EVALUATION OF WORK PIECE TEMPERATURE MEASUREMENT TECHNIQUES FOR MILLING OF Ti6Al4V

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ABSTRACT

Ti6Al4V is one of the most widely used titanium alloys in aerospace applications, but its machining remains a challenge. This is partly due to the lack of understanding of the thermal- and mechanical constraints during milling. Extensive research has been done in the past investigating catastrophic tool failure of various tool materials. However, not much research has been done to investigate the cause of work piece failure. The catastrophic effect of overheating the work piece and the resulting alpha case formation in titanium is well known. Current techniques of temperature measurement of the machined surface can be divided into two categories: contact- and optical methods. In this study these temperature measurement techniques were studied and evaluated. The response time of contact methods are found to be to relatively slow. The optical methods have the advantage of immediate response, allowing capture of intermittent heat generation as required in milling. The infrared camera temperature measurement experiments were conducted with a special setup in order to have a good visual of the temperature flow. The results of these experiments were found to correspond with literature.

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1. INTRODUCTION

Titanium alloys have been used widely in many industries; more specifically Ti6Al4V is very popular in the aerospace and bio-medical sectors. This is due to its high strength-to-weight ratio and excellent corrosion resistance. These exceptional qualities do however reduce the overall machinability of titanium. As Ti6Al4V has a very low thermal conductivity, high chemical reactivity and low modulus of elasticity [1], the cutting speeds (v_c) are limited to relative low speeds [2]. During milling of Ti6Al4V the high tool work piece temperatures and large friction phenomena between the tool and work piece interface cause excessive tool wear and degradation of work piece quality. The exposure to excessive temperatures during machining can even lead to work piece fatigue. Disastrous accidents have occurred where component failure could positively be traced back to alpha-case formation [3]. Alpha case is a relatively unknown topic, but a very real risk factor in aerospace manufacture [4]. Civil aviation does conduct scheduled inspections to detect early signs of fatigue failure, which is a typical consequence of alpha-case during machining. Alpha-case, therefore, has to be designed out of the manufacturing process. The topic is complex and all analysis possibilities have by no means been exhausted [3]. Large aerospace companies will therefore benefit greatly in further research and is expected to support this field of research. An accurate and real-time temperature measurement method is therefore needed to ensure superior work piece quality and a reduced chance of failure due to fatigue [1]. Knowing this, it will be possible to improve the cutting speed in order to increase productivity. There are two main categories of temperature measurement, namely: conduction and radiation. The most commonly used method is the utilization of thermocouples which is classified under the conduction category. Radiation can be divided into the infrared and the optical thermocouple techniques. This paper evaluates several temperature measurement techniques and illustrates experimental results of an infrared camera temperature measurement experiment. The experiment was conducted with a special milling setup in order to have a good visual of the temperature flow.

2. DIFFERENT TEMPERATURE MEASUREMENT METHODS

There are various methods to measure the temperature during machining, but the biggest challenge being the measurement of temperature during the application of lubrication strategies to the work piece. The various temperature measurement methods will be investigated and the advantages and disadvantage compared.

2.1 Conduction

Conduction is the transfer of energy from more energetic particles of a material to the adjoining less energetic ones by means of the interactions between the particles [5].
Figure 1 illustrates the conduction measurement methods that were explored.

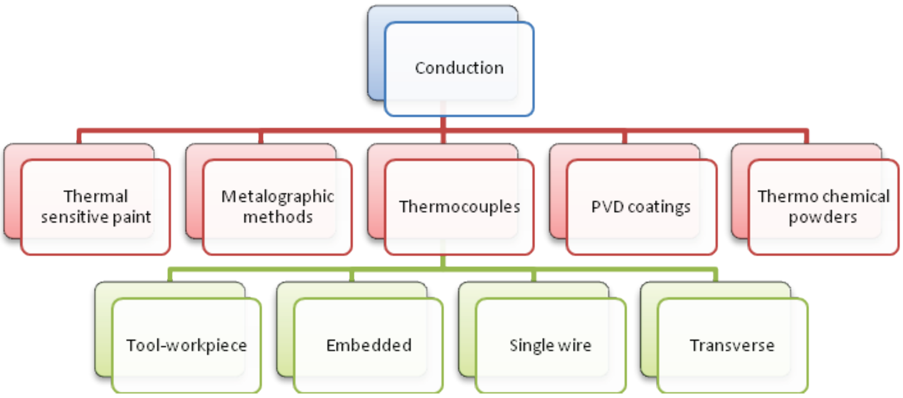


Figure 1: The various conduction temperature measuring methods that were explored [6, 7, and 8]

Conduction methods make use of instrumentation that measures the temperature difference between two points that are in direct contact with each other. Heat will be transferred from a location that has a higher energy level to one that is lower with the means of interpreting this transfer value to give a temperature measurement.

2.1.1 Thermal sensitive paints

Thermal sensitive paints change color in response to a change in temperature due to a chemical reaction at specific temperatures [9]. The paint should be applied to accessible areas of the cutting tools or work pieces in order to get the approximate temperature value to which it is exposed [9]. Using this method in cutting tools, it is recommended to use a split-tool setup [10]. The cutting tool is divided into symmetrical halves, the paint applied to the one side of the tool and reassembled before cutting. The aspects of thermal paints are summarized in Table 1.

