



Faculty of Engineering

**Development of a Cutting Edge Temperature Measurement Device for
End Mill Tool using Infrared Radiation Technique**

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Development of a Cutting Edge Temperature Measurement Device for End Mill Tool using Infrared Radiation Technique

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ABSTRACT

In current times, high speed machining (HSM) is no stranger in the manufacturing industry. It is also a fact that temperature plays an important role in productivity every process where HSM is involved. Therefore, it is vital for manufacturers to monitor the cutting temperature but this has been proven to be quite challenging due to difficulty of determining cutting temperature at high cutting speed. This research focused on the relationship between the infrared radiation of an object to its temperature and the application of its theory to develop an accurate temperature measuring device, which is also known as a pyrometer. The developed pyrometer used a fiber optic to harness infrared radiation which was channeled to a photocell and converts it to electrical signal. The electrical signal was amplified and can be seen on a digital oscilloscope. A calibration experiment was conducted to identify the relationship between output voltage on the oscilloscope and the temperature. The developed pyrometer was used in an experiment which involves actual cutting to determine the effect of radial depth of cut on cutting temperature in different cutting speed. For each depth of cut, the temperatures were analysed and compared for different cutting speed. Based on the data from the experiment, it can be seen that as radial depth of cut increases, the cutting temperature increases. The same trend can be seen when the cutting speed is increased which shows a significant rise of cutting temperature.

Keywords: Pyrometer, photocells, end milling, infrared radiation, cutting temperature.

Pembangunan Peranti Pengukuran Suhu Tepi Pemotongan untuk Alat Pengisar Hujung Menggunakan Teknik Sinaran Inframerah

ABSTRAK

Pada masa kini, Pemesinan Berkelajuan Tinggi (HSM) adalah sesuatu yang tidak asing di dalam industri pembuatan. Ianya juga fakta bahawa suhu memainkan peranan yang penting di dalam produktiviti setiap proses yang melibatkan HSM. Oleh sebab itu, amat penting bagi pengeluar untuk memantau suhu pemotongan tetapi hal ini telah terbukti sebagai sesuatu yang agak mencabar berikutan daripada keadaan yang sukar di kawasan pemotongan. Kajian ini memfokuskan kepada hubungkait antara sinaran inframerah dari sesuatu objek dengan suhu dan mengaplikasikan teori tersebut untuk menghasilkan satu alat mengukur suhu yang dikenali sebagai meter suhu sinaran atau Pirometer. Pirometer yang telah dibangunkan menggunakan fiber optik untuk mengumpul sinaran inframerah yang akan disalurkan ke sebuah fotosel dan akan ditukarkan menjadi isyarat elektrik. Isyarat elektrik tersebut akan digandakan dan boleh diperhatikan melalui sebuah osiloskop. Ujikaji penentukuran akan dijalankan untuk mengenalpasti hubungkait antara voltan keluaran dan suhu. Pirometer yang dihasilkan akan digunakan di dalam satu ujikaji yang melibatkan pemotongan sebenar untuk menentukan kesan kedalaman pemotongan jejari dan paksi terhadap suhu pemotongan bagi kelajuan pemotongan yang berbeza. Bagi setiap kedalaman pemotongan, suhu akan dianalisis dan dibandingkan bagi kelajuan pemotongan yang berbeza. Berdasarkan data dari ujikaji, boleh dilihat bahawa apabila kedalaman pemotongan jejari meningkat, suhu pemotongan juga meningkat. Corak yang sama boleh dilihat apabila kelajuan pemotongan ditingkatkan membuatkan suhu pemotongan meningkat dengan ketara.

Kata kunci: *Pirometer, fotosel, pengisar hujung, sinaran inframerah, suhu pemotongan.*

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LIST OF ABBREVIATIONS

AM	additive manufacturing
ASTM	American Society for Testing and Materials
BC	Before Century (Year)
c	Speed of light in vacuum
cm	centimetre
D*	Specific detectivity
dc	Core diameter
e.m.f	electromotive force
Eb λ	Monochromatic Emissive Power
h	Planck constant
Ib λ	radiation intensity
InAs	Indium Arsenide
InSb	Indium Antimonide
k	Boltzmann's constant
m	metre
mL	millilitre
ms	millisecond
NA	Numerical aperture
°C	Celcius (Temperature)
°K	Kelvin (Temperature)
PVD	Physical Vapor Deposition
FENG	Faculty of Engineering, UNIMAS

CHAPTER 1

INTRODUCTION

1.1 Project overview

One of the main physical unit quantity to describe the world phenomenon is temperature. By referring to the definition of temperature by the Oxford Dictionary, “temperature is a degree or intensity of heat present in a substance or object, especially as expressed according to a comparative scale and shown by a thermometer or perceived by touch”. Temperature resembles the measurement of the average kinetic energy of each atom in a substance (Richard and Rusty, 2006). An atom inside an entity that interacts with the external kinetic energy sources, experiences a movement or vibrations intensely (Yunus and Michael, 2011). The external energy will weaken the bonds between atoms and thus resulting in freedom of motion state. This freedom of motion are also called as vibration movements, which will cause the interspace between atoms increased (Sewell, 1999). Due to the interspace increase, a solid state will change its form to liquid and further increase of interspace will lead to gas state.

Based on second law of thermodynamics, an energy is flowing from a high reservoir to a lower reservoir (Yunus and Michael, 2011). The flow of energy from the machining process behaves similarly as mentioned by the second law of thermodynamic. The heat energy that is generated through cutting process will spread to the cutting tool and workpiece (Putz et al., 2015). Therefore, thermal conductivity of cutting tool’s material and workpiece plays an important role in energy transfer process. Workpieces that are made of low thermal conductivity such as titanium and nickel-based alloys will cause most of the heat generated

to flow into the tool, thus accelerating tool fatigue and failure due to the added thermal stress to the cutting tool (Ezugwu et al., 1999). Rise in cutting temperature might cause deformation of the cutting edge if the tool material is not enough hot-hard and hot-strong (Benabid et al., 2014). The main consequences are the cutting edge may experience thermal shock that causes thermal flaking and fracturing.

Machining is a process of removing unwanted material from a raw material to get a desired shape. It is one of the main key process in the manufacturing field as it is capable to manufacture a high precision of product's dimension. In conventional machining process, the tolerance of the product is high meanwhile modern machining process such as CNC has the lowest tolerance. The demand of higher precision product is increasing, as the application of product are getting sophisticated and complex over time. Unfortunately, the machining process requires a cost of frequent cutting tool replacement (Colding, 1961 and Hernández et al., 2017). Price of cutting tool is not cheap. The price for harder material is more expensive than the price of normal cutting tools. Cutting tool tends to get wear if used over a prolonged time. Replacement of wear cutting tools for every batch of products is necessary in order to ensure the quality of machined products.

Machining process deals with the existence of cutting temperature and considered as the one of the major concern when selecting the suitable cutting parameters such as feed rate and cutting depth. A wrong selection of cutting parameters might lead to the uncontrolled temperature rise, thus increasing the possibilities of cutting tool wear and workpiece defect. Past researcher has found that most of mechanical energy involved in machining process is converted to thermal energy (Palazzo et al., 2002). Therefore, machining industries opt to

use a coolant in a machining to absorb the deficit heat generated as well as preventing chip and metal debris from accumulating at tool and workpiece interface (Seah et al., 1995).

Due to the critical impacts of temperature on the workpiece and cutting tool as stated above, it is important for the machinist to monitor the temperature during the machining process. Generally, the temperature of the cutting process can be determined in an analytical and experimental way. Since the industrial revolution of 1700s begins till date, researcher have developed several temperature measurement techniques in metal cutting (Hartman, 2009). They are:

- i. Calorific method by Benjamin Thompson (1798) as quoted by Shaw (1984),
- ii. Tool-work thermocouple by Shaw (1984),
- iii. Infrared thermography by Reichenbach (1958),
- iv. Embedded thermocouple by Kato and Fuji (1990, 2000),
- v. Remote measuring/inverse methods by Stephenson (1991),
- vi. Single wire thermocouple by Black, Qi, and Mills (1995),
- vii. PVD film method by Kato and Fuji (1996),
- viii. Infrared thermometers by O'Sullivan, and Cotterell (2002),
- ix. Fibre Bragg Gratings by Morgan, M.N. (2004),
- x. Thermographic Phosphor Thermometry by Feist, Heyes, Choy, Nicholls, (2004).

Choosing the temperature measurement technique is depend on the type of machining application. Generally, normal machining process of metal workpiece requires non-sophisticated technique such as thermocouple method. However, in high speed machining, response rate or transient speed of temperature measurement becomes a main requirement. High speed machining also produced an extremely high temperature where contact method of measurement technique are not reliable as it may damages the sensor's probe. The advantages of a non-contact approach compared to a contact approach are (Gruner, 2003):

- i. It is fast (in the ms range)
- ii. Facilitates measurements of moving object (moving cutting tool)
- iii. Allowing the measurements of hazardous or physically inaccessible objects
- iv. Measurements of high temperature (greater than 1300°C) present no problem
- v. There is no interference – no energy is lost from the target
- vi. No risk of contamination and mechanical effect on the surface of work-piece.

A more detailed explanation of various temperature measurement technique will be explained in Chapter 2.

1.2 Problem statement

Cutting temperature has been widely acknowledged as one of the main factors that influenced the performance of high speed machining process. The elevated temperature generated significantly affect the process efficiency, the chip formation mechanics, and surface quality of the machined parts. The research of thermal fields in machining are very important for future development of new technologies, which aim to increase tool life and reduce manufacturing costs. It has been regarded that the temperature prediction for machining process is an important matter primarily due to the effect that it has on tool wear and its constraints on productivity. The determination of temperatures and temperature distribution in the tool-workpiece area is difficult (Vukota, 2010). Therefore, the development of accurate temperature measurement techniques has been slow (Vukota, 2010). This is due to the challenging nature of machining conditions such as small dimensions, high speeds and large temperature gradients. The numerical approach of determining the temperatures and temperature gradients near the cutting edge is considerably difficult even for a very simple cutting condition (Trent and Wright, 2000).

In the current manufacturing industry, a manufacturer used a thermocouple to measure a cutting temperature. Thermocouple is one of a simple temperature sensor technique consisting of two dissimilar metals in thermal contact. The contact point produces a small open circuit voltage as a function of temperature. However, this technique requires that both tool material and work material has to be electrically conductive. Limitation to this technique is cutting fluid cannot be used, calibration is tedious and laborious, secondary voltages may occurs and many tool-workpiece where combinations do not form an ideal thermocouples setup. Furthermore, its transient speed is not fast therefore, it is not suitable for high speed application like high speed machining (HSM). Furthermore, during

machining process, a chemical (oxidation) reaction might occur at the contact surfaces. This will change the physical properties of cutting tool and work piece in terms of electrical conductivity and exhibits error in cutting temperature reading.

The study of machining process is getting complicated when another variable are added into the analysis such as coolant, the interrupted cutting due to multi-tooth cutters and the behaviour of the chips (Mourtzis et al., 2014). Although various temperature measurement methods have been developed, the machining research community is still looking for improvement for these methods with accordance to the rapid technology advancement. Therefore, a good consideration need to be accounted when choosing a requirement for temperature measurement device such as the measurement range, sensor sensitivity, sensor resolution, and time response of sensor.

Based on the review paper published by Usamentiaga et al. (2014), a utilization of infrared radiation emitted from cutting tool's edge during machining process as a temperature measurement purpose is possible. Thus, an accurate temperature measuring device that are designed specially on detecting infrared radiation was developed and detailed explanation of analysis were presented in the subsequent chapter.

1.3 Hypothesis

The emitted infrared waves from the high speed cutting process can be utilized as a real-time temperature reading when using a high speed pyrometer.

1.4 Research objectives

In this dissertation, a discussion of the material and tools selection, specifications of devices, detailed planning of experiment and analysis method were discussed critically in order to ensure the pyrometer developed are reliable for research purpose. The objectives of this project also include:

- i. To develop a cutting edge temperature measurement device for high cutting speed.
- ii. To study a cutting profile analysis
- iii. To assess cutting performance of machining AISI 1095

1.5 Scope of study

This project also covers the following scope of study:

- i. Study on the mechanism of metal cutting and heat generation in milling.
- ii. Study on the theory and application of radiation infrared for temperature measurement.
- iii. Study on the effect of cutting parameters on cutting temperature.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Generally, milling is a process of removing materials from a work piece by using rotary cutters to acquire a product with the desired dimension and shape (Gupta, 2017a). Milling is a part of subtractive manufacturing (SM) technique compared to its counterpart, additive manufacturing (AM) techniques. This process begins to be used in the manufacturing industry dated back in the early 18th century (Kalpakjian et al., 2016).

