such as the point-spread function are small due to the low point spread (less than 10 μm), and due to the relatively small gradients in temperature along the plane of the chip-tool interface.

2.5 Results

Many cutting experiments have been carried out under different cutting conditions in a tube turning configuration with tubes of 25.4 mm (1 in) diameter and 1.2 mm wall thickness. The feed ramps up to steady state over the first revolution and the radiant intensity data is imaged by the cameras during the third revolution (second revolution at steady state) as shown in Figure 2.5. The average cutting force is about 145 N and the average thrust force is about 80 N for the cutting condition shown which are comparable to that during cutting with WC tools. The once-per-revolution oscillations likely arise from a variation in wall thickness due to non-concentricity of the OD and ID, or due to residual run-out of the tube. From the graph shown for cutting with a tool having an edge chamfer of 45 μm (Figure 2.5), it can be noted that the cutting force is higher than the thrust force during cutting while the thrust force is higher during the last revolution, i.e., during the clean-up portion of the cut at zero feed rate. For tools with the largest radii of 200 μm, the average cutting force is 260 N and the thrust force is 380 N (about 1.5× larger than the cutting force).

The first cut typically shows clean images without any degradation of the tool as in Figure 2.4. Thereafter, the cutting edge is found to slowly degrade by chipping. All results reported here are from the first cut with a clean cutting edge. It is found that there is negligible build-up of Ti onto the rake face implying that the front surface of the chip is being directly observed as it slides over the rake face of the tool.
The images show a nearly symmetric pattern about the cutting edge arising from reflection by the flank face of radiation emitted by the rake face as discussed above. The intensity pattern of the reflected image of the rake face is slightly different from that on the direct image but it is still remarkably close.

Images taken at different cutting conditions are converted into temperature maps using the procedure outlined in Figure 2.10 and as described above. Figure 2.13 shows temperature maps obtained for two cuts at cutting speeds of 1 m/s and 2 m/s. Note that the fringe ranges in the images are different and the peak temperature at 2 m/s is 140 K greater than that at 1 m/s, while the pattern of the distribution is the same. Figure 2.14 shows the temperature distribution for three different edge radii of 30 µm, 100 µm and 200 µm, showing that the temperature increases with increase in edge radius.

The symmetric pattern around the peak of the temperature profile is used to locate the cutting edge and its extent in the images and the profiles. Each of the images is a record of a

![Figure 2.13](image)

**Figure 2.13.** Effect of cutting speed on temperature distribution for (a) 1 m/s (b) 2 m/s speed and 50 µm feed. The cutting edge radius for both cases is 30 µm. Note that the fringe ranges are different and that the peak temperature is about 140 K higher.
600 µm wide zone of the total 1.2 mm width of the contact zone and shows both the uniform distribution along the middle of the cutting width as well as the decrease in temperature towards the side faces. While a lower bound on the magnitude of the decrease in temperature at the sides can be estimated from these images, the decrease is underestimated due to the residual runout of the tube which causes the gradient to get smoothed out.

The chip material is in contact with the rake face till it leaves contact and curls away from the rake face. In the region of contact, the tool temperature can be expected to be very

Figure 2.14. Effect of cutting edge radius on temperature distribution for (a) 30 µm (b) 100 µm (c) 200 µm edge radius. The cutting speed and feed for all cases are 1 m/s and 50 µm.
close to that of the chip due to the intimate contact between the chip and the tool due to the high contact pressure which causes the contact thermal resistance to be negligible.

One-dimensional temperature profiles are obtained using the procedure shown in Figure 2.10 as described above. In the profiles only the direct image is processed for obtaining the variation of temperature with increasing distance from the cutting edge along the middle of the chip. Figure 2.15 compares the temperature profiles for the two cutting speeds and Figure 2.16 compares the temperature profiles for three cutting edge radii. It can be seen that the patterns are very similar and that the temperatures increase with speed and edge radius. In

![Figure 2.15](image.png)

**Figure 2.15.** Effect of cutting speed on temperature profile. The expanded total uncertainty shown around the profiles is less than 6 K at all points.
the measured profiles shown in Figures 2.15 and 2.16, the temperature increases with increasing distance from the cutting edge in the chip flow direction, reaches a maximum and then begins decreasing. The increase in temperature is of the order of 100 °C to 130 °C for the cutting experiments reported here with four out of five experiments showing an increase of 130 °C.