Advantages	Disadvantages
Simple technique	Application is limited to controlled heating conditions
Inexpensive to set up	Not very accurate due to high temperature gradients and low thermal sensitivity of thermo-colors
Gives a rough indication of temperature distribution	Not used with cooling

Table 1: Advantages and disadvantages of thermal paints [9, 10]

Although it is not very accurate, thermal sensitive paints is a very simple and inexpensive technique. It can be used to indicate the temperature distribution in dry and controlled heating conditions.

2.1.2 Metallographic methods

Most materials exhibit a change in microstructure with a change in temperature [9]. Metallographic methods work on the principle that when the microstructure at a given temperature is known, it can be used to compare it to the microstructure of another material. This comparison can also be done by measuring the changes in hardness using a micro-hardness test [9]. Observing the structural changes throughout a material, the temperature isotherms can then be deducted and allocated to certain regions. The advantages and disadvantages are summarized in Table 2.

Advantages	Disadvantages
Attains relative accurate results	Technique only applicable to materials exhibiting a change in microstructure with temperature
Used with cooling	Many common cutting materials such as carbides or ceramics cannot be used
	Several calibrations are required to obtain good correlation
	Technique requires high cutting speeds resulting in excessive wear

Table 2: Advantages and disadvantages of metallographic method [9]

The metallographic method is very practical, as it can be used with cooling to attain fairly accurate results. Frequent calibration and excessive tool wear with excessive temperatures at elevated cutting speeds, reduces the attractiveness of the technique.

2.1.3 Thermocouples

Thermocouples are based on the Seebeck effect that occurs in an electrical conductor, when there is a temperature gradient along its length [11]. This thermally induced current is associated with a voltage drop that will be present in any conducting material experiencing a thermal gradient [12]. This gradient can exist across two junctions (called hot and cold junctions) where an electromotive force (emf) will be generated across the junction. The emf generated is a function of the materials used for the thermocouple and also of the temperatures of the junctions [13]. Table 3 shows the temperature range of eight standard thermocouples.

SLD	Popular Name	Materials (color code) (positive material appears first)	Typical Temperature Range	Seebeck Coefficient at 100°C μV/°C
S	-	Platinium-10% rhodium vs. platinum	-50 to 1767 °C	7.3
R	-	Platinium-13% rhodium vs. platinum	-50 to 1767 °C	7.5
B	-	Platinium-30% rhodium vs. platinium-6% rhodium	0 to 1820 °C	0.9
T	Copper-constant	Copper (blue) vs. a copper-nickel alloy (red)	-270 to 400 °C	46.8
J	Iron-constant	Iron (white) vs. a slightly different copper-nickel alloy (red)	-210 to 760 °C	54.4
E	Chromel-constant	Nickel-chromium alloy (purple) vs. a copper-nickel alloy (red)	-270 to 1000 °C	67.5
K	Chromel-Alumel	Nickel-chromium alloy (yellow) vs. a copper-nickel alloy (red)	-270 to 1372 °C	41.4
N	NIcrosil-Nisil	Nickel-chromium-silicon alloy (orange) vs. Nickel-chromium-magnesium alloy (red)	-270 to 1300 °C	29.6

Table 3: Standard thermocouple types [9]

The thermocouples that contain noble metals such as platinum and platinum-rhodium combinations are called noble metal thermocouples and are indicated as Type B, R, and S. The rest are called metal thermocouples and are indicated as Types E, J, K, and T which can be chosen primarily based on the temperature range within which measurements need to be taken [9].

2.1.3.1 Embedded thermocouples

This thermocouple is inserted into a hole drilled into the work piece material. In order to measure accurately, the thermocouple is situated very close to the cutting surface. Figure 2 illustrates embedded thermocouples in a milling operation.

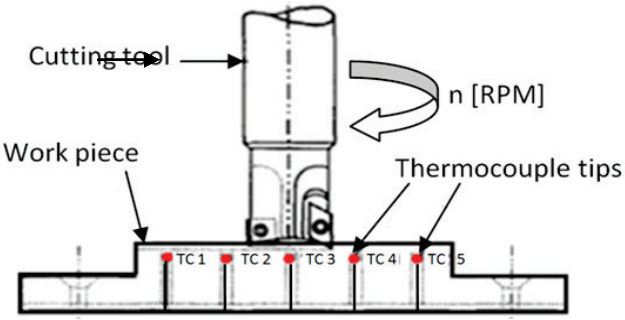


Figure 2: Embedded thermocouples [14]

This method is not ideal for determining surface temperatures, but by using heat transfer models, it is possible to predict the temperature [11]. The main problem with a thermocouple is that it does not respond to rapid changes of temperature. It is also difficult to calibrate embedded thermocouples at high temperatures [11]. The hole should be filled with thermal conductive cement that has thermal properties close to that of the material so that all air around the thermocouple is removed. The presence of the thermocouple holes in the work piece influences the heat conduction through the material, which can create accuracy problems. It still remains a relatively simple technique that is easy to use. The positive and negative aspects are summarized in Table 4.