The demand of a metal product have increased drastically prior to industrial revolution (1760 – 1820). This situation had forced the business owner, the engineer and the scientist to create an alternative way to cater the demand. During industrial revolution, various inventions have been introduced in the manufacturing process such as milling machine, boring machine, and screw-cutting lathe machine. Based on the history of manufacturing technology, it was stated that an engineer, Eli Whitney was an inventor of milling machine during 1810s. His other notable work was a cotton gin machine, a machine that separates cottonseeds from its cotton fiber. By the time onwards, most modern machines are created after his idea such as moving workpiece's table, interchangeable spindle, interchangeable cutting tools, and belt-driven spindle motor. At post industrial revolution era, the milling machine have evolved to a variety of interchangeable parts and advanced cutting tools material such as made of carbide, tungsten and diamond.

2.2 Common cutting tool for end milling process

Cutting tool is an essential part in a milling operation. It is used to remove material by its own movement powered from the milling machine or directly from its shape. Cutting tools are usually made from high-speed steel and are available in various shapes and sizes for various purposes (“Fundamentals of Tool Design Study Guide: Cutting Tool Materials”, 1997).

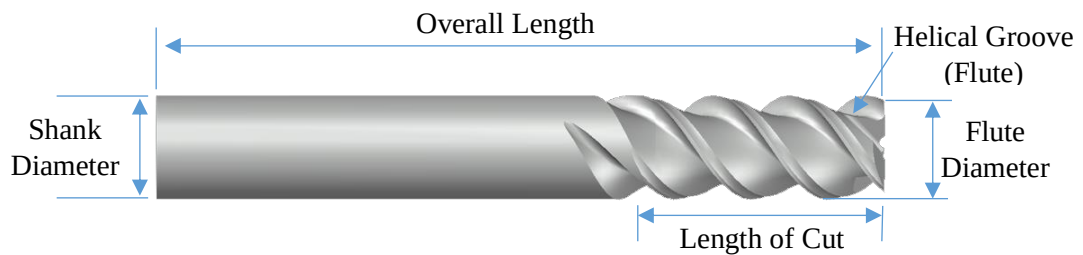


Figure 2.1: Overview of a typical cutting tool with 3 flutes (Stephenson and Agapiou, 2016)

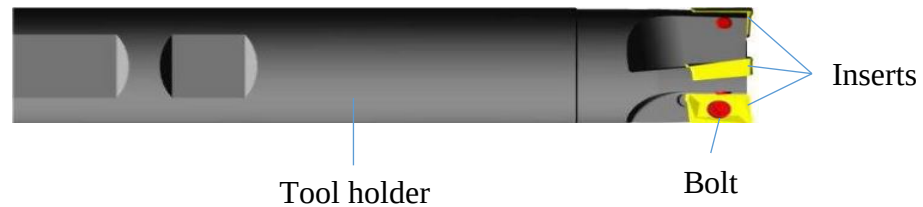


Figure 2.2: A typical indexable end mill cutter for APKT inserts (“Fresatura Milling, n.d.)

AKPT means the designation code for milling inserts where, A=Shape of Insert (85 Degree Parallelogram) P=Side Reak Angle (11 Degrees) K=Tolerance (K is tighter tolerance on height, thickness and IC than M), and T=Hole. High speed steels are heavily alloyed, ferrous, conventionally cast tool materials that can be divided into four main categories based on ASTM A600 (Bayer et al., 1989 and Gupta, 2017) which are Tungsten, increase

tempering wear resistance, Molybdenum, improve toughness, Vanadium, increase wear resistance of finishing tools, and Cobalt, improve heat resistance.

Apart from high-speed steels, there were other main type of cutting tools materials. Their comparison of hardness with temperature variation were shown in Figure 2.3. Referring to Figure 2.3, the hardness of cutting tool materials is reducing when the temperature are increase.

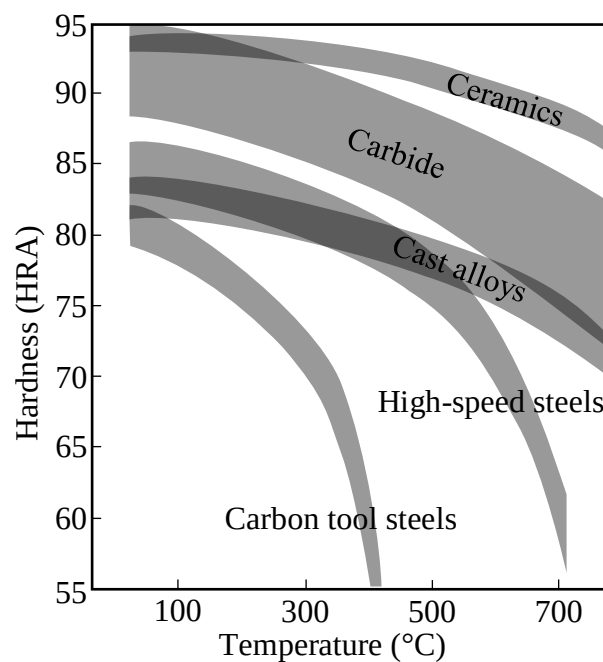


Figure 2.3: Hot hardness of different cutting tool material (Kalpakjian, 2016)

In the metal industry, end mill is usually used for vertical milling machining. End mill are tools with cutting teeth at one end and the sides. End mill is widely used primarily due to its huge variations in diameter size and design characteristics, thus allowing the machining of almost any shapes and dimensions. Cutting tools are sometimes coated with different structured hard/soft thin layers, which aims to increase tool life by increasing its

hardness as shown in Figure 2.4. These coatings also enable cutting tools to operate at higher cutting speeds, thus increasing productivity (Figure 2.5).

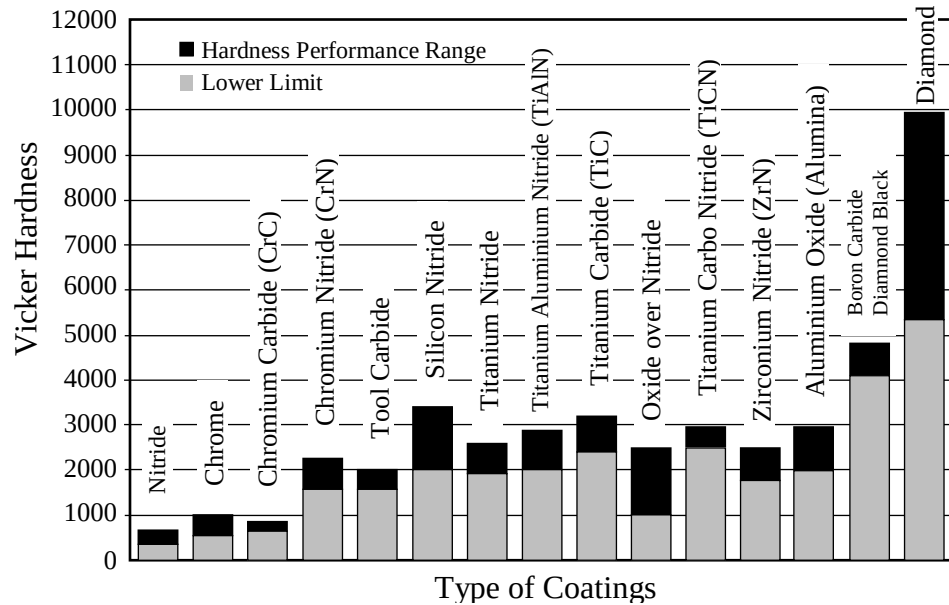


Figure 2.4: Comparison of micro-hardness for several types of coatings (Stephenson and Agapiou, 2016)

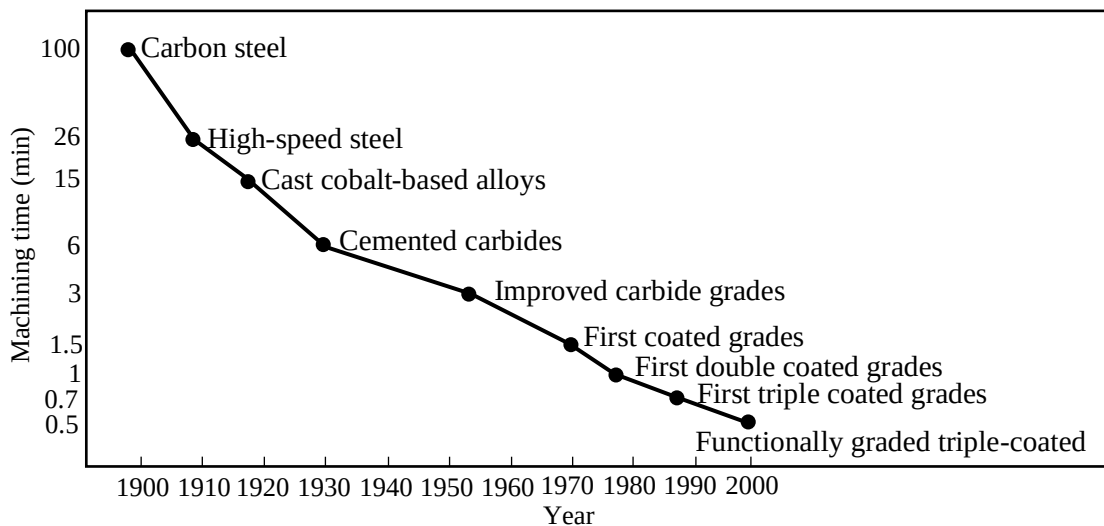


Figure 2.5: Effects of multi graded coating technology on machining time (Kalpakjian, 2016).

2.3 Effects of workpiece material on temperature generation during machining

Type of workpiece's material plays an important role in machining field. Each material have different physical and chemical properties that induces a specific range of cutting forces and cutting temperature. Heat generation is closely associated with the cutting forces based on the cutting speed, chip load, and type of wear developed during cutting process. Meanwhile the machinability of the workpiece materials depends on the degree of cutting forces.

Machinability is a measurement of machining difficulty of the workpiece. Cutting forces and the machinability difficulty tend to increase with the hardness of the base metal and/or its surface. As mentioned by Marines et al. (2013), the machinability of steel tends to decrease in the following order:

Ferrite (low C) $\Rightarrow$ Pearlite (soft) $\Rightarrow$ Bainite $\Rightarrow$ Pearlite (high C) $\Rightarrow$ Martensite (high C)

They also mentioned that the difficulty of machining increases where steel is alloyed with the following elements, in this order:

Cr $\Rightarrow$ Cr-Mo $\Rightarrow$ Ni-Cr-Mo $\Rightarrow$ Ni-Cr-Mo-V

Sekulić et al. (2010) have studied the influence of mechanical properties of workpiece material on the main cutting force in face milling of the workpiece with difference in hardness. The experiment conditions is shown as below in Table 2.1.

Table 2.1: Experiment conditions and mechanical properties of material used during machinability test

Workpiece material		Tensile strength (MPa)	Hardness / HB	Cutting tool material	v / m / min	s ₁ / mm / tooth	a _p / mm
Code (JUS)	Code (DIN)						
C4732	42CrMo4	975	265	HM P25	89.17	0.28	1
NL500	GGG-50	495	170	HM P25	89.17	0.28	1
AlSi10Mg	G-AlSi10Mg	85	49	HM P25	281.48	0.28	1

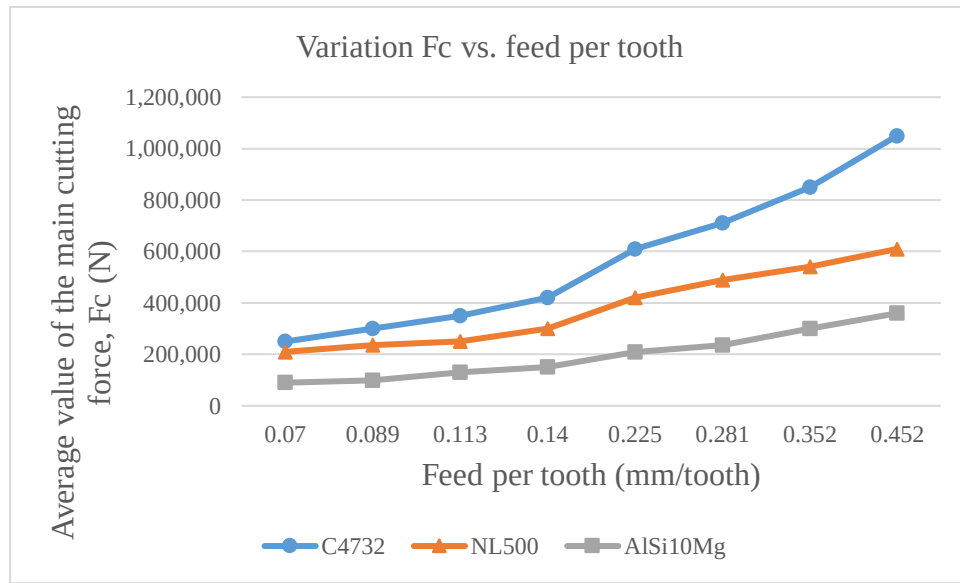


Figure 2.6: Variation of cutting force, F_c against Feed/tooth

They found that as the material hardness increase, the average cutting forces also increase as shown in Figure 2.6. There is a close relation between cutting force and heat generation. It can be explained through the understanding of an energy required to remove a specific volume of material from the workpiece. Cutting energy is defined as follows:

$$E = \frac{F_c v_c}{J} = k_c Q_w = k_c A v_c \quad \text{Equation 2.1}$$

where F_c is the cutting force, v_c is the cutting speed, J is the mechanical equivalent of heat, k_c is the specific cutting energy, Q_w is the metal removal rate, and A is the chip cross section

A degree of specific cutting energy, Q_w depends on the energy required by a cutting tool to cut the specific volume of the material. This energy can be determined by identifying the cutting force that are existed during machining process. Based on the equation above, the specific cutting energy, k_c is governed by two parameters which are cutting energy, E_0 and material removal rate, MRR or Q_w . Cutting energy, E_0 is influenced by cutting speed, v_c , cutting force, F_c and, physical and mechanical properties of the workpiece's material. Meanwhile, MRR is influenced by volume of material is removed during machining process. In machining case, the rate of material removed, Q_w is bound by depth of cut, cutting speed and the feed rate.