Figure 2.16 also shows the expanded uncertainty in the temperatures computed for each point using equation (2.14). For all points, the expanded uncertainty is within 6 K. It is
very interesting to note that due to the higher cutting speed, the temperature at the cutting edge is itself higher and the gradient in temperature is nearly the same. At first glance it might be expected that the higher frictional power due to the larger chip speed would lead to a larger rise in temperature. However, noting that the mass flow rate of the chip is also higher, it is understandable that the increase in temperature is not significantly higher. The higher overall temperature is reflective of the lower fraction of the heat that the tool is able to extract out of the deforming material at higher cutting speeds.

Figure 2.16 also indicates the extents of the cutting edge region calculated from the viewing geometry and the known cutting edge radius by short vertical line segments. It is interesting to note that the peak temperature for these large cutting edge radii occur within the cutting edge region as would be expected since the feed is less than the cutting edge radius. In fact, for the 200 µm edge radius, the entire contact length is within the cutting edge radius causing the effective rake angle to be more negative than the tool rake angle of -5°. This is a second factor, in addition to the larger cutting edge radius, that contributes to a higher average plastic strain within the chip causing the overall chip temperature to be higher as observed in Figure 2.16.

Comparing Figures 2.15 and 2.16, it is interesting to note the greater effect of cutting speed on temperature. It should be noted that this is the case even with very high cutting edge radii of 100 µm and 200 µm compared to typical values of 30 µm to 40 µm used for commercial cutting of Ti-6Al-4V.
To the right of the peak temperature over the second half of the contact length, the temperature of the interface starts decreasing even though the chip is still in contact with the tool and the sliding action is producing frictional heat.

For all cutting conditions, the temperature profile along the chip flow direction is seen to reach a fairly constant slope once the chip loses contact with the tool. This can be interpreted as the rate at which the heat diffuses from the surface that was previously heated by friction into the interior of the chip. In this region, it should be borne in mind that the small oscillations observed in intensity and temperature in the 2D temperature maps arise from interference effects and the best estimate for the true temperature is the linear fit to the data in this region.

The proof that the chip has curled out of contact with the rake face in this region is that faint interference fringes are formed by the radiation reflected back into the air-gap region by the rake face of the tool. Such fringes are not observed over either the first or the second half of the contact length. In fact, an attempt was made to identify the point at which the air-gap is zero, i.e., the end of chip-tool contact, based upon the observed fringe spacing. However, it was found that the spacing between fringes did not fit the pattern $\sqrt{mAR}$ that is expected for a chip of constant curvature.

Based on the above interpretation of the temperature distribution plots and the profiles, the location where the chip leaves contact with the tool can be estimated by identifying the point beyond which the chip starts cooling at a fairly constant rate. From this, it can be clearly noted that the peak temperature is reached well before the end of contact is reached. Noting that the rising and falling slopes around the peak are approximately the same,
it can be estimated that the peak temperature is reached at about one-half the length of contact.

The temperature distribution in the direction of the cutting edge shows a higher temperature in the middle of the chip as compared to the sides of the chip. This can be attributed to the increased strain and energy dissipation in plane strain at the middle as compared to the deformation occurring in plane stress along the side faces of the workpiece.

2.6 Discussion

The new design of the transparent tools in the form of a simple cube has many advantages including the simplification of the optical arrangement and the dramatic increase in number of usable cutting edges. The new tool material choice of YAG for the transparent cutting tools also has many advantages. There are no birefringence effects as encountered with sapphire and the high temperature hardness and toughness of YAG are higher than that of sapphire. These improvements have permitted the successful machining of Ti-6Al-4V in the solution treated and annealed condition.

The actual light collection efficiency of the optics has been quantified and accounted for by a calibration process in which a blackbody is viewed through the tool. The absence of spurious reflections in the simplified optical arrangement has been verified. The variation in intensity at different focal planes along the axis of the blackbody has been determined and corrected for. The reflection losses in the blackbody radiation, at the entrance into the YAG tool as well as the increased emissivity into a YAG block as compared to air have been accounted for.
Thanks to these improvements, full-field thermographs of the average steady state temperature at the chip-tool interface have been acquired with a remarkably low expanded uncertainty in the measured temperature, less than 18 K for the temperatures reported here and better than 10 K for temperatures above 1049 K (776 °C). This has been achieved by using visible wavelength thermography using the fact that the exponent relating the intensity to temperature increases as the wavelength of light used decreases helping reduce uncertainty due to uncertainty in emissivity.