Advantages	Disadvantages
Simple in construction	Numerous holes in tools/work piece is difficult and expensive
Simple operation and signal processing	Limited transient response
Ease of remote measurement	Limited spacing
Low cost	Numerous holes can alter heat conduction, affecting strength of tool/work piece
	Not used with cooling

Table 4: Advantages and disadvantages of embedded thermocouples [13]

An embedded thermocouple is a very effective measuring device that is simple in construction, operation and signal processing. There are some disadvantages such as expensive drilling of holes that could lead to an alteration of the conduction rate through the material.

2.1.3.2 Tool-work piece

The Shore-Gottwein-Herbert technique [9] uses two bodies in relative motion as the two elements of a thermocouple in order to measure temperature. This technique is useful in illustrating the effect of cutting conditions such as feed rate (f_z) and cutting speed (v_c). The problem is that the absolute values are not accurate and should only be used for comparisons. The thermo-electric emf generated between the tool and work piece is measured during cutting where the cutting zone forms the hot junction and an electrical connection to a cold part of the tool and work piece, forms the cold junction. To ensure accuracy, the work piece and tool need to be electrically insulated from the machine tool [15]. A typical setup of this technique is shown in Figure 3.

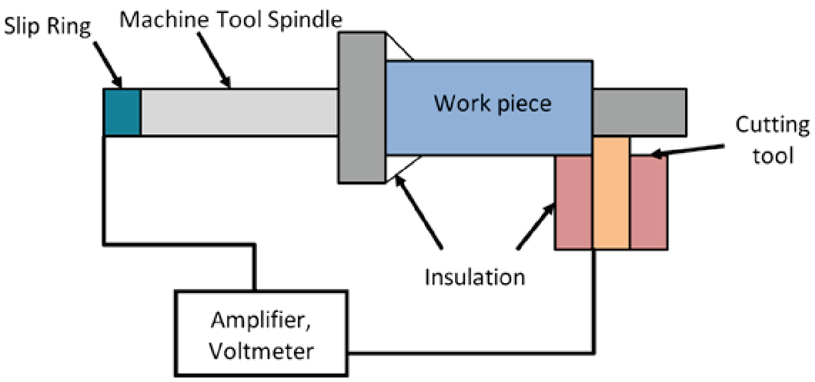


Figure 3: The tool-work thermocouple experimental setup [11]

The presence of very large thermal gradients in the area of the largest material inhomogeneity is actually not standard thermocouple practice [12]. However, researchers have tried to conduct numerical and theoretical analysis of the dynamic thermocouple to determine the effect of a variable temperature on the tool-work interface [12]. This is a very practical method to obtain qualitative information and can be used to provide an indication of trends in interface temperatures as well as correlations with tool wear [12]. The advantages and disadvantages are summarized in Table 5.

Advantages	Disadvantages
Relatively simple to use	Not used with cooling
Has good dynamic response	Accurate calibration of the tool and work piece thermocouple pair is very difficult
Used where cutting interface is inaccessible for direct measurement techniques	Only measures mean temperature over entire surface – high local or flash temperatures occurring for a short period of time cannot be observed

Table 5: Advantages and disadvantages of the tool work piece thermocouple temperature measuring technique [9, 11, 16 and13]

This technique has a good dynamic response that is simple to use for measuring temperatures in inaccessible areas. The problems though are that accurate calibration is very difficult and it is only possible to measure the mean temperature without the effect of cooling.

2.1.3.3 Single wire

This technique uses a single wire thermocouple system where a sample is divided into two across the line of cutting. Thereby, a thin insulated conductor is introduced Figure 4 is an illustration of this setup.

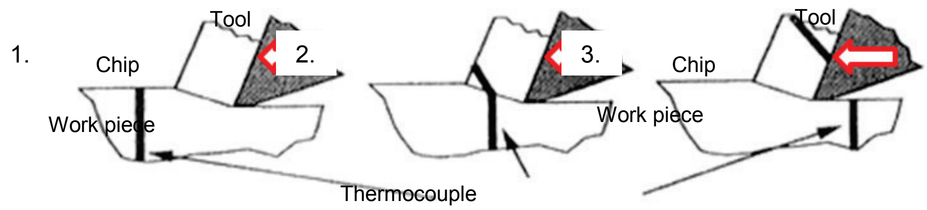


Figure 4: The single wire thermocouple measuring process [11]

As this conductor (thin wire) is exposed to the machined surface of the work piece, it comes in contact with the sample body and a signal is produced. During the milling operation this wire will be cut, exposing it and forming a thermocouple between the wire and the tool [15]. The signal is only generated for a very short period of time as the cutting tool makes contact with the wire. The temperature measurement is recorded for a very short interval using a very high sampling rate [11]. Since this thermocouple is simply a variation of the embedded thermocouple, many of the advantages and disadvantages will be same with a few exceptions as shown in Table 6.