Based on the experiment conducted by Marines et al., the harder the mechanical strength or material hardness, the higher the cutting force which means the specific cutting energy will increase. An experiment conducted by Marines et al. is aligned with experimental studies made by Vernaza et al. (2002) where they concluded that the higher the mechanical strength of the work material, the greater the heat generation during machining process. San-Juan et al. (2015) have conducted an experiment on milling process of AISI 316L. Their finding is that increasing the cutting speed will cause cutting force decrease and cutting temperature increase. The cutting temperature is associated with cutting energy spent during machining process. This phenomenon is occurred with the accordance of parameter relationship in Equation 2.1. Heat distribution from the heat generated during milling process will be explained further in Section 2.4.

There are another factor that leads to the increase in cutting force, which is the existence of wear. Tool wear have caused the irregularities in the cutting force's magnitude. Further explanation is in Section 2.6.

2.4 Terminology of metal cutting

Metal cutting is carried out by the correlation of motion between the work piece and the cutting tool. This can be done by using a wedge-shaped single-point or multipoint cutting tool. As the tool rotates, the tooth of the tool cuts the material while the flute (deep helical grooves running up the cutter) pulls the chips that are formed.

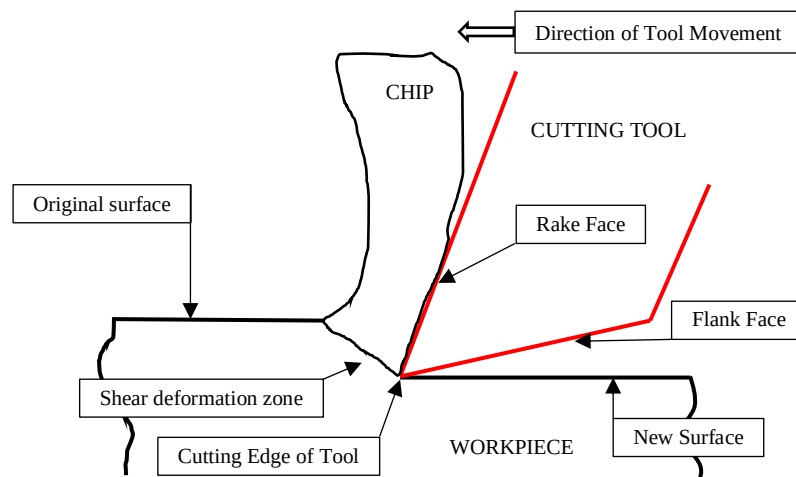


Figure 2.7: Basic terminology of metal cutting (Longbottom and Lanham, 2005)

2.4.1 Heat generation in metal cutting

Majority of work done is converted to heat energy during metal cutting operation (Trent and Wright, 2000). The rest of the energy remains as an elastic energy in the chip. In any metal cutting operation, it is common for heat generation exist. This heat generation is closely associates with plastic deformation and friction. Thus, there are three factors which affect heat generation during milling operation (Palazzo et al., 2002). First factor is heat generation at the primary deformation zone (PDZ). The work piece experiences large irreversible plastic deformation and viscous dissipation. Second factor is heat generation in the secondary deformation zone (SDZ). It is caused by work done in deforming the chip and in overcoming sliding friction at the tool-chip interface zone.

The chip material is deformed consequently and portion of it adhered to the tool face. Within this zone, the last layer of atoms of the chip material is static in position. The adjacent layers gradually increases in velocity until the bulk chip velocity is achieved. This phenomenon will cause sticking and sliding friction section, which produces heat due to the combined shear and friction action (Longbottom and Lanham, 2005).

Due to complexity in understanding plastic deformation, many previous theoretical researches ignored this part of heat as stated by Uzorh and Nwuforh (2013). Abukshim et al. (2006) and Dinc et al. (2008) also stated that heat generation in the primary and secondary zones depend on the cutting conditions. Thirdly, heat generation at the tertiary deformation zone (TDZ). It is work done to overcome the friction which occurs at the rubbing contact between the tool flank face and the newly machined surface of the work piece.

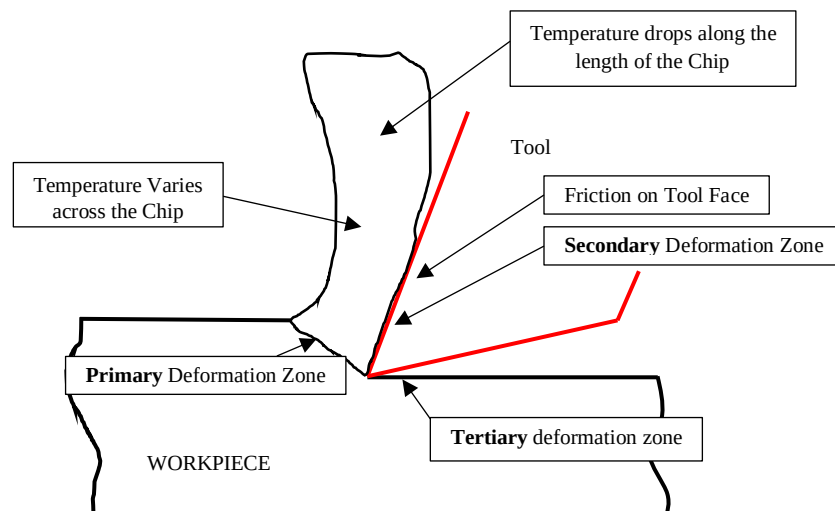


Figure 2.8: Illustration of heat generation zones (Longbottom and Lanham, 2005)

The heat fluxes during metal cutting can be schematically distinguished, as in Figure 2.9 (A). The heat generated at chip, tool, and workpiece are denote as q_c , q_t , and q_w respectively.

For each heat flux origin from primary, secondary, and tertiary deformation zone are denote as q_1 , q_2 , and q_3 . The total heat flow into the region of chip is denotes as $q_c = q_{1c} + q_{2c}$ where q_1 is from heat flowed from the plastic shearing region or PDZ, and q_2 is from the sliding friction between the tool and chip or SDZ. Total heat flux to tool is, $q_t = q_{2t} + q_{3t}$ where q_3 is from tertiary deformation zone contact surface of workpiece and flank area or TDZ. Meanwhile, total heat flux to workpiece is $q_w = q_{1w} + q_{3w}$ where q_1 is from PDZ and q_3 is TDZ.

As shown in the Figure 2.9 (B), as cutting speed increases, a larger proportion of the heat generated is carried away by the chip, and less heat goes into the workpiece. When cutting speed increases, the time in which the heat fluxes q_{1w} and q_{2t} flow into the workpiece and the tool is consequently shortened. For example, for steel cutting at the cutting speed of 150 m/min, 75-80% of heat is transported by the chip, 10-15% is conducted into the tool, and the remaining 5-10% is conducted into the workpiece. On the other hand, for aluminum machining at the same cutting speed the most amount of heat of about 75% flows into the workpiece (Grzesik, 2010). As a result, at extremely high cutting speeds (typically >1000 m/min) characteristic for high-speed machining, the majority of the generated heat is evacuated with chips, and the cutting temperature diminishes substantially.

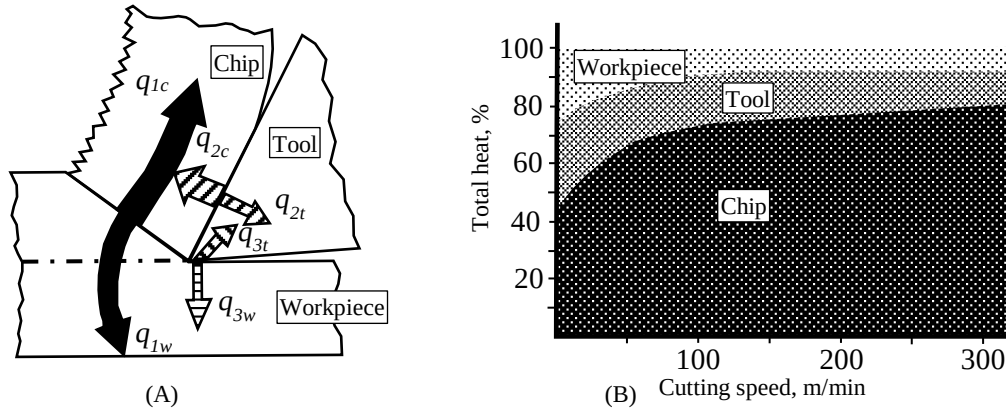


Figure 2.9: (A) A scheme of heat flow and (B) percentage of the heat generated going into the workpiece, tool, and chip, as a function of cutting speed (Grzesik, 2010)

2.4.2 Cutting parameters and its effect on temperature at shear/deformation region

Prior to any machining process, a set of cutting condition need to be identified. They are cutting parameters. These parameters determine the quality of the finished product. Any wrong decision on these parameters may cause an unfavourable high cutting temperature, which directly contribute to the risk of temperature-induced defects. As mentioned by Trajcevski et al. (2009), these parameters are:

- i. Cutting speed
- ii. Feed rate
- iii. Depth of cut

Each of these parameters accelerate the rate of heat generation. This rate of heat generation increase as the cutting speed increase. This is mainly due to the less time available for the heat generated to conduct into the workpiece (Grzesik, 2010). A majority of heat is dissipated by means of heat interaction between tool-chip surfaces. As mentioned in previous

section, the temperature carried away by the chip plays a vital role in removing the cutting temperature effectively.

2.4.3 Heat dissipation in metal cutting

During the process of metal cutting, the heat generated will be dissipated through several medium. They are (Longbottom and Lanham, 2005);

- The heat is discarded through the chip.
- The work piece acts as a heat sink.
- The cutting tool acts as a heat sink.
- Coolant, where used will help to draw away the heat.

Various researchers have conducted experiments to determine the percentage of heat that goes to the cutting tool. Their findings are shown in Table 2.2.

Table 2.2: Findings from various researchers regarding heat distribution to the tool

Researcher	Findings	Experiment
Moriwaki et al. (1993)	50% of heat generated goes to the tool while the rest goes to the workpiece.	Machining of annealed oxygen-free copper (99.99%) with single-crystal
Takeuchi et al. (1982)	10 to 30% of the total heat generated enters the tool.	Machining of carbon steel (C = 0.55%) using P15 carbide tooling at a cutting speed of 100 m/min.

Table 2.2 continued

Lo Casto et al. (1989)	Between 56% and 25% of heat is transmitted into the tool.	Machining AISI 1040 with a P10 sintered carbide insert at cutting speeds of 99-240 m/min.
Grzesik and Nieslony (2003)	35 to 20% of heat goes into the tool.	Machining of AISI 1045 with a multilayer coated tools at cutting speeds of 50-210 m/min.

2.4.4 FEM analysis on predicting cutting temperature

One of the way to study the heat distribution at chip formation is through modelling the machining process by Finite Element Method (FEM). FEM is a powerful tool when it comes to obtaining difficult from experimental methods. Grzesik (2006) have made a simulation on the cutting process for uncoated coating tool, coated cutting tool and workpiece, AISI 1045 carbon steel. The mesh model is shown in Figure 2.10. Figure 2.10 (A) shows that there are three layer of coating added to the tool substrate. Figure 2.10 (B) shows the shape of deformed chip during the machining process. The simulation is based on Lagrangian technique with explicit dynamic modelling software with adaptive remeshing in order to simulate the plane-strain orthogonal metal cutting.