The most important feature of the results in Figures 2.13 through 2.16, and the most valuable conclusion is that very high temperatures of the order of 1273 K (1000 °C) are encountered along the rake face of the cutting tool. Even at the cutting edge, the temperature is fairly high, ranging from 1050 K to 1200 K. For titanium, these high temperatures can be rationalized based on the high strength, low thermal capacity and low thermal diffusivity of Ti-6Al-4V. The specific cutting energy measured here is sufficient to raise the temperature to very high values. Using temperature dependent thermal properties of Ti-6Al-4V (Ozel and Sima, 2010) and assuming that all the cutting energy goes into heating up the chips, the average chip temperature is calculated to be 1091 K (818 °C) for 30 µm edge radius and 1507 K (1234 °C) for the 200 µm edge radius. The average chip temperature is likely smaller because of dissipation of part of the cutting energy at and inside the machined surface and conduction of part of the dissipated energy from the chip into the tool and the machined surface. However, the measured chip-tool interface temperature can be expected to be higher than the average chip temperature because the frictional heat source is located along the chip-tool interface. The experimental results here show the net result of these competing factors with great accuracy.
and thus are very valuable for verifying and fine-tuning material properties (mechanical as well as thermal properties) and friction models.

Over the contact region, the tool face is expected to be at the same temperature as the chip due to the intimate contact between the chip and the tool which causes the contact resistance to be negligible. However, the tool does not emit since it is transparent and the emission arises from the chip.

The interference fringes appearing in the region where the chip has curled out of contact with the tool are due to light emitted by the chip getting partially reflected back by the rake face and then getting reflected back by the chip into the tool. Since 8.9 % of the power is reflected back by the rake face, the magnitude of the intensity oscillations may be expected to be 17.8 %. The intensity in the region of the chip that has curled out of contact with the tool has to be scaled up by $1 / 0.91$ to compensate for the reflection loss, and further, after conversion to temperature, smoothed by a linear fit to approximate the constant cooling rate of the hot surface by the diffusion of heat into the body of the chip and to remove the oscillations.

The temperature increases rapidly from the cutting edge over approximately the first half of the contact length at a rate of about $130 \text{ K} / 75 \mu\text{m}$. It then decreases at a higher rate over the second half of the contact length decreasing by $200 \text{ K}$ over about $100 \mu\text{m}$. Thereafter, the rate of decrease of temperature abruptly reduces and the temperature decreases only about $50 \text{ K}$ over $350 \mu\text{m}$. As noted previously, the constant cooling region can be interpreted as the region where the chip surface being observed, that has curled out of contact with the tool, cools by heat flow into the relatively cooler body of the chip.
The reason for the initial increase in temperature is obviously frictional dissipation at the chip-tool interface. The friction force at the sliding interface between the chip and the rake face of the tool over which the chip slides at high speed leads to power dissipation along the sliding interface. This frictional power causes both the chip temperature and the tool temperature to increase over the first half of the contact region.

The reason why the temperature then starts to decrease over the second half of the contact is likely a combination of several factors. Over the second half of the contact length the normal stress decreases causing the frictional stress and power dissipation to decrease. Due to the chip still being in contact with the tool here, the tool surface acts as a good heat sink causing the temperature to decrease. In addition, the flat geometry of the tool here as opposed to the convex geometry of the tool near the tool tip supports a larger rate of heat removal by the cutting tool in this region (this is similar to the shape effects on skin thickness in solidification). In other words, the heat generation as well as the thermal resistance of the tool is lower over the second half of the contact length causing the interface temperature to actually decrease. Such a pattern of temperature distribution where the temperature increases over the first half of the contact and then decreases over the second half of the contact has also been observed in both 2D and 3D FEA simulations as well as in most of the other experimental observations reported to date. However, it should be noted that if a very rough tool surface is used to enforce sticking friction even in the lightly loaded region as opposed to Coulomb friction, it is likely that the rate of decrease of temperature may be much smaller. It may even be possible to cause the temperature to reach a plateau within the contact region rather than
decrease. However, there would be a thin layer of work material stuck to the tool over which the bulk of the chip would move.