Advantages	Disadvantages
Simple in construction	Not used with cooling
Simplicity in operation and signal processing	Errors due to uncertainty in cutting zone
Ease of remote measurement	Extremely short contact times might cause conduction problems
Low cost price	

Table 6: Advantages and disadvantages of thin wire thermocouples [13, 15]

The thin wire thermocouple is very simple in construction and easy to process its signals. It can be obtained at a relatively low cost and is ideal for remote measurement. As a result of the very short contact times, conduction problems might lead to errors and result in inaccurate readings. Since conduction is influenced by a fluid, cooling would be a problem.

2.1.3.4 Transverse thermocouple

Transverse thermocouples were developed in order to obtain a three dimensional tool temperature distribution on the end-, clearance-, and rake face of the tool within the chip-tool interface area [9]. This technique is an adjustment of the tool-work piece thermocouple, where the contact between the chip and tool changes continuously as the cutting proceeds [9]. The transverse thermocouple setup is illustrated in Figure **5**.

This method is based on the principle that a thermo-electric junction is formed between the tool and a sharply pointed probe of a dissimilar material. By changing the position of the probe as it moves, a continuous temperature distribution can be measured relative to some specified edge [9].

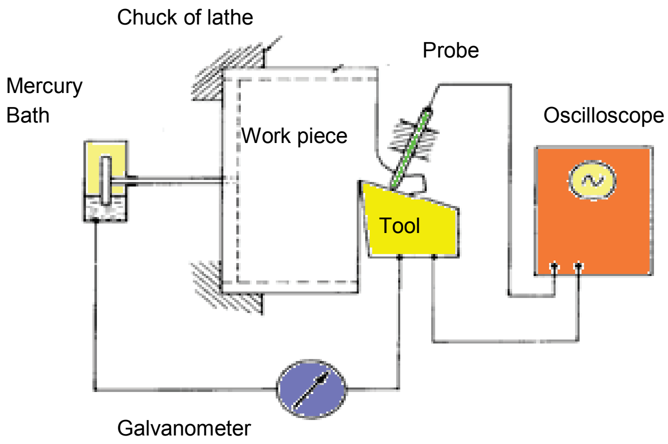


Figure 5: Transverse thermocouple setup [9]

The probe is continuously moved along the tool surface where the spot temperature is recorded. The advantages and disadvantages using the transverse thermocouple setup are summarized in Table 7.

Advantages	Disadvantages
Gives a 3D temperature distribution	Not used with cooling
Can give valuable information on location of tool wear	Complex setup

Table 7: Advantages and disadvantages of transverse thermocouples [9]

This method is useful in obtaining a three dimensional (3D) temperature distribution that can lead to important information on the location of tool wear. The problems with this technique are that it is very complex to set up and is not used with cooling.

2.1.4 PVD coatings

A Physical Vapor Deposition (PVD) coating is applied to a split-tool in an aqueous solution to act as a thermal sensor. This method determines the internal temperature of a solid body during milling. Several kinds of materials with different melting points are physically-vapor-deposited on the cutting tool's split surface [17]. In Table **8** different PVD coatings with their melting temperatures are summarized.

PVD film material	Symbol	Melting Point [°C]	Purity
Tellurium	Te	450	99.999
Lead	Pb	328	99.999
Bismuth	Bi	271	99.999
Indium	In	157	99.99
Alloy*	Alloy	96.6	99.99

* Composition (wt %) Bi : Pb : Sn = 50 : 28 :22

Table 8: Melting point and purity of PVD film materials [17]

Each of the film materials melt at a specific temperature, and can therefore be used as thermal sensors to determine the temperature distribution near the cutting edge. Using calibration tests it can be determined that the temperature at the boundaries between the melted and un-melted films is equal to the melting temperature of the specific film material [17]. Machining experiments [9] with the PVD material tellurium are illustrated in Figure **6**.

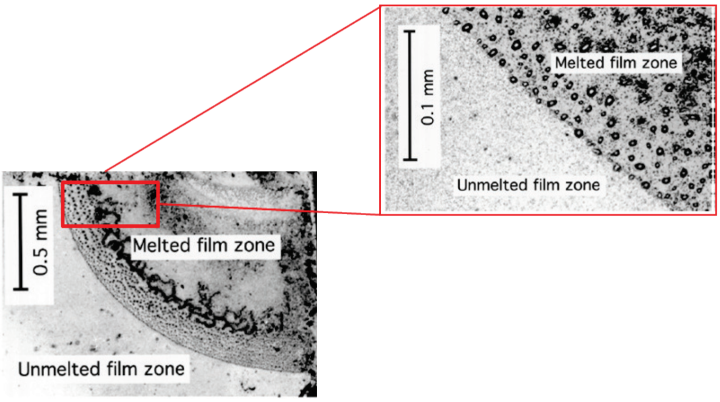


Figure 6: Photomicrograph of PVD coated (tellurium) surface [9]

It can be seen that the boundary between the melted and un-melted regions is clearly distinguishable. This boundary is the isotherm of 723K which is the melting temperature of tellurium as was indicated in Table **8**. The advantages and disadvantages of PVD are summarized in Table 9.