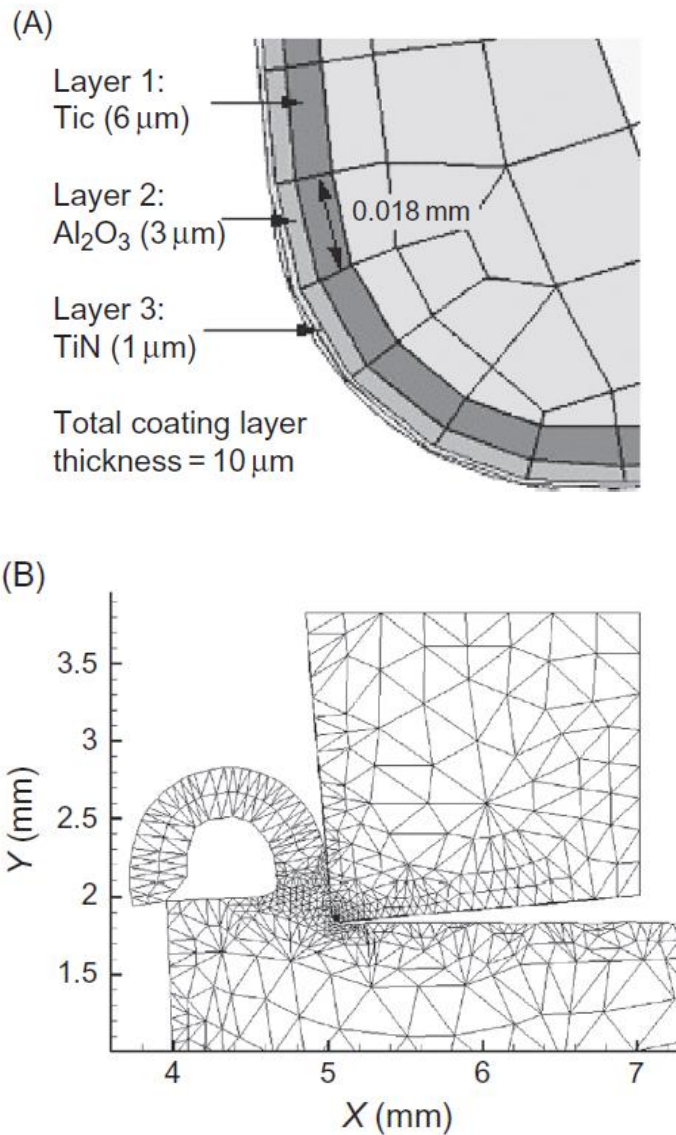


Figure 2.10: (A) The mesh model for a TiC/ Al_2O_3 /TiN-coated tool and (B) shape of the deformed chip after a tool path of 4.0 mm

The FEM simulations shown in Figure 2.11 have revealed that cutting tool coatings influenced distinctly the performance and intensity of the thermal interactions when turning C45 carbon steel. In particular, coatings change both the heat transfer and its distribution in the cutting zone, as shown in Figure 2.11 (B). In comparison to an uncoated P20 carbide tool [Figure 2.11 (A)], the triple coating applied caused a decrease in the fraction of heat flowing

into the tool. On the other hand, it can be observed that more heat is transferred to the chip and the workpiece. Moreover, coatings cause areas with the maximum temperatures to be localized near the chip and workpiece.

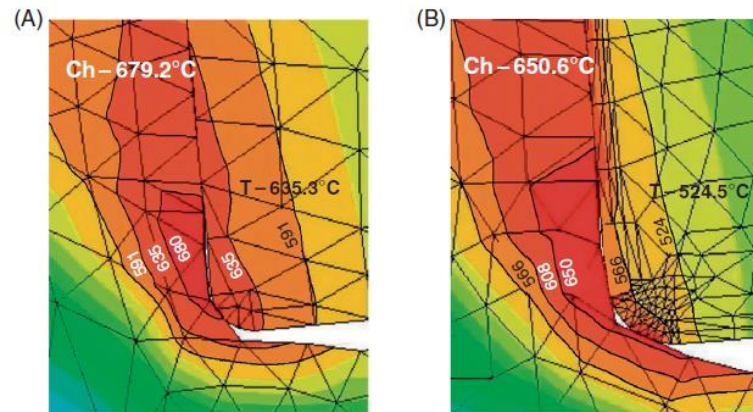


Figure 2.11: Magnification of temperature distribution in the vicinity of the cutting edge. (A) P20 uncoated carbide; (B) TiC/Al₂O₃/TiN-coated carbide. Workpiece, AISI 1045

2.4.5 Thermal conductivity of the workpiece on the heat generation

Apart from MRR, cutting speed and cutting energy, the thermal conductivity of the workpiece material have a have an influence on the heat flux during heat generation of cutting process. A workpiece material with different thermal conductivity have different heats distribution at tool, chip, and workpiece as illustrated in Figure 2.12. Furthermore, thermal conductivity of a material will not fixed at certain value if the material itself experiences changes in temperature. High thermal conductivity of the workpiece will attracts more heat to the workpiece and dissipated at wide area. Thus, the workpiece experiences thermal deformation due to thermal expansion (Grzesik, 2016). Meanwhile, low thermal conductivity are subject to higher increase in temperature during machining due to their inability to rapidly dissipate heat (Giasin, 2016) and consequently affecting chip formation,

leading to bad surface finishing and dimensional precision, and ultimately reducing the tool life (Guimarães, 2019)

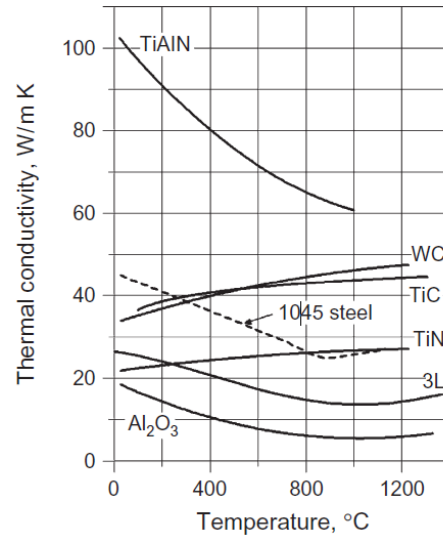


Figure 2.12: Influence of temperature on thermal conductivity (Netzsch Incorporation, 2016)

2.4.6 Chip formations

Deformation of cutting tool's edge is also commonly associated with the rate of feed. High feed rate will result in higher deformation. Thus, it can cause an increase in heat generation. However, area of contact surface between chip and cutting tool are also increase. This situation had assisted the discharge of heat by means of conduction, as rate of heat conduction is directly related with area of contact surface. As a result, high feed rate have its own unique advantages other than high material removal rate, it has better heat conduction compared to low feed rate. Among these three parameters stated previously, cutting speed has a strong influence on cutting temperature, followed by feed rate and depth of cut (Trajcevski, Kuzinovski and Cichosz, 2009).

There are four classification of chip types as shown in the Figure 2.13. Chip (A) discontinuous is formed when machining hard and brittle materials such as bronze, brass, and cast iron. These chips are small segments, which adhere loosely to each other. They are formed when the amount of deformation to which chips experience a repeated fracturing. Chip (D) is continuous, it is usually found when machining ductile materials such as wrought iron, mild steel, copper, and aluminium at relatively high cutting speeds. It is formed as ductile materials have minimal tendency to fracture at shear plane. Continuous chip formation is the most desirable for excellent surface finishing. It comes in the multiform such as straight, tangled, and helix coil.

There are other chip gradation exist in between Chip (A) and Chip (D) which are Chip (B) and Chip (C). Chip (C) is segmented chips where the each segment boundary presence at the chip undergo intense shear with relatively lower deformation. Such chips can be found for most materials as cutting speeds are increased to high levels, but limited only to material with low thermal conductivity and low thermal capacity such as titanium alloys and austenitic stainless steels, and at cutting at moderate speeds.

Material with low thermal conductivity will cause thermos-plastic instability, called adiabatic shear. If the speed is increased further, the separation of segments becomes more distinct, until complete separation as shown in Chip (B). If the heat generated is not dissipated quickly enough, the catastrophic shear becomes localized and narrow segments formed are separated by relatively fewer undeformed regions.

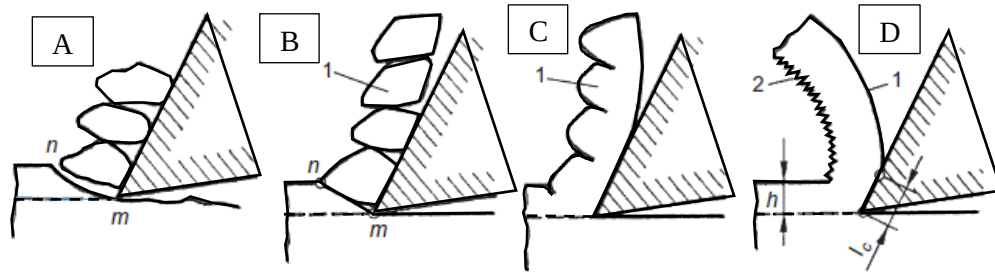


Figure 2.13: Classification of chip types: (A) discontinuous, (B) elemental, (C) segmented, (D) continuous

2.5 Tool wear

Tool life is defined as the change in the shape of the tool from its original shape during cutting process due to the gradual loss of tool material (Alden, 1989). A cutting tool can be considered broken from various means which falls on two main categories (Marinov, 2012). They are:

- i. Case 1 – gradual wear
- ii. Case 2 – abrupt tool failure

Among these two, Case 1 is the desired wear as the tool get wear because of prolonged usage. It is based on the amount of wear on the tool profile. The cutting efficiency are affected and reduced but still at an acceptable level. Furthermore, this wear indicates the longest possible use of the tool. If the tool are used beyond acceptable range, the tool eventually will fail (Case 2).

When the tool finally reaches its life expectancy, the user has two options whether to re-sharpen the tool or replace permanently with a new one. The latter option applied when the resource for tool re-sharpening is absent or the tool does not allow for re-sharpening.

Gradual wear occurs at three main locations on a cutting tool which makes it easier for it to be categorized. These gradual wear are explained further below.

- i. **Crater wear** – The sliding of the chip will cause the existence of crater wear which is a concave shape of defects. It will weaken the tool wedge and increase its chances to break. Despite its impacts, it has its advantage where the rake angle will increase and reducing the cutting temperature and cutting force. Usually, crater wear is not the main concern in machining process as it is considered as normal situation.
- ii. **Flank wear** – As the name implies, flank wear takes place on the tool flank due to the frictional force between the tool flank and the machined surface of the work piece. They are also known as wear-land. It is measured by the width of the wear land, VB as shown in Figure 2.14. The increasing flank wear width has a correlation with the increasing cutting force. Each tool has its limits on the VB value. If the flank wear exceeds VB value, the tool might break because of high cutting force. Thus, it has high associations with tool failure.

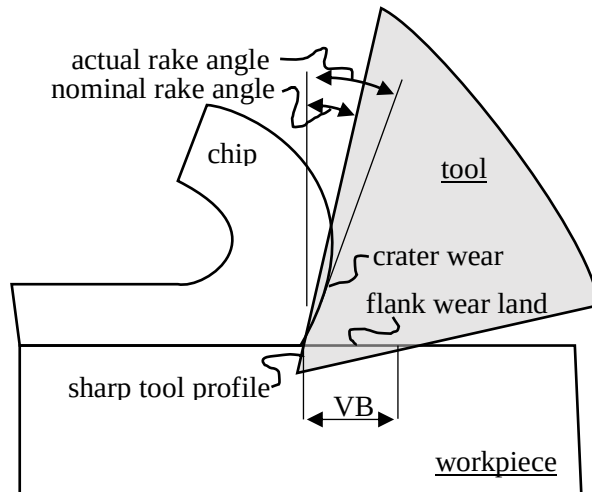


Figure 2.14: Cross-section of a worn cutting tool showing the effect of crater wear on the tool rake angle and the flank wear land (Marinov, 2012)

- iii. **Corner wear** – Corner wear can be found at the corner of the tool and can be considered as a part of the wear land together with flank wear due to the absence of a distinguished boundary between those two. However, corner wear is considered as a separate type of wear due to its effect on the precision of the machining process. This type of wear shortens the cutting tool and as a result, dimensional error on the product might occur.

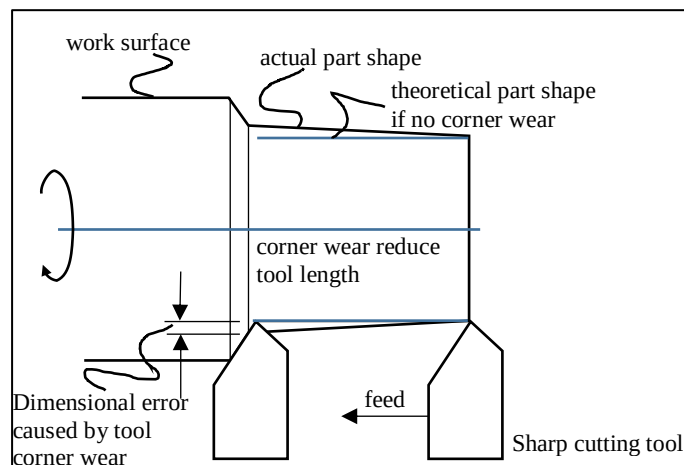


Figure 2.15: The effect of tool corner wear on the dimensional precision in turning (Marinov, 2012)

Wear of cutting tool exist at many form such as flank wear, edge wear, cratering or top wear, chipping, deformation, thermal cracking and built-up edge. Among them, edge and flank wear are the most common type of tool wear if the work piece is highly abrasive such as cast-irons. Cratering exists behind the cutting edge, and frequently happens during machining of long chipping steels. If the crater grows greatly where it reaches cutting edge, the cutting tool will fail immediately. Stronger cutting tool material such as titanium or tantalum carbide can overcome this problem. Chipping on a tool edge is the unpredictable type of tool wear and failure. It is started when a high point on an edge breaks. Stronger carbide grade, different edge preparation, or changing the lead angle will eliminate this tool wear. Built-up edge (BUE) is a deposit of the work piece material adhering to the rake face of an insert and it can break off, causing a pieces of carbide from the tool to tear off. BUE commonly occur when machining a ductile workpiece. To overcome it, cutting parameters is changed to higher rake angles, and faster cutting speed, and high pressure cutting fluid. Cutting tools deforms because of built-up of heat. Heat resistant tool can prevent the deformation as well as reducing the cutting speed. Thermal cracking occurs when cutting tools or inserts experience heating and cooling cycles repeatedly. This can be overcome by applying cutting fluid into the cutting process. Figure 2.16 shows the type of tool wear that usually happened.