The reason why the rate of decrease of temperature over the second half of the contact is larger than that observed once the chip has curled out of contact is that the tool does not act as a heat sink in these areas. In addition, the thermal diffusivity of Ti 6-4 (2.85E-6 m²/s) is only about one-half that of YAG (5.2E-6 m²/s). Furthermore, with increasing distance from the cutting edge, the temperature gradient in the direction of the thickness of the chip, which causes heat to be conducted into the bulk of the chip, decrease as the bulk gets heated. These factors, coupled with the geometry factor mentioned above, result in the cooling rate becoming much smaller once the chip has curled out of contact. The relative cooling rates in contact and out of contact may be different from that reported here for other work material and tool combinations.

During the calibration process, one potential reason why temperatures may have been overestimated in the work by Muller-Hummel and Lahres (1997) became clear. For the first time, in this work we have taken into consideration the fact that the emissivity of metals when in intimate contact with tools made of high refractive index material is significantly higher than the emissivity into air. The more reflective the metal, the more significant this effect is. The underestimation of emissivity due to not taking this effect into account likely caused the temperatures to be overestimated, even resulting in some values above the melting point of the materials being machined.

The images shown here comprise a record of the “steady state” time averaged intensity of radiation emitted by the chip material along the rake face. The images don’t show any sharp
features because they are blurred by the motion of the chip and are the record of the time averaged intensity emitted by the chip from different spatial locations. In the case of shear banded chip formation, it is observed from a 2D plane strain FE simulation of orthogonal cutting of Ti-6Al-4V at 1.5 m/s and 225 μm feed, that the peak interface temperature fluctuates 50 K due to shear banding at a frequency of about 6 kHz. At such rates of shear banding, each image is an average of the temperature fluctuations over hundreds of shear banding cycles. Since shear banding becomes less intense with decrease in feed, the fluctuations in temperature are expected to be of lower amplitude and of higher frequency for the 50 μm feed used here. For small amplitude oscillations, the time average of intensity and the time average of temperature would correspond to one another through the same measurement equation, and the measurements made indeed reflect the time average of temperature at each spatial point.

To resolve the time variations of temperature, it is possible to carry out near IR pyrometry using longer wavelengths where there is much more radiation than in the wavelength range used here. For instance, the spectral radiance at 2 μm is 89× that at 0.7 μm, for a grey body at 1000 °C. In addition, the bandwidth can be increased to 1 μm or more from the approximately 0.1 μm bandwidth used here. These changes will permit using about 1000× lower exposure times of the order of 80 μs. The penalty would be that the uncertainty due to uncertainty in emissivity will be higher by a factor of 2 or more. Since it is likely that temperature oscillations due to shear banding are larger than the uncertainty in temperature due to all other sources of error, this trade-off is a favorable one. Additional gains in frame rate (i.e. further reductions in the exposure time) can be obtained by decreasing the magnification for instance by a factor of 3 or 4. These calculations suggest that there is sufficient IR radiation

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to image the temperature fields at the highest speeds that any given IR camera can support. This will be one focus of future investigations.

In addition to changes during shear banding, tracking the evolution of temperature over time will also provide fundamental insights into whether there is a “steady state” towards which the rake face temperature field evolves in tube and disc turning or whether the heat flowing into the tube or disc results in pre-heating effects that increase in a logarithmic manner with respect to the cutting distance as described by Nakayama (1956). If the latter possibility turns out to be the case, it will be important to use long duration planing-type cuts to obtain truly steady state thermal distributions that can be used to validate FEA and other models of metal cutting.

The repeatability of this data has to be studied in detail by carrying out repeat experiments under identical cutting conditions with identical cutting edge radii. Also, leveraging the fortuitous finding that Ti-6Al-4V chips slide over the rake face without significant adhesive transfer to YAG, visible light high speed photography can also be carried out through the transparent tools to try to map the velocity field along the chip-tool interface. By coating the transparent tools with commonly used tool coatings, the effect of these tool coatings on the friction at the chip-tool interface can be studied.

Since the temperature distribution near the side faces of the workpiece is significantly less than that along most of the rest of the interface due to plane stress deformation along the sides as compared to plane strain deformation in most of the material, the temperature profiles reported here can be compared directly with that output by 2D plane strain FEA. The low cost of 2D FEA simulations compared to 3D FEA simulations makes it much easier to use this data to
fine-tune constitutive models for the material deformation as well as friction. Another benefit of using YAG as the cutting tool material is that the thermal constants to be used in the simulations are accurately known.