Advantages	Disadvantages
Small mass of the thin film has only a slight effect on heat transfer characteristics	Only give temperatures in intervals displayed by specific melting points of PVD
Influence of film's physical characteristics have negligible effect on internal temperature	Not used with cooling
Good indication of temperature distribution	

Table 9: Advantages and disadvantages of PVD coatings [17]

The positive aspects of PVD coatings are that it does not influence the heat transfer characteristics of the work piece and it does not have a noticeable effect on the internal temperature. The PVD film melts in specific contours, making the temperature distribution easily distinguishable. Although these contours give an indication, it can only melt in the intervals of the PVD melting points which make it a very rough stepwise interval indication. This film can also not be used with cooling fluids as it would damage the PVD coating

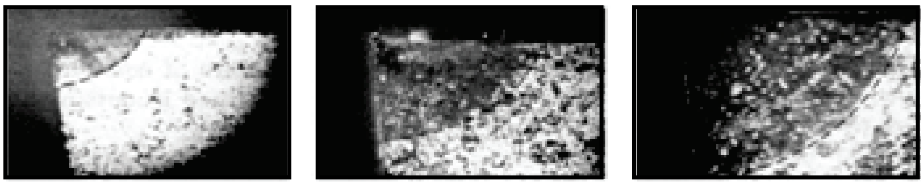
2.1.5 Thermo chemical powders

The cutting tool used is divided into two symmetrical parts where fine powders are scattered on the one side of the tool. An aqueous solution to ensure adhesion are used to put the two halves together prior to cutting. The temperature distribution is obtained using different powders with different melting points. Table 10 summarizes commonly used powders and their melting and boiling points [15].

Chemical symbol	Melting point °C	Boiling point °C
NaCl	800	1413
KCl	776	1500
CdCl	568	960
$PbCl_2$	501	964
AgCl	455	1550
Zn	419	907
KNO_3	339	-
Pb	327.4	1750
$SnCl_2$	246.8	623
Sn	231.9	2270

Table 10: Powders of chemicals used and their respective melting points [5]

This technique is repeated using one type of powder at a time. The results are combined by superimposing the boundary lines of the different tests to determine the temperature isotherms. Figure **7** is an illustration of the melting boundaries of three different powders (NaCl, $PbCl_2$ and KNO_3) with a carbide tool.



NaCl (Melting Point 800°C) $PbCl_2$ (Melting Point: 501°C) KNO_3 (Melting Point 339°C)

Figure 7: Optical micrographs of the sandwich surface tool using powders of NaCl, PbCl2 and KNO3 [9]

The powders melt in such a way that there is a clear distinction between the melted and un-melted areas. The advantages and disadvantages of the thermo chemical powders are summarized in Table 11.

Advantages	Disadvantages
No calibration needed as the powders have constant melting points	Tests have to be repeated numerously to account for each powder being used
Gives good indication of temperature distribution with the use of isotherms	Not used with cooling
Relative simple procedure	

Table 11: Advantages and disadvantages of thermo chemical powders [9]

The chemical powders are easy to use and have constant melting points. No calibration is needed and the temperature distribution can be illustrated clearly as isotherms. The only problem with this is that numerous tests have to be conducted in order to obtain the isotherm of each powder. Cooling is also limited as this will interfere with the powder at the surface interface.

2.2. Radiation

Radiation is the energy emitted by matter in the form of electromagnetic waves or photons as a result of the changes in the electronic configurations of the atoms or molecules [5]. Figure 8 illustrates the radiation measurement methods that were explored during this research study. Thermal radiation is the form of radiation emitted by all bodies that have a temperature above absolute zero and therefore have interaction of the atoms and molecules [5].

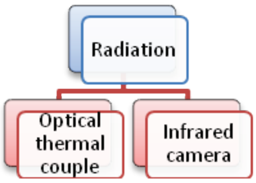


Figure 8: Radiation temperature measuring methods [6, 7]

Emissivity quantifies the ability of an object or material to emit thermal radiation. It is defined as the ratio of emitted radiation radiated by a body to the radiation of a true black body at the same temperature; emissivity is therefore a dimensionless quantity. Emissivity (ε) depends on the body and can be measured with an infrared thermometer by comparing the temperature measurements of the object made with the infrared thermometer with that of another temperature measurement technique such as a thermocouple. An ideal black colored body will have an emissivity value of ε=1 and any real life object will exhibit an emissivity of ε<1.

2.2.1 Optical thermocouple

An optical fiber is placed beneath the work piece with which a change can be detected in the induced wavelength. The Bragg gratings are made by illuminating the core of an appropriate optical fiber with a spatially varying pattern of intense ultra violet light [11]. Short wavelength UV photons have enough energy to break the extremely stable silicon-oxygen bonds so that the structure of the optic fiber is damaged leading to a slightly increased refractive index. This adapted fiber can then operate as a wavelength selective mirror [11]. This reflective wavelength is affected by any variation in the mechanical or physical properties of the grating region. A change in temperature will lead to a change in the effective refractive index as a result of the thermo-optic effect. To implement this technique on a work piece, it must be placed on the optical tube or the optical tube must be placed in a sandwich between the piece that will be cut and a backing apparatus [11]. The advantages and disadvantages are summarized in Table 12.