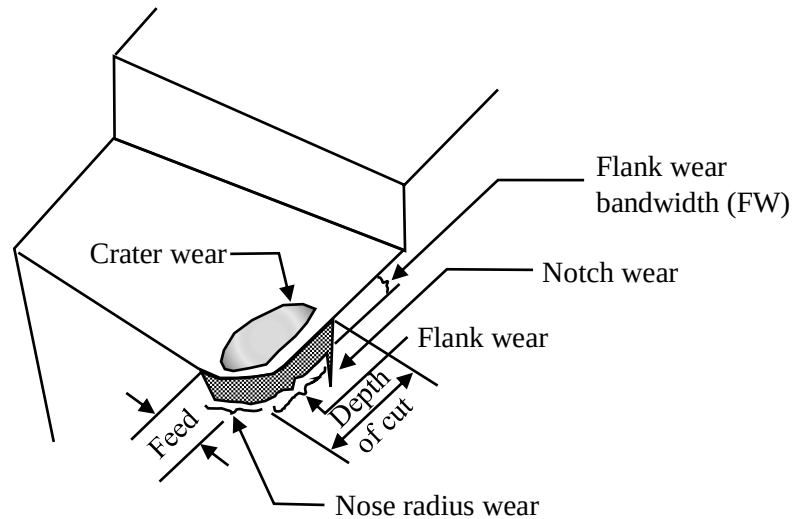


Figure 2.16: The effect of tool corner wear on the dimensional precision in turning (Marinov, 2012)

2.6 Tool life

Tool life equation as postulated by Taylor (Rao, 1977) emphasized on cutting speed parameters as cutting speed is giving more influence over tool life (Fernández-Abia, Barreiro, Lacalle and Martínez, 2011). Tool wear is a condition of loss of the tool material and causes irregular change of shape of the tool from its original shape. During HSM, temperature tends to accumulate on the cutting tool and workpiece which led to tool failure. This is due to cutting tools are continuously in abrasive state or rubbing process at contact surface. High contact temperatures at the tool-chip and tool-work interfaces will contribute to the weakening of the cutting tool properties where it may cause chemical (oxidation) and diffusion wear. Furthermore, chip formation process, which experiences cyclic nature, will cause cracking due to thermal fatigue (Astakhov, 2007). Once the tool wear reaches its limit, the cutting tool needs to be replaced to continue the machining process efficiently.

Tool wear is a main concern because it is undesirable process conditions where it can deteriorate maximum productivity of a production. Certain cutting conditions have to be

identified by a company in order to maximize productivity. Even though there are many research has been done on studying tool wear, the outcome is still not clear enough since different type of metric are used to measure the wear of the tool (Alhadeff et al., 2019) Various theories have postulated to clarify the wear mechanism in HSM, but the difficulty of performing cutting experiment has caused inconsistencies in formulation of cutting tool wears theory. The main element of tool wear is a combination of physical, chemical and thermochemical phenomena. Usually, a cutting temperature co-exist with a tool wear. Till date, a cutting temperature during machining process is measured by thermocouple. There are other parameter correlates with tool wear such as vibrations, and cutting forces. In a recent research, most researcher focuses on the temperature as it is the most suitable parameter to correlate the tribological conditions at the interfaces with the tool wear.

2.6.1 Thermal radiation

In a molecular view of a substance, a thermal motion of charged particle in a matter will cause an emission of electromagnetic radiation. The agitation of group of atoms resembles internal energy of the material. In absolute zero condition, a group of atoms are in a fixed state which inimum particle motion is exist. Therefore, such matter is in the form of minimum attainable entropy or lowest energy state. If temperature of a matter is in state of greater than absolute zero ($-273.15\text{ }^{\circ}\text{C}$ or 0 K), a group of atoms propagates and inter-atomic collisions are possible to occur which causes kinetic energy of the atoms or molecules to change. The charged particle experiences changes in acceleration due to collision. This phenomenon is called as dipole oscillation which electromagnetic radiation. As a result, thermal radiation is release to the surrounding. Electromagnetic radiation spectrum resembles spectrum of energies at a respective temperature (Bramson, 2013). As for today, researcher have discover a range of radiant energy at a wavelength scale of radio waves (10^{-}

10^0 m) to cosmic rays (10^{-14} m). A range of radiant energy in the form of heat is the focus of this research. Radiation emitted from heat is termed as thermal radiation or infrared radiation.

The term ‘infrared radiation’ is given due to the majority of this radiation is located in the electro-magnetic spectrum above the visible red-light in the infrared domain. Infrared radiation carries an energy, which is, can be utilised to determine the temperature of the material (Huda et al., 2002). Figure 2.17 shows the wavelength and frequency domains for the thermal radiation in vacuum, and their respective position on the electromagnetic spectrum.

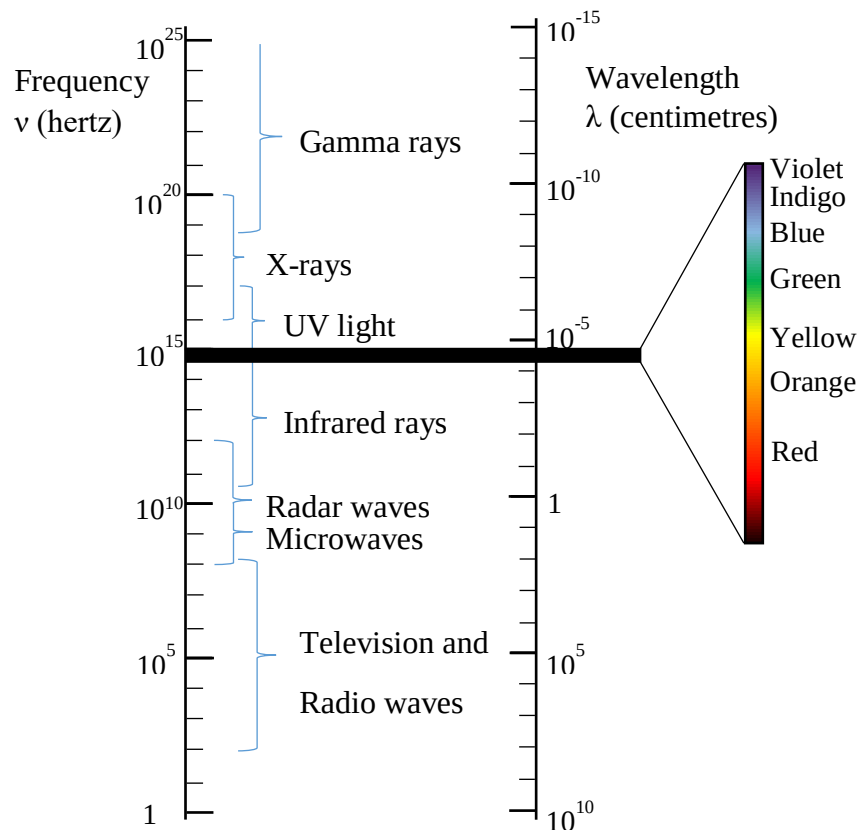


Figure 2.17: Electromagnetic Spectrum (Bisquert, 2018)

Based on Figure 2.17, the thermal radiation domain is divided into three consecutive sub domains respectively to their decrease in wavelength, which are the infrared range, the visible range, and the ultraviolet range. The infrared region is further divided into two sub-types, namely, near infrared, and the far infrared.

The intensity of thermal radiation, I is defined as the radiant energy per unit time per unit solid angle per unit area of the emitter projected normal to the line of view of the receiver from the radiation element. It represents quantitative expression of the intensity of electromagnetic in thermal radiation from source over the entire electromagnetic spectrum.

Planck (1972) postulated that spectral density of electromagnetic radiation emitted by a black body at a particular temperature, T in thermal equilibrium state, represents the amount of energy it produces as radiation of different frequency. He verified the relationship between wavelength, λ and the blackbody's absolute temperature, T through an experiment by observing the spectral distributions of hemispherical emissive power and radiant intensity in vacuum of a blackbody. Planck redefined the equation of thermal radiation intensity, $I_{b\lambda}$ based on Wien's Law as shown below (Stewart and Johnson, 2016):

$$I_{b\lambda} = \frac{2hc^2}{\lambda^5 \left\{ \exp\left(\frac{hc}{k\lambda}\right) - 1 \right\}} \quad \text{Equation 2.2}$$

Where, Boltzmann's constant, $k = 1.3805 \times 10^{-23} \text{ J/K}$

Planck constant, $h = 6.6256 \times 10^{-34} \text{ J/s}$

Speed of light in vacuum, $c = 3 \times 10^8 \text{ m/s}$

The standard unit for thermal radiation intensity is watt (W) per steradian (sr) per unit area (m²), per metre (m) or W.sr⁻¹.m⁻³. The use of thermal radiation intensity equation is to measure the distribution of radiant heat flux per unit area and solid angle (sr), from a particular point of thermal radiation's source. Integration of monochromatic intensity, $I_{b\lambda}$ over the entire radiation spectrum gives the total intensity of blackbody radiation, $I_{b\lambda}$ as shown in Equation 2.3.

$$I_b(T) = \int_{\lambda} I_{b\lambda}(\lambda, T) d\lambda \quad \text{Equation 2.3}$$

Equation 2.3 represents the energy transferred by the ray (i.e., from direction of source) per unit time, solid angle, and unit area normal to the direction of the ray.

Monochromatic hemispherical emissive power of the black surface, $E_{b\lambda}$ is obtain by multiplying Equation 2.2 with π , as shown in Equation 2.4

$$E_{b\lambda}(\lambda, T) = \pi I_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5 \left\{ \exp\left(\frac{C_2}{\lambda T}\right) - 1 \right\}} \quad \text{Equation 2.4}$$

Where, $C_1 = 2\pi h c^2 = 3.742 \times 10^{-16} \text{ W.m}^2$

$$C_2 = hc/k = 1.439 \times 10^{-2} \text{ m.K}$$

The unit of $E_{b\lambda}$ is W/m³, which means, energy per unit time, wavelength, and surface area.

Equation 2.4 is used to illustrate monochromatic emissive power, $E_{b\lambda}$ with respect to temperature and wavelength function. The illustration is shown as a locus shape in Figure 2.18. The maximum value of $E_{b\lambda}$ is obtained by differentiating the Equation 2.4 equal to zero. Solving Equation 2.4 gives a Wien's displacement law. Wien's displacement law describes the maximum monochromatic emissive power, $E_{b\lambda}$ at an absolute temperature. The

wavelength of maximum $E_{b\lambda}$ varies inversely with the absolute temperature. The wavelength of the blackbody radiation energy is gradually shorter as temperature increase.

In other words the monochromatic emissive power $E_{b\lambda}$ represents the heat flux that leaves a surface area along all the rays intersected by the hemisphere, per unit of wavelength interval (Stewart and Johnson, 2016).

The total hemispherical emissive power of blackbody E_b can be obtained by integrating Equation 2.2 with respects to all the wavelength of the radiation spectrum as shown in Equation 2.5.

$$E_b(T) = \int_{\lambda} E_{b\lambda}(\lambda, T) d\lambda \quad \text{Equation 2.5}$$

Substituting Equation 2.3 into Equation 2.4, the result of this integration is the Stefan-Boltzmann law shown in Equation 2.6.

$$E_b(T) = \sigma T^4 \quad \text{Equation 2.6}$$

Where $\sigma = 5.6697 \times 10^{-8} \text{ W}/(\text{m}^2.\text{K}^4)$ is the Stefan-Boltzmann constant.

By referring to Equation 2.2 and Equation 2.6, the total energy radiated from a surface depends closely on the surface's temperature. By measuring the total energy radiated, the temperature of an object can be identified. The infrared radiation pyrometer works is based on this occurrence. Unfortunately, a blackbody concept is an ideal surface which means, an actual surface has a total emissive power less than that of a blackbody (Stewart and Johnson, 2016). The emissive power of this actual surface is greatly affected by the emissivity of the surface. The ratio of the total emissive power of the actual surface to that blackbody at the same temperature is called as emissivity.