2.7 Conclusions

The combination of a new design for transparent cutting tools and a new choice of tool material have made it much easier to carry out in-situ observations of the chip-tool interface through these transparent cutting tools. Hard to machine alloys such as Ti-6Al-4V in the hard (STA - solution-treated and annealed) temper can be successfully machined using transparent cutting tools made of YAG.

The temperature increases over the first half of the contact length and then decreases over the second half. A peak temperature of 900 °C has been found for cutting at 1 m/s cutting speed and 50 µm feed. The peak temperature increases to 1050 °C for 2 m/s cutting speed and 50 µm feed. Both the cutting edge temperature and the peak temperature increase with increasing cutting edge radius.

Thermography in the red or near infrared wavelengths is inherently less sensitive to uncertainties in emissivity of the polished chip surface being observed. It has been shown that full-field temperature measurements of the chip-tool interface can be carried out with an expanded uncertainty less than 10 K for most of the reported data. The accuracy and the spatial resolution of the data presented here permits researchers to use this data to verify and fine-tune material and friction models used in simulations of cutting.

The key developments accomplished here have established the feasibility of carrying out many interesting follow-up research studies aimed at establishing reference data sets for
validating machining simulations and for improving our understanding of the machining process of hard to machine materials.

2.8 Acknowledgements

Support provided by the National Science Foundation through grant number (1000819, Program Managers George Hazelrigg and Zhijian Pei) is gratefully acknowledged. Support provided by the National Institute of Standards and Technology, to VM via an IPA agreement with Wichita State University, and to TM via an MSE research grant (Project Manager Alkan Donmez) is also gratefully acknowledged. This work could not have been completed without the generous two week loan of a 19708-S1 miniature cavity blackbody source by Electro-Optical Industries (Brent Lindstrom), which is hereby gratefully acknowledged. Michael Graham of Northwestern University is thankfully acknowledged for providing the Ti coated YAG discs used for the reflectivity measurements.

2.9 References


CHAPTER 3

CONCLUSIONS

Temperature distributions along the tool-chip interface were obtained in the steady state orthogonal machining of Ti-6Al-4V with a high level of accuracy. Yttrium Aluminum Garnet (YAG) was identified as a new transparent tool material which could successfully machine this ‘difficult-to-machine’ alloy. A unique fixture was developed to hold this transparent tool using which cameras sensitive to visible and infrared radiation observed the machining process in-situ.

The time averaged temperature maps obtained using the visible/near IR camera showed a hot region adjacent and parallel to the cutting edge. The temperature was uniform in the direction along the cutting edge, but decreased near the side boundaries of the chip. Time averaged temperature profiles showed an increase of temperature with distance from cutting edge. The temperature reached peaks of 900 °C to 1050 °C at half of the contact length and then decreased for the cutting speeds used. The uncertainty for values reported in maps was 10 K and that in profiles was 6 K. The cutting temperature increased with cutting speed and tool edge radius.

This research study has successfully predicted temperature distributions among other valuable insights through visible and IR thermography during steady state orthogonal machining of difficult-to-machine materials such as Ti-6Al-4V using transparent cutting tool. This is the first successful effort of this kind and yielded results with high accuracy and resolution. Therefore, this has provided researchers with data that can now be used to compare, validate and modify the various machining and simulation models.
REFERENCES
REFERENCES


APPENDIX A

Study of Temperature Transients using High Speed Visible and Infrared Thermography of the Tool-Chip Interface through Transparent Cutting Tool while Machining Ti-6Al-4V

A.1 Introduction

The second chapter focused on high accuracy visible and near IR thermographic measurements at the tool-chip interface while cutting Ti-6Al-4V using a transparent cutting tool made of YAG. There were two important motivations to carry out such a task. Firstly, cutting temperature influences the rate of tool wear and in effect the life of the tool (Takeyama, 1963), tool performance and dimensional accuracy of the workpiece. Secondly, the cutting process models depend on temperature dependent properties of the material. These models are very important for optimizing the process and many have been developed and proposed over the years. But only a few comparisons have been reported between predicted temperatures and measured values with less uncertainty. Many researchers have made attempts at this task through different methods, but have not been able to predict temperature distributions with high accuracy while cutting difficult-to-machine materials.