Advantages	Disadvantages
Very responsive method	Adaptations to work piece not practical in industry
	Not used with cooling

Table 12: Advantages and disadvantages of optical thermocouples [11]

2.2.2 Infrared cameras

The infrared light emitted by objects is focused with a special lens to enable it to be scanned by a phased array of infrared-detector elements. Several thousand points in the field of the detector array forms the elements that create a comprehensive temperature pattern called a thermogram. This thermogram is translated into electric impulses that are sent to a signal-processing unit where the information is converted into data for the display. It is also possible to acquire spot temperatures by directing the cross hairs of the camera at a desired position and getting a reading for that point [11].Table 13 summarizes the advantages [16] and disadvantages [11] using an infrared camera to measure the temperature.

Advantages	Disadvantages
No disturbance of temp field	Chips and opaque materials disturb thermal images
Good indication of temperature distribution	Limited use with cooling as result of interference
Relatively easy to use	Emissivity of materials need to be extremely accurate increasing number of calibrations

Table 13: Advantages and disadvantages of infrared cameras [11, 16]

Thermal cameras are easy to use and are effective since they do not disrupt the temperature field in the work piece as they measure the temperature distribution. The problems associated with this are that the line of sight of the camera needs to stay clear of any opaque materials such as machining chips and cooling fluids. Also, since the camera is largely dependent on the emissivity of the material it is very important to use accurate emissivity values. The problem with this high level of accuracy is that it might lead to an increased number of calibrations and costs if not done correctly.

3. EVALUATION OF THE TEMPERATURE MEASUREMENT TECHNIQUES

In evaluating the different techniques, it is seen that the advantages and disadvantages make each technology suitable for a specific applications. The development of these techniques makes it possible to obtain a few that is comprehensive enough to use in almost any application. As shown in Table 14 very little of these temperature measuring techniques can accommodate a lubrication strategy, which is necessary for the milling of Ti6Al4V. Since some machining processes are extremely fast, the response time of the measuring equipment needs to be capable of measuring in extremely short intervals. It is seen from Table 14 that this is unfortunately not possible in many measuring techniques and should therefore also be considered for improvement.

Metallographic methods and embedded thermocouples have been used successfully in cooling applications, but some of the other techniques can also be used with cooling if it is used in a specialized setup. Using reverse side irradiation, techniques such as the infrared cameras and the optical thermocouples can also be used to obtain measurements with cooling. Some techniques have an overall good rating in most of the criteria and can therefore be used successfully in machining applications. The thermocouple is one example of this. Being one of the oldest methods, it has been used successfully over the years in many different applications. It is robust, easy to use and fairly accurate.

	Cost	Accuracy	Use with Liquid Cooling	Ease of Calibration	Transient Response	Simplicity
Thermal Sensitive Paints	*Good*	*Not Good*	*Bad*	*Good*	*Average*	*Good*
Metallographic Methods	*Average*	*Good*	*Good*	*Bad*	*N/A*	*Average*
Thermocouples	*Very Good*	*Good*	*Bad*	*Good*	*Bad*	*Good*
Embedded Thermocouples	*Very Good*	*Good*	*Good*	*Good*	*Bad*	*Good*
Tool-Work Piece Thermocouple	*Average*	*Average*	*Bad*	*Very Bad*	*Bad*	*Good*
Single Wire	*Very Good*	*Average*	*Bad*	*Good*	*Bad*	*Good*
Transverse Thermocouple	*N/A*	*Good*	*Bad*	*Bad*	*Average*	*Bad*
PVD Coatings	*N/A*	*Good*	*Bad*	*Good*	*Average*	*Good*
Thermo Chemical Powders	*N/A*	*Good*	*Bad*	*Very Good*	*Average*	*Very Good*
Optical Thermocouple	*Average*	*Good*	*Bad*	*Bad*	*Very Good*	*Good*
Infrared Camera	*Average*	*Good*	*Bad*	*Bad*	*Very Good*	*Good*

Table 14: Evaluation of temperature measurement techniques

The infrared camera is a relative new technology, but has great potential to measure the temperature flow in the work piece during machining operations. This technique is accurate and has a very fast response time. It is fairly simple to use and lubrication strategies can be used with a special experimental setup. As shown in the table above it is apparent that every temperature measuring technique has its own advantages and disadvantages. It is however possible to use it more effectively with a specialized experimental setup. It was therefore decided to conduct an experiment in which an infrared camera was set up in a specific manner as shown in Figure 10.

4. EXPERIMENTAL SETUP AND RESULTS

In order to determine an emissivity value for titanium with respect to temperature (cutting speed) a Ti6Al4V sample was cut to size and heated in a furnace. A small hole was drilled into the bottom of the sample; that was used to insert a thermocouple. The sample was heated and temperature measurements taken at two chosen values (300°C and 600°C). All the temperature values of the thermocouple and infra-red thermometer (Raytek MX-4+) were recorded through the supplied Raytek software and the output used to calculate the emissivity. The experimental results and those from literature [8, 17 and18] are shown in Figure 9.