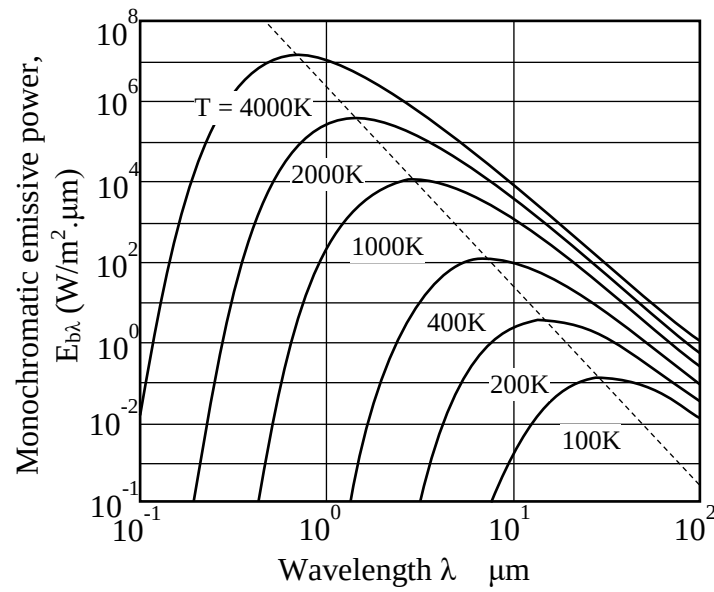


Figure 2.18: Radiant energy of blackbody (Bisquert, 2018)

Influence of the object's emissivity in infrared radiation measurement can be reduced when bichromatic pyrometer is used in this study.

2.6.2 Cutting temperature related studies on milling process by previous researcher

Previous researcher have done extensive studies on the milling temperatures. Sato et al. (2011) have studied the temperature and force variation existed during the milling process of titanium alloy Ti-6Al-4V. They compare the differences of the cutting temperature between down milling and up milling. They discovered that cutting temperature gradient is higher in down milling compared to the latter. Ye et al. (2011) also found that increasing cutting speed will reduce finished surface temperature, but increasing tool-chip contact temperature. Furthermore, Ueda et al. (2001) and Kiprawi et al. (2017) studied the effects of cutting speed and depth of cut on cutting tool temperature of cemented carbide insert. They concluded that the increasing cutting speed and depth of cut will increase the cutting temperature.

A comprehensive study to compare cutting edge temperature under different cutting conditions is performed by Yassin et al. (2009b). By using laser-sintered material as a workpiece, they found that cutting speed is the major factor of changes in cutting temperature followed by the depth of cut and feed per tooth. They also found that there is increase about 5% in cutting temperature when fine metallic powder surround the sintered material. Apart from experimental method Komanduri et al. (2001) have used the functional analysis approach to determine the distribution of temperature in the chip, the tool, and the work material. The analytical solution is based on the temperature rise distribution due to shear plane heat source in metal cutting. Effects of lubricant in machining of stainless steel (SUS304) as discussed by Sasahara et al. (2016). By using thermocouple, they found that the cutting point temperature decrease when a lubricant is applied. They also discovered that the cutting temperature of driven rotary cutting is lower than that of the non-rotational fixed tool and the tool wear is decreased.

In a latest research, Di et al. (2017a) have performed a study on end milling using carbide tool with a difficult-to-machine materials, TiAl6V4. They made a comparison between an experimental method by using thermocouple technique at low cutting speed and mathematical model. They found that increasing cutting speed and feed per tooth will increase the temperature at the tool-chip interface. Di et al. (2017a) have used a simplified analytical model of the cutting loads and stress zone during cutting process based on research conducted by Ma et al. (2016). Ma et al. (2014) used a Finite Element Method (FEM) model and showed that initial tensile stress makes the cutting stress distribution within the workpiece become more tensile. This condition is caused by thermal effect from cutting temperature. Di et al. (2017b) furthered the analytical model research by relating the cutting temperature with flank wear. They postulated that flank wear gives an impact on tool

temperature directly, but the growing of flank wear loses its influences on tool temperature. The tool temperature begins to rise at high rate, then becomes steady state, which is temperature rise slowly until reaches peak value.

2.7 Comparison of conduction techniques and radiation techniques in measuring machining's temperature

The interfacial temperatures play a major role in the performance of machining processes, and a general move toward dry machining increases the importance of understanding how machining temperatures are affected by the process variables involved (cutting parameters, cutting tool materials, cooling methods, etc.) and by other physical factors involved into cutting process, such as plastic deformation, friction and tool wear. Based on this fact, a number of various measuring techniques of cutting temperatures were developed in the past and now new ones are developing successively. The main two groups of temperature measuring techniques (contact/noncontact or conduction-based/radiation-based) adapted to machining are schematically illustrated in Figure 2.19.

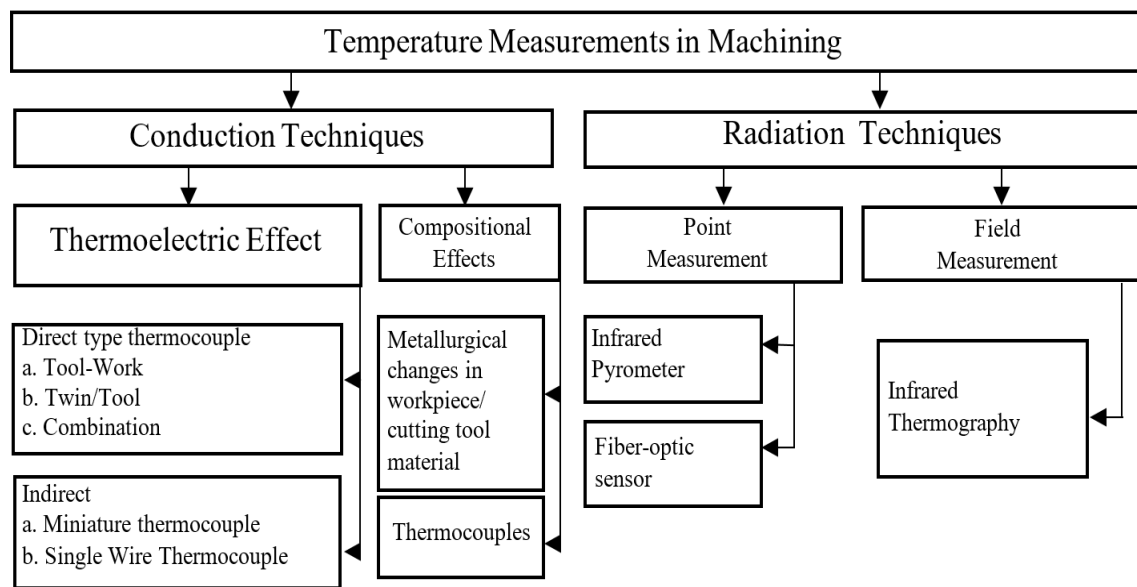


Figure 2.19: Temperature measurement techniques in machining (Sullivan, 2001)

Generally, conduction techniques involved in utilization of thermocouples set up to determine the temperature changes by direct contact meanwhile radiation techniques captures the infrared radiation emitted by the object and then interpreted into temperature chart (Bhirud, 2017).

Measuring cutting edge temperature of end milling is challenging due to the cutting tool rotates at high speed and spot size of measured cutting temperature is small. Using thermocouple technique at tool-work as hot and cold junction is not applicable as it indicates the average temperature of the tool-work material contact area (Goyal et al., 2014). Another drawback is the response time of the thermocouple is significantly slow to match with the rotation of cutting tool at high speed. Therefore, the reliability of using thermocouple technique to measure cutting temperature is not acceptable.

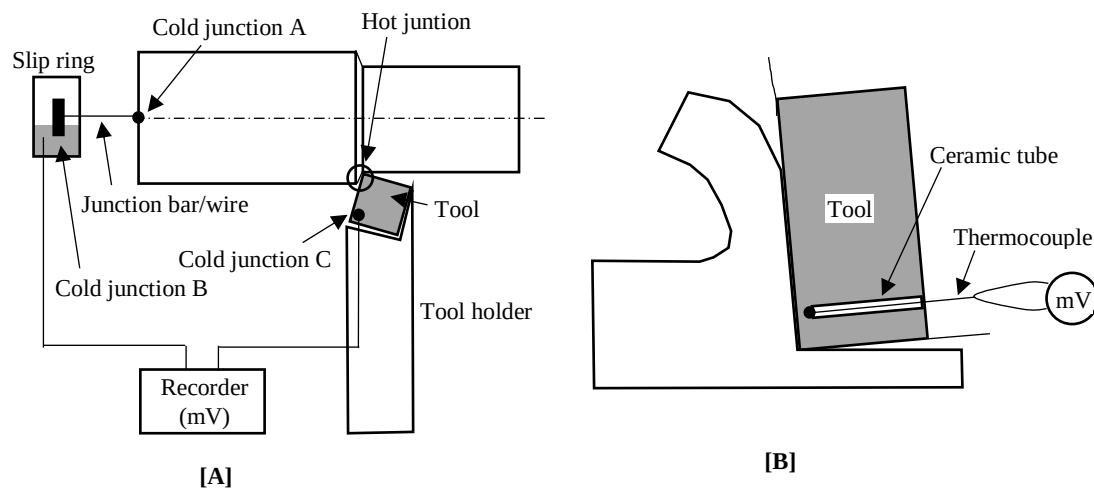


Figure 2.20: (A) Tool/work thermocouple circuit and (B) inserted thermocouple (Childs et al., 2000)

Another alternative for cutting temperature measurement is by measuring the thermal radiation emitted from the cutting edge of tool. Thermal radiation emitted from the cutting edge of tool can be detected by infrared photocells.

In order to eliminate the problem of emissivity effect, which strongly influences the evaluated temperature measurements, a two-colour pyrometer technique was developed (Huda et al., 2002). For a two-colour pyrometer, the measured temperature is independent of the surface emissivity when grey-body behaviour can be assumed.

As shown in Figure 2.21A, an optical fibre of 2 m length is inserted into a thin plastic pipe and in a fine 0.6 mm hole, and is fixed when the distance between the incidence face of the fibre and the rake surface approaches 1 mm.

The calibration is obtained by sighting on radiating surfaces of known, uniformly distributed temperature. The measurements are performed when infrared rays radiated from

the tool/chip interface are received by an optical fibre, then divided into two fibres by a fused fibre coupler.

Each fibre leads the infrared rays to two infrared detectors, which have different spectral sensitivity. The electric signals converted from infrared energies by these cells are amplified and stored into digital memory. The temperature is obtained from the ratio of the output voltage of the two cells.

In the upper scheme (Fig. 2.21C), germanium (Ge) and indium antimonide (InSb) are used as detector and quartz (SiO₂) fibre is selected to measure temperature higher than 500°C. The Ge filter is added to the InSb cell to reduce the short wavelength of infrared rays and improve the sensitivity of the apparatus at high temperature range. In the lower scheme, the infrared energy is received by a chalcogenide optical fibre and led to a two-colour detector consisting of InAs and InSb detectors (the first one responds to incident radiation from 1 to 3 μm and transmits waves 3 μm , whereas the second one responds to radiation from 3 to 5 μm).

It was proven experimentally that the temperature measured by the two-colour pyrometer was the maximum temperature in the target area of the optical fibre by an accuracy of at least 90% (Ueda, 2006).