The cutting images obtained in the previous chapter were the records of radiation intensity at steady state and were time averaged for one turn of the workpiece. Therefore the images are motion blurred and don’t show any sharp features. The radiation emitted from different spatial locations is averaged over time. Therefore the most important objective of the study presented in this chapter is to resolve the time variations of temperature. This is only possible by imaging the cutting process faster by reducing the exposure time of each image. This is performed by two methods. The first is using IR thermography using wavelengths longer
than what was used previously. Longer wavelength has much more spectral radiance which, along with a few other changes in imaging configuration, enables the use of exposure times which are up to 1000 times lower than what was previously used. The second method makes use of the current visible/near IR thermography where the duration of exposure is reduced by binning. It is a process where multiple image pixels are treated as a single unit. This has an additional advantage of reducing the influence of read noise on the signal to noise ratio, but by compromising the image resolution.

High speed IR thermography is carried out in the Manufacturing Engineering Laboratory at NIST where the currently ongoing projects aim at measuring temperatures in orthogonal machining. Some of their approaches have been to use high speed IR based measurements in the case of machining alloyed titanium (Ivester, 2011) and to study the effect of diamond coating on the machining process (Ivester et al., 2012). Their novel approach based on simultaneous visible and thermal imaging of machining called MAnufacturing Deformation MAcro videography System (MADMACS) is discussed by Whitenton et al. (2005) and Whitenton (2010). The factors of uncertainty have been well documented by Whitenton et al. (2010), but the experiments thus far have only measured the temperatures from the side face of the tool.

The study presented in this chapter extends the use of the high speed IR thermography system at NIST to estimate the time resolved temperature measurements during orthogonal machining of difficult-to-machine materials using transparent YAG tool. The objectives of such a study are twofold. Predicting the temperature distribution during cutting in configurations similar to that in chapter 2 validates the results obtained. Moreover, the evolution of temperature with respect to time predicts the existence of a steady state for the rake face
temperature. A blackbody calibration procedure similar to what was performed in chapter 2 is used to convert the IR images to temperature maps. The use of transparent tool helps to eliminate the effect of chips moving in unexpected directions on imaging of the cutting process.

The second method to resolve the time variation of cutting temperature, other than IR thermography, is by imaging the cutting process at much lower exposure times in the same arrangement as in Figure 2.1 using the LaVision Imager Intense camera and Leica MZ16 stereomicroscope setup used in chapter 2 (Hijazi and Madhavan, 2008). This reduction in exposure time is achieved by binning where multiple image pixels are treated as a single unit. This reduces the influence of read noise on the signal to noise ratio, but reduces the image resolution. Furthermore, high resolution visible wavelength photography using the same camera system along with digital image correlation yields a map of chip velocity field along the interface. This has become possible due to the property of Ti6-Al-4V chips to not adhere on to the YAG tool surface.

Chapter 2 mentions the sticking friction and retarded flow regimes in metal cutting. The current smooth surface of the YAG tool rake face is roughened to impose sticking friction even when the normal contact pressure is not high. The temperature predicted then is related to shear stress through friction. Shear stress is a very important quantity in machining models and is validated using these experiments.

Though some of the observations are unable to be explained still, the results of the earlier study gave deeper insights into the optical configuration of the cutting setup used. This calls for an improvement of an important element of the current tool holder design which is the mirror. It plays the crucial role of reflecting the radiation from the tool-chip interface to the
camera objective. Therefore the task of shaping the mirror better to maximize the amount of radiation reflected into the camera is undertaken.

The importance of predicting tool-chip interface temperature, at a time when industry is pushing for higher and higher speeds, has been thoroughly discussed. Therefore, another important objective of this study is to estimate temperature distributions at speeds greater than that in the previous part of the study, which were up to 2 m/s. The same cutting setup as used before (Figure 2.1) is used for the purpose of studying the tool performance and cutting process at higher temperatures caused by increasing the cutting speed. YAG is expected to perform better than other transparent materials as well as commercial tool materials at elevated temperatures.