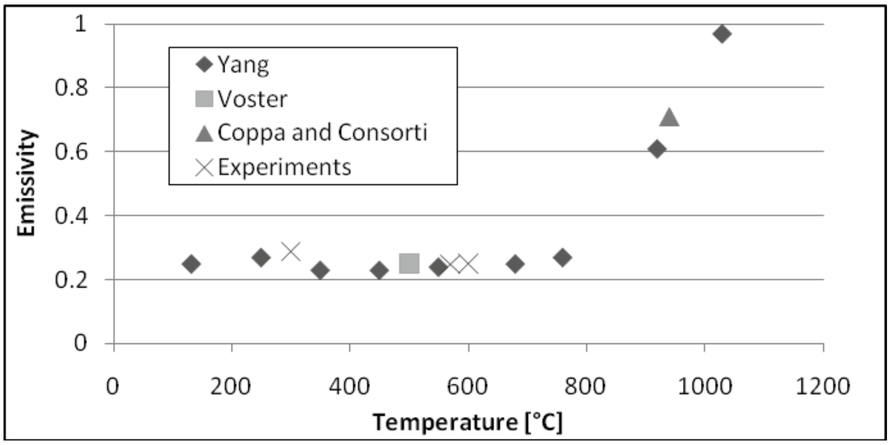


Figure 9: The emissivity against temperature from different literature sources including results from this experiment.

The experiment was designed so as to permit observation of the 2D chip formation during milling Ti6Al4V. Table 15 details the experimental equipment and the milling parameters used. The spindle axis was positioned horizontally with the well-balanced cutting tool over the thin (a_p=2mm) work piece as illustrated in Figure 10.

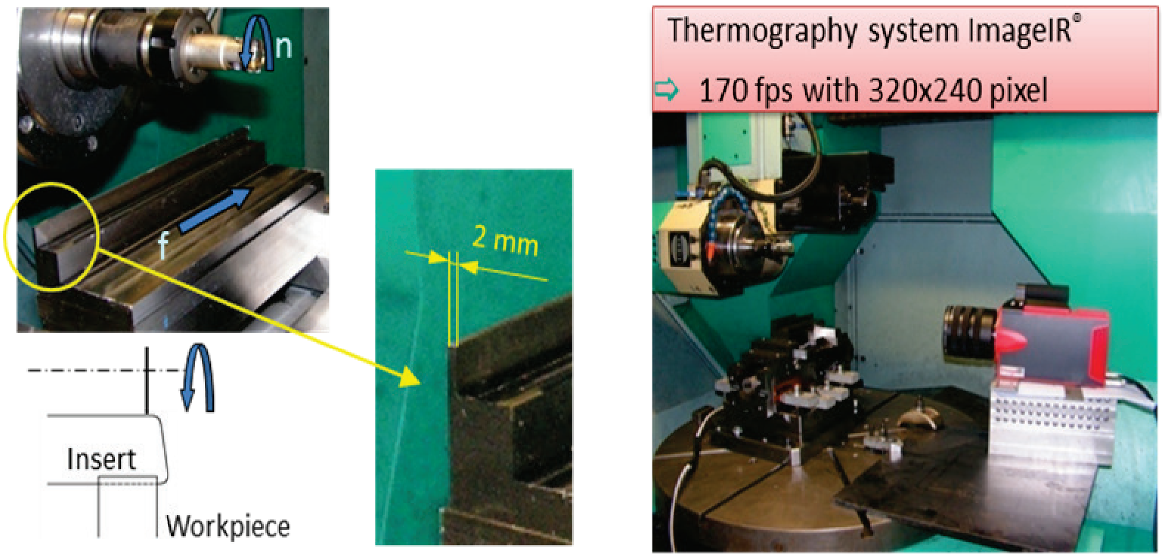


Figure 10: Experimental setup of the temperature measuring experiment during a milling operation

A Thermography system ImageIR® was used to measure the temperature. The experiments were conducted on a DIGMA 850 HSC machine. This was done under dry cutting conditions. The experiments were conducted at a radial depth of cut of 1 mm and ranging from v_c=40-80m/min at a f_z=0.25 mm/z as recommended by the tool supplier.

Machine tool	DIGMA 850 HSC
Tool and inserts	HM90 E90A-D20-3W20 with γ_a=7°
	Cemented carbide: APKT 1003R8T-FF
	(TiAlN PVD coated)
Coolant	Dry machining
Infrared camera	Thermography system ImageIR® Software: IRBIS Professional 2.2
Cutting speed (v_c)	20-80 m/min
Feed per tooth (f_z)	0.25 mm
Axial depth of cut (a_p)	2 mm
Radial depth of cut (a_e)	1 mm

Table 15: Experimental equipment

The rotation angle of the tool and the formation of the chip could be related to visual observations and the temperature measurements as illustrated in Figure 11. As illustrated in the figure there is a rise in temperature as the cutting speed (v_c) increases. The volume of the work piece that undergoes a temperature increase also expands with an increase in cutting speed.