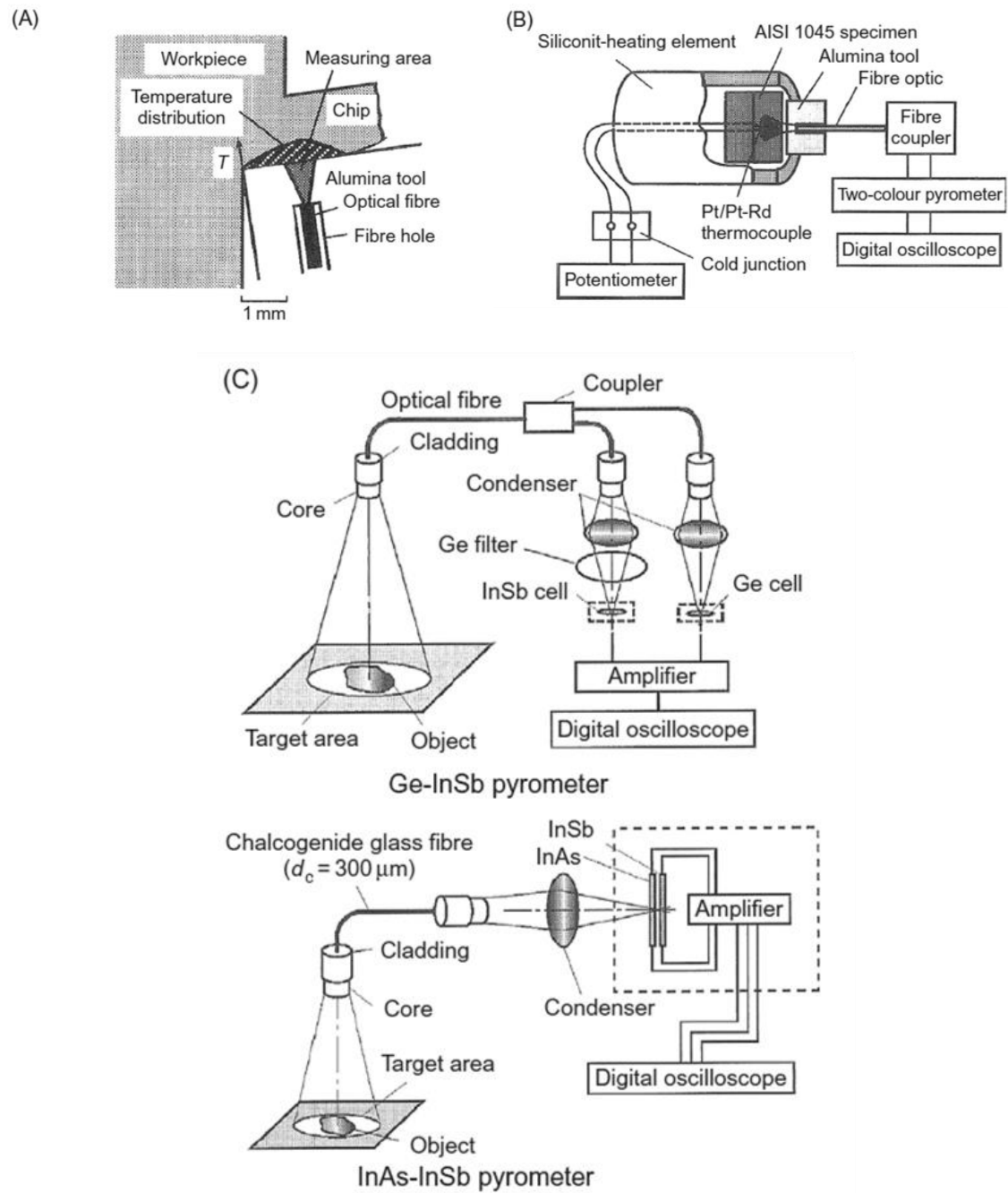


Figure 2.21: Measurement of cutting temperature using two-colour pyrometer
 (A) Illustration of optical fibre setting, (B) scheme of calibration setup and
 (C) two structures of two-colour pyrometers (Grzesik, 2016)

2.8 Basic principles of two-colour pyrometer

The schematic diagram setup of two-colour pyrometer with an optical fiber is shown in Figure 2.22 (Kiprawi, 2017). The heated insert carbide of cutting tool emits an infrared radiation and then accepted by chalcogenide optical fiber. The infrared radiation is then directed towards the InAs and InSb detectors inside photocell. Both of these detectors are mounted in sandwich configuration.

Photocells are kept in a condition of $-196.15\text{ }^{\circ}\text{C}$ by using liquid nitrogen to reduce signal instability and increase sensitivity. These photocells convert the infrared energy to electrical analogue signal in a scale of millivolt. An amplifier is used to amplify the electrical signal. The output signal is monitored and recorded by using digital oscilloscope.

Due to the differences in spectral response range between two cells, the temperature can be obtained by calculating the ratio of the output voltages.

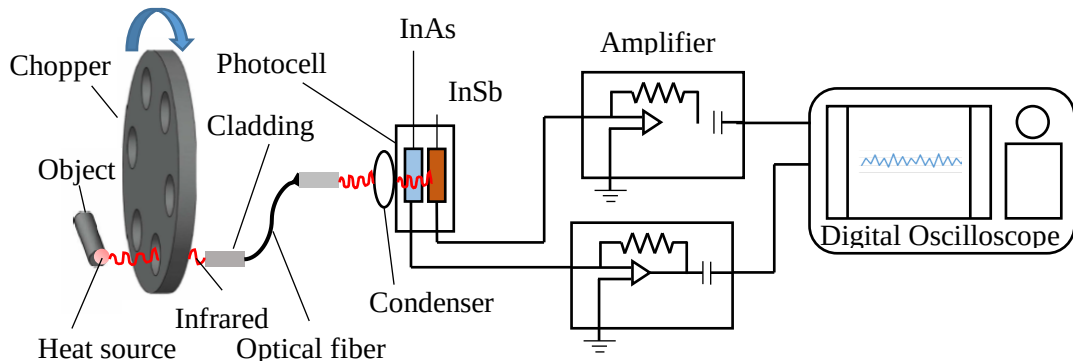


Figure 2.22: Fundamentals structure of bichromatic pyrometer with optical fiber. (Kiprawi, 2017)

Since these cells have different spectral sensitivity, the temperature can be obtained by calculating the ratio of the output voltages.

2.9 Specific detectivity of InAs and InSb

Each of InAs and InSb sensor installed in the photocells have its own specific detectivity respectively as shown in Figure 2.23. Specific detectivity of photocells resemble the signal to noise ratio of input with respect to detection area and detection bandwidth. Generally, it resembles the degree of performance of the photodetectors to detect particular signal or wavelength. Based on Figure 2.23, InAs and InSb's specific detectivity were plotted. The lowest specific detectivity of InAs is 1.5 to 3.5 μm which means InAs photocells will be unable to detect signal outside the range of 1.5 to 3.5 μm as the external noise's wavelength overwhelm signal wavelength during detection. Similar explanation applies on InSb too. Referring to Figure 2.23, the configuration of Hamamatsu's InAs and InSb that are in sandwiched mode gives high specific detectivity, D^* ranging from 35 % to 100% for a wavelength 1.5 to 5.5 μm . Therefore, the external noise did not affect much on the signal reading for an infrared emission with a wavelength 1.5 to 5.5 μm .

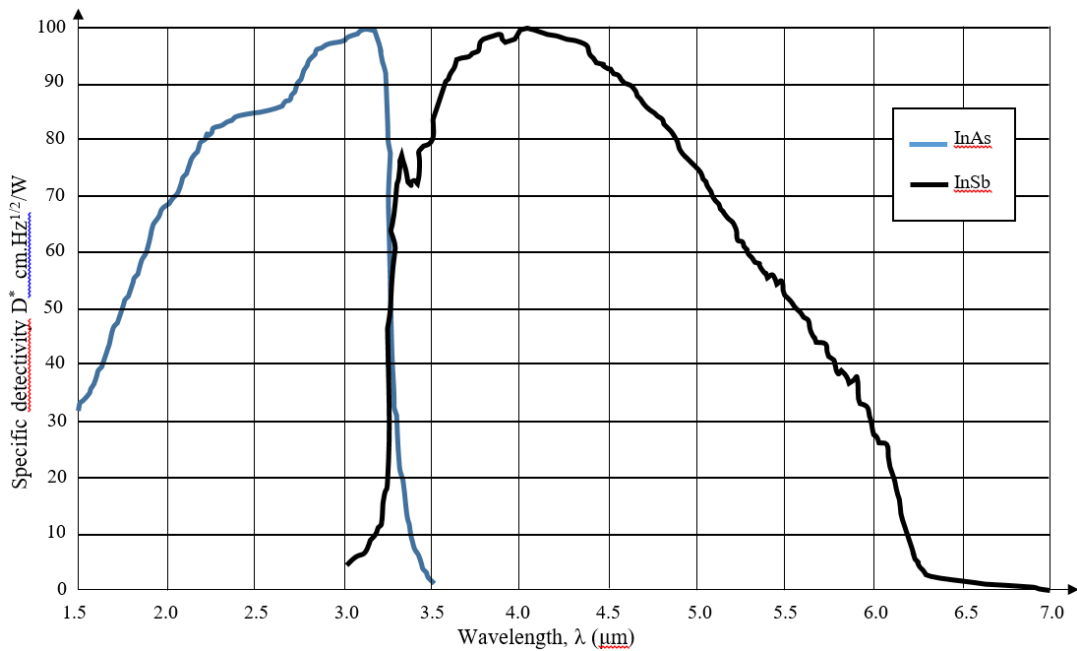


Figure 2.23: Specific detectivity of InAs and InSb photocells (Hamamatsu, 2017)

2.10 Transmission loss

Transmission loss in an electromagnetic application is a normal occurrence. Some of the transmission loss are avoidable and certain are not. Therefore, a precaution need to be taken in order to minimize the transmission loss. These are the common factor of transmission loss from the optical fiber:

1. Physical – Breakages, Bending
2. Impurities,
3. Fluctuation of density
4. Absorbance by chemical bonds
5. Attenuation loss

During calibration process and cutting experiment, all of these possible transmission loss factors were considered in a selection of optical fiber type.

Transmission loss in the optical fiber is unavoidable because of the material composition of fiber core. Every different material used in the design of optical fiber have different absorption capability (Okoshi, 2012). Impurities, non-homogenous density, dispersion and structural defectiveness in the fiber are also the main causes of the transmission losses. Recent technology in the manufacturing of optical fiber have reduced greatly number of impurities in the optical fiber. Structural defectiveness can be avoided if the optical fiber is handled properly without causing micro and macro bending. Another structural defectiveness is uneven uniformity at the geometry of core-cladding boundary. Most of these factors are from the manufacturer of optical fiber and it need to be concerned in the evaluation the transmission quality. In order to reduce the transmission loss, both end of the optical fiber need to be ensured clean and no any particles exist at the tip surface.

Signal loss due to physical dimension factor can be avoided if the procedure of experiment take account the handling precaution instructed by the manufacturer. A sudden drop or shock might cause the core to cracks and cause the signal waves unable to travel. Meanwhile, bending angle of the optical fiber has its limitation as stated by the manufacturer. The bending of optical fiber can cause the reflected radiation will have a transmission angle at lower than critical angle. Even though the radiation enters the optical fiber with incident angle higher than critical angle, it might be refracted to cladding region later if the optical fiber are bent beyond its limit.

Existence of impurities are also one of the main factor in transmission loss. Usually, the impurities are originate from the manufacturing process of the optical fiber. Recently, most manufacturer have reduced the content of impurities in their product significantly. Therefore, the effect of impurities existence are negligible if it is purchase directly from the manufacturer. If one-self makes the customized optical fiber, then this factor are need to be concerned.

Variations of density along the core of optical fiber are also one of the main factor in transmission losses as the core is made of transparent material which have intrinsic spatial density function (Okoshi, 2012). Fluctuation of density inside the optical fiber will cause the travelled light to refract from its path. Based on Snell's law, the refractive index are dependent on the density of transparent materials. The fluctuation of density might cause the travelled light to refract and scattered. This phenomenon is known as Rayleigh scattering.

In a field of infrared spectroscopy, a sample is emitted with an infrared light from infrared spectrometer in order to study its chemical structure. Generally, a portion of infrared light that are passing through the sample was absorbed by chemical bonds as mentioned in

Figure 3.8 in Section 3.5.5. Since the optical fiber are made of arsenic trisulphide, As_2S_3 , it is expected that the chemical bonds exist. Therefore, a portion of infrared light emitted from the insert too might get absorbed to the chemical bonds of As_2S_3 . This absorbance of infrared by chemical bonds will reduce the total volume of infrared light enters and thus, exits with lesser intensity of infrared light.

Attenuation loss is a loss of light energy to travel inside the optical fiber. Each photons in an infrared radiation loses its momentum as distance increase. Therefore, attenuation loss is directly proportional to the length of the cable.

During calibration process and cutting experiment, all of these possible transmission loss factors were considered in a selection of type of optical fiber and its handling precautions.

2.11 Summary

Previous research that are related with pyrometer development have been successfully studied and reviewed. Based on the review, it was found that there are various temperature measurement technique used in machining process. Generally, infrared radiation technique to measure temperature of cutting edge machining process is less explored by current researcher as it is not widely available for commercial purpose. In Chapter 3, a method to develop the pyrometer for cutting edge temperature measurement will be discussed comprehensively by every components and techniques involve. It was expected the pyrometer is fully functioning after several commissioning stage during calibration process.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Measurement of infrared radiation level emitted from a heat source is crucial to determine the corresponding temperature. Specifically, the cutting edge of cutting tool emits an infrared radiation due to the work done to machine the workpiece. Harnessing infrared radiations from cutting edge of tool is important to determine its cutting temperature. Specific materials and apparatus need to be identified in order to develop this temperature measuring device. Prior to usage of pyrometer in milling machine, the pyrometer needs be calibrated to its corresponding temperature. This is due to each material will emit unique level of infrared radiation corresponding to its temperature based on its emissivity which means, two different objects with similar measured infrared radiation levels might not have similar temperature for both (Bramson, 2013).

From the calibration process, the calibration curve equation can be formulated to obtain the relationship between output voltage of InAs-InSb photocells and its corresponding temperature (Ueda, 2001). By doing so, the voltage output value obtained from the photocells can be substituted into the calibration equation to determine current temperature.

Figure 3.1 shows a flowchart of calibration process before a cutting experiment is conducted. Solid end mill tool and insert carbide are used as a specimen which are heated then in order to emit infrared radiation. After heating, a DC motor is switched on to turn a chopper in order to simulate the intermittent cycle of cutting tool. Since the photocells

produce a low voltage level, an amplifier is installed then to amplify the signal. Digital oscilloscope will record all signal received from the photocell and thermocouple. A calibration graph is then plotted to find calibration equation. Once the pyrometer is successfully developed, an experiment will be conducted to test the performance of pyrometer. There are two stages in the cutting experiment. First stage is the study of development of cutting profile signal produced by pyrometer for each successful cutting pass. Second stage is study of cutting performance when machining AISI 1095 at medium cutting speed and high cutting speed.