A.2 Experimental Setup

A.2.1 NIST Camera System

The Manufacturing Engineering Laboratory at NIST developed a novel dual spectrum high speed camera to measure cutting temperature (Figure A.1). This system called MADMACS has a medium speed IR and a high speed visible camera combined to be a synchronous imaging system which images the same scene. The image size is 960 μm by 720 μm and the IR camera acquires 160 pixel by 120 pixel images at the rate of 600 frames/s in a wavelength range of 3 μm to 5 μm. The visible camera acquires 256 pixel by 128 pixel images at a much faster rate of 30 000 frames/s. The integration times are kept very small (10 μs – 30 μs) to avoid motion blur. Cutting forces are measured by the dynamometer. Further details about MADMACS can be found in Whitenton (2010) and Whitenton et al. (2010).
A.2.2 NIST Orthogonal Cutting Setup

As compared to tube turning experiments in chapter 2, the orthogonal machining experiments at the NIST machining setup (Figure A.2) is disk turning where the workpiece is a 3 mm thick disk. The setup is a modified Computer Numeric Control (CNC) machining center. The machining arrangement for cutting experiments using transparent tool from the viewing direction of IR camera is shown in Figure A.3. The tool-chip interface is at the 180° position of the disk workpiece. The transparent tool holder with the new mirror is mounted directly on to the existing dynamometer and the camera images the cutting process in the same configuration as shown in Figure A.1. The disk workpiece has two motions: rotation on horizontal spindle axis and, up and down along vertical axis.

Figure A.1. NIST dual-spectrum camera system (Whitenton et al., 2010; Figure 2)
Figure A.2. NIST orthogonal machining setup (Ivester et al., 2012; Figure 2 (a))

Figure A.3. NIST orthogonal machining arrangement from viewing direction of camera
A.2.3 Experimental Setup with Visible Camera

The tube turning experiments are carried out on the same high speed lathe, as discussed in section 2.4.2, in which the cutting tool is held stationary while rotating tubes are fed into the tool as shown in Figure 2.1. Tubes of 25.4 mm (1 in) OD and 1.2 mm wall thickness are prepared from solid rods of solution treated and annealed Ti-6Al-4V and held in a collet on the spindle of the lathe. The solid rod is drilled and bored in 25.4 mm (1 in) increments to permit secure holding of the workpiece with minimal runout. The cutting tool is held within the specially designed tool holder with a $-5^\circ$ rake angle as shown in Figure 2.2. The tool holder is mounted on a Kistler 9367B tri-axial dynamometer that measures the cutting and thrust forces. All the results reported here are obtained from tool edges retained at the original $45^\circ$ chamfer about a few microns wide that they were supplied with.

The radiation is imaged by the LaVision Imager Intense cooled low noise camera that is mounted on the Leica MZ16 stereomicroscope (Hijazi and Madhavan, 2008). The 1x plan apochromatic objective (NA 0.14) and the 1.5x coupler are used along with an 8x optical zoom to achieve an effective magnification of 12x on the $1376 \times 1024$ CCD array. To resolve the time variation of cutting temperature, the cutting process is imaged at much lower exposure times of 5 ms for the 1 m/s cuts and 1 ms for the 2 m/s cuts as compared to 80 ms and 40 ms used in chapter 2 for imaging one turn of the workpiece. The acquisition time thus increased to 33.3 frames/s for 5 ms exposure and 38.5 frames/s for 1 ms exposure. This reduction in exposure time is achieved by binning an 8 by 8 array of pixels and treating them as a single unit. This reduces the influence of read noise on the signal to noise ratio, but reduces the image resolution. Each image size is now 172 pixels by 128 pixels. Each 51.6 µm square pixel thus
images an approximately 4.48 µm square region of the tool surface and the total field of view is still 770 µm × 570 µm.

The lab is darkened and the background images at room temperature are obtained prior to each cutting experiment, averaged, and subtracted pixel-by-pixel from the in-situ images recorded. The cutting experiment is begun by initiating the acquisition of a long sequence of images with the camera. The programmable timing unit that triggers the camera also issues a trigger signal that begins the feed motion at the set rate. A total of 6 turns of the workpiece are cut at constant feed. The same steps of data processing as in the flow chart in Figure 2.10 are followed. The exposure time in equation (2.3) is taken as 64 (8 × 8) times the camera exposure time i.e., 320 ms for 1 m/s and 64 ms for 2 m/s cuts. The results in this case are a sequence of maps and profiles over time for the same cut.