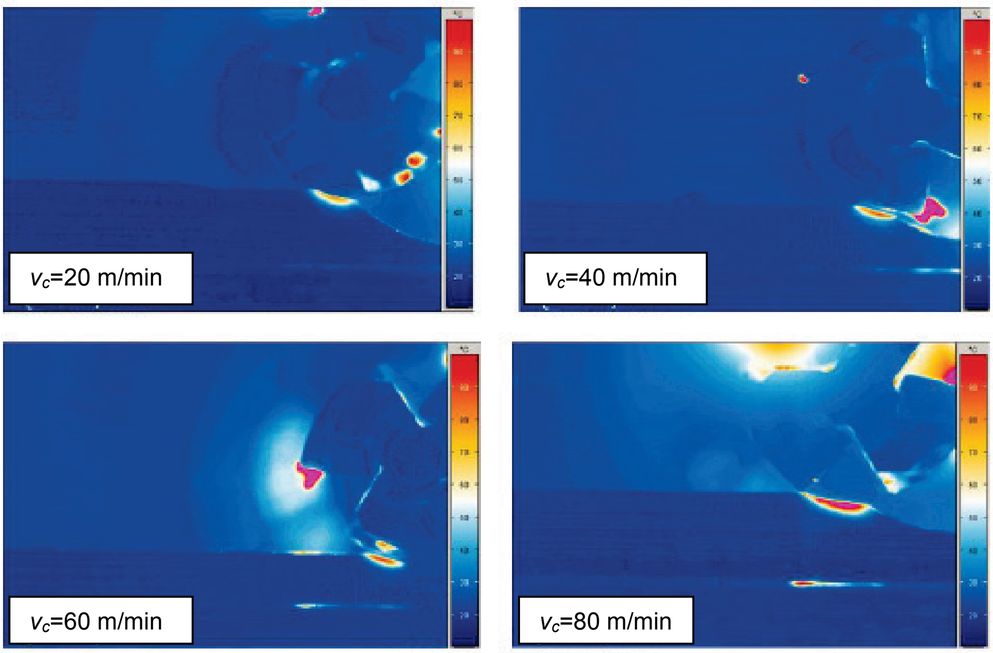


Figure 11: Temperature illustration for different cutting speeds (f_z=0.25mm/z, temperature range=10-100°C)

From the figure it is possible to see the areas with the highest temperatures in this selected range (10-100°C). As expected this occurs at the cutting edge of the tool and also at the chip-tool interface. Due to titanium's low thermal conductivity, the high temperature does not penetrate very deep into the machined material as predicted by theory, since most of the heat is carried away by the Ti6Al4V chips [11] or penetrated into the cutting tool edge. Figure 12 illustrates the maximum temperature for the experimental cutting speeds measured with a much higher selected range (≈600-850°C).

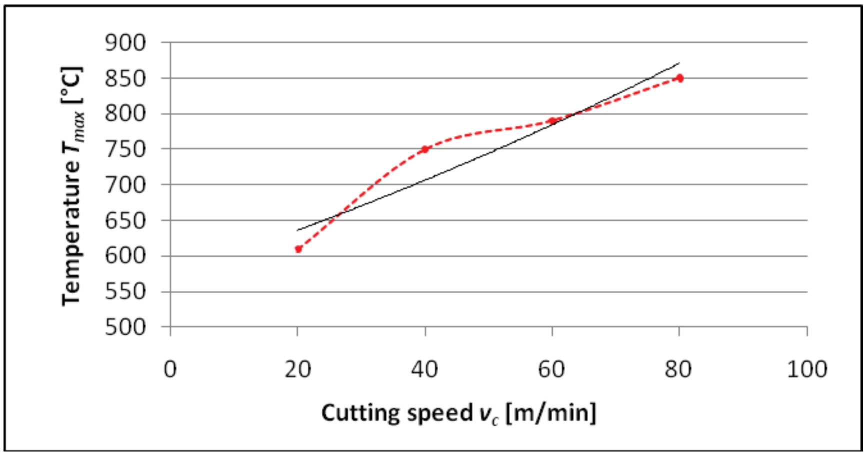


Figure 12: Maximum cutting temperature relative to cutting speed (40-80 m/min) with f_z=0.25mm/z

These results indicate a definite rise in temperature as the cutting speed increases. With these results it is possible to determine the depth at which overheating can occur. Determining the wear rate of the cutting tool at a specific temperature will give valuable information on determining the optimum cutting conditions at a minimum cost. These results can also be used to extrapolate values to higher cutting speeds. Thereby, it will be possible to determine at which cutting speed the temperature increase may cause alpha case formation of the work piece.

5. CONCLUSION

Temperature measurement techniques were studied and evaluated. The response time of contact methods were found to be to relatively slow. The optical methods have the advantage of immediate response, allowing capture of intermittent heat generation as necessary during milling. The infrared camera temperature measurement experiments were conducted with a special setup in order to have a good visual of the temperature flow. It was clearly illustrated that the maximum cutting temperature increases with an increase in cutting speed as shown in Figure **12** . Due to Ti6Al4V's low thermal conductivity, the heat is concentrated in a small area around the cutting edge. The combined effect of the concentrated temperature at the tool edge, the serrated chip formation and low modulus of elasticity cause rapid tool wear.

These results were greatly facilitated with the use of temperature measuring techniques that could be used to show what happens at the cutting interface with certain parameters. In evaluating the different techniques, it is possible to increase the accuracy of temperature measurements by indicating which technique is most suited for a specific situation.

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