A.3 Preliminary Results

The sequence of temperature maps for 1 m/s and 2 m/s speed at 50 µm feed are shown in Figure A.4 and A.5 with the corresponding frame numbers. The average temperature profiles over 200 µm width of the cutting edge for the same cuts are shown in Figures A.6 and A.8. Figures A.7 and A.9 show the variation of maximum temperature on the rake face from the two sets of average profiles. They indicate that temperature increases and tends to stabilize at a maximum, but there are fluctuations of the order of 10 °C to 20 °C.
Figure A.4. Temperature maps for cut with 1 m/s speed and 50 μm feed with corresponding frame numbers
Figure A.5. Temperature maps for cut with 2 m/s speed and 50 μm feed with corresponding frame numbers
Figure A.6. Average temperature profiles for cut with 1 m/s speed and 50 μm feed

Figure A.7. Variation of maximum of average temperature profile with frame number for cut with 1 m/s speed and 50 μm feed
Figure A.8. Average temperature profiles for cut with 2 m/s speed and 50 μm feed

Figure A.9. Variation of maximum of average temperature profile with frame number for cut with 2 m/s speed and 50 μm feed
A unique fixture was designed to hold the cubic YAG tool and a mirror. It is shown in Figure 2.2. The precise mirror cutout to fit in the space was determined using Solid Works. The mirror had to be oriented such that the hot and bright chip near tool-chip interface can be observed by the camera. The four different views shown in Figure B.1 show how the light ray reaches the

Figure B.1. Determining the mirror orientation in tool holder pocket by tracking a light ray from object (chip) to observer (camera)
observer (camera) via the mirror. It should be noted here that refraction through YAG was not taken into account. The precise shape of the mirror to be placed in the space was determined and the result is shown in Figure B.2. This shape was precisely cut from an acrylic front surface mirror slab using a diamond cutter and was adhered on to the fixture using high temperature epoxy.

This was used in chapter 2, the results of which gave deeper insights into the optical configuration of the cutting setup used. The YAG refraction was not taken into account for the first design. This design caused the existence of the secondary angle of 11° for the camera viewing axis (discussed in section 2.4.2) which resulted in needing additional compensations for the radiation intensity measured by camera. Moreover, some aspects of the cutting image were unable to be explained. This called for an improvement of the mirror as it plays the

Figure B.2. 3D Solid Works model of mirror cutout
crucial role of reflecting the radiation from the tool-chip interface to the camera objective. Therefore the task of shaping the mirror better to maximize the amount of radiation reflected into the camera was undertaken.

Rather than a light ray, a cone of light was modeled to originate at the center of tool cutting edge which traveled to reach the camera objective by getting reflected from the mirror front surface. The correct Numerical Aperture (NA) for the lens objective used and the refractive index of air-YAG interface were taken in to account to determine the cone angles. The dimensions and angles determining the mirror orientation in the Solid Works model were driven by a Microsoft Excel sheet using Visual Basic programming. An iterative procedure was used to align the mirror such that the secondary angle of $11^\circ$ is eliminated. Moreover, the cone of light had to be targeted on the centroid of the mirror front surface to maximize the amount of radiation reaching the camera objective. This is shown in Figure B.3.
Figure B.3. Determining the mirror orientation in tool holder pocket by tracking a light cone from object (chip) to observer (camera)
APPENDIX C

Calibration Report of Miniature Blackbody Model 19473

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Certificate No. 11177
1) Calibration is performed under a room temperature condition of 27°C ±5°C and humidity of between 30% and 70%.
2) The Radiation Source was calibrated using an EOI model 123S Thermocouple standard, with identification number 90681-2. The standard limits of error are ±1.5 degrees (C) or ±0.25% of set temperature, whichever is greater. The standard used in calibration is traceable to National Institute of Standards and Technology (NIST) Test number 279735, and is in compliance with MIL-STD-45662A, ISO-9002, and ANSI/NCSL Z540.3-2006.
3) A Total Uncertainty Ratio (TUR) of 4.1 with a confidence level of K=2 (approximately 95%) was maintained unless otherwise noted.
4) This report may not be reproduced, except in full, without written permission from Electro Optical Industries.

Signed: Ricardo Hernandez  Date: 04/16/2013
Signed: Quality Assurance  Date: APR 16 2013