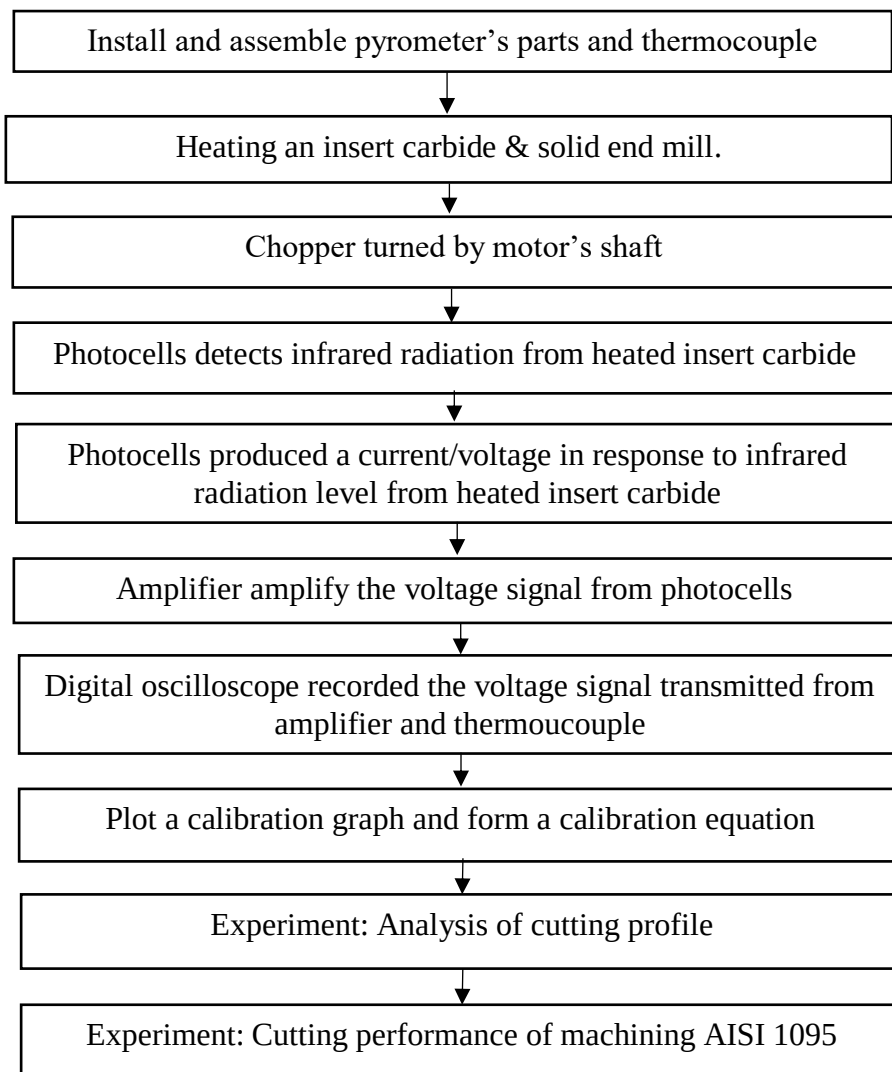


Figure 3.1: Flowchart of methodology

3.2 Procedure for calibrating the pyrometer

A calibration was performed for insert carbide coated with Titanium Carbo-Nitride (TiCN). This insert carbide was taken from indexable end mill tool holder. The insert was then heated up until 1000°C by butane pencil torch. Refractory ceramic fiber or isowool was wrapped around the insert carbide. A heated insert carbide emits an infrared radiation that travels through optical fiber and condenser before being accepted by InAs and InSb photocell sensor. Terminals output behind photocell were connected to amplifier to amplify the signal. High speed digital oscilloscope is connected to the amplifier to measure, record and visualize the signal in a graphical form.

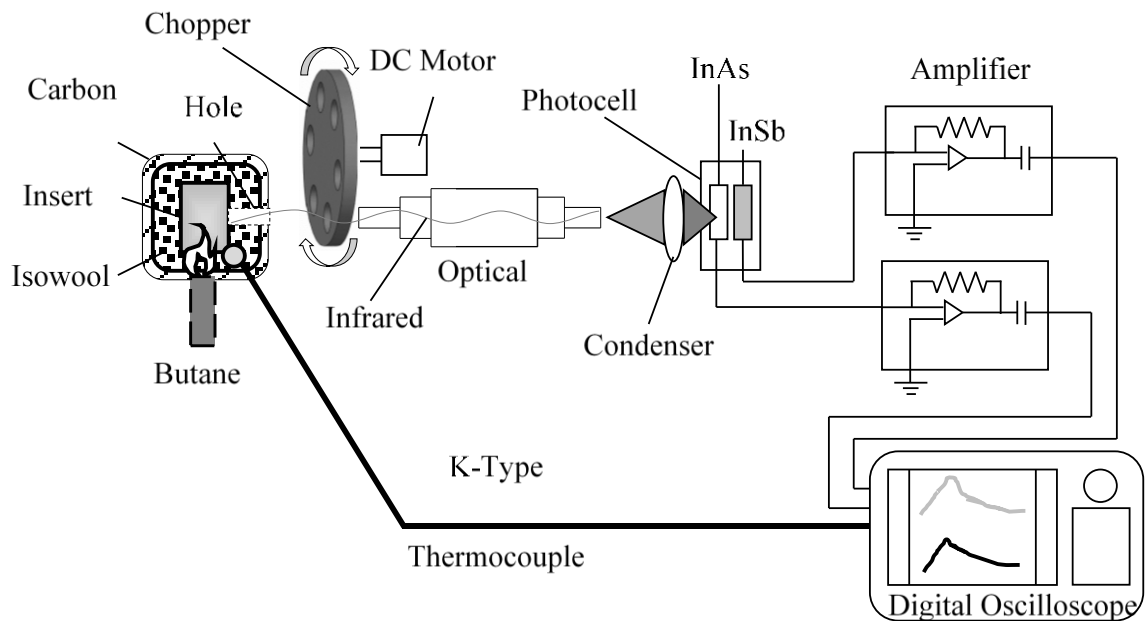


Figure 3.2: Schematic illustration of temperature calibration

Procedure for calibrating the pyrometer is shown below:

1. All of the materials and apparatus above will be set up according to the schematic diagram in Figure 3.2.
2. Pour 30 mL of liquid nitrogen into the photocell and wait for 1 minute. Then pour another 30 mL and wait for 3 minutes before pouring the rest of the liquid nitrogen (about 10 mL).
3. Commissioning all electrical cable connection and try to obtain signals by heating the sample in low temperature. An infrared radiation will be emitted from heated insert carbide and passed through a chopper's hole then received by optical, photocells and oscilloscope.
4. InAs and InSb photocells are susceptible to external signal noise. Wait for it to stabilize first and then heat up the sample with the pencil butane torch until it reaches 1000°C.
5. Allow the sample to cool down while taking its temperature at every 10 seconds.
6. A set of data consists of photocells signal, and thermocouple readings were obtained and analyzed in Xviewer Software, Matlab, and Microsoft Excel. It is then will be tabulated in Microsoft Excel and a graph along with the polynomial equation will be formulated. This equation represents the relationship between the actual temperature and the voltage shown on the oscilloscope.

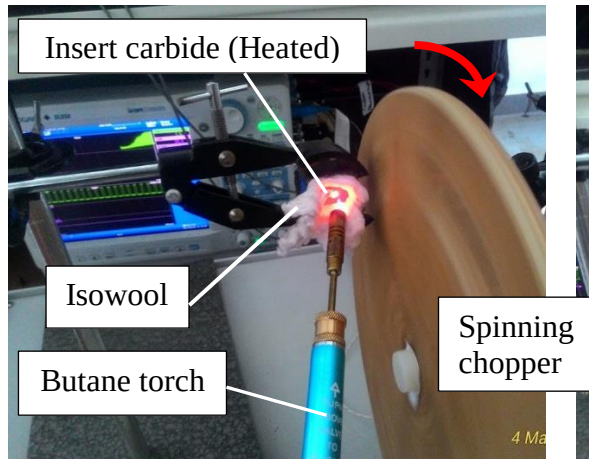


Figure 3.3: Insert carbide was heated until near to 1000°C by using a butane torch

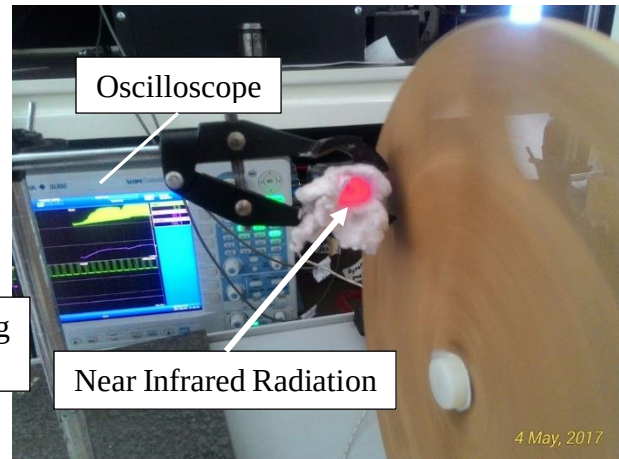


Figure 3.4: Insert carbide emitted a near infrared radiation (closest to visible light region in an e.m.f spectrum)

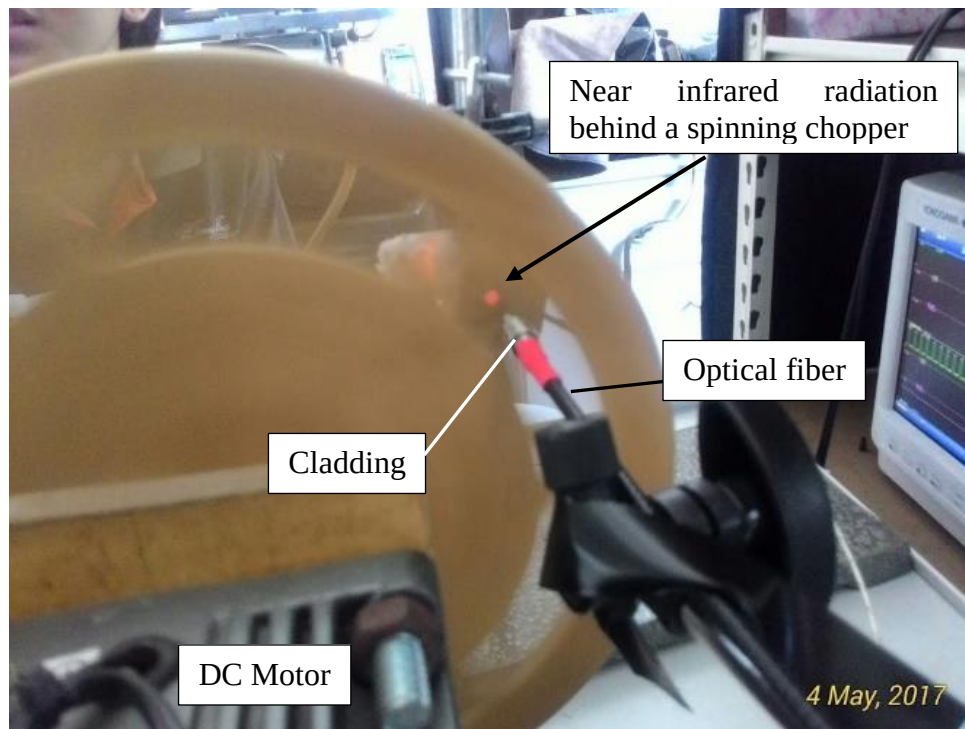


Figure 3.5: Optical fiber received an infrared radiation emitted from the heated insert carbide

3.3 Main components of two-colour pyrometer and its specifications

A proper selection of apparatus, tools, and materials is important before executing an experiment. The accuracy of developed pyrometer are totally dependent on the material selection. In this section, the characteristic of the main components of two-colour pyrometer which is type of optical fiber, the infrared detector and other components of the pyrometer were discussed.

These are the list of the main components used for developing the pyrometer.

1. **Flexible Optical fiber:** Functioned as infrared transmitter (Mendez, 2011). One end of this optical fiber was pointed to the heated work piece to harness its infrared radiation while the other end was pointed to the infrared photocell.
2. **Infrared detectors:** Used to change energy from infrared radiation to electrical signal (Capper, 2013).
3. **Condenser:** Used to condense the infrared rays radiated from the optical fiber (Grzesik, 2008 and Ueda, 2006).
4. **Amplifier:** To amplify photocell's electrical signal output
5. **Oscilloscope:** A device to record and visualize signal output from photocells
6. **Chopper (Used only for calibration):** Chopper was used to simulate the rotation of the cutting tool. A chopper is a circle disc with a number of holes drilled on it. The chopper will be connected to a motor by using a belting system. The signal is only allowed to pass through the holes as the chopper rotates (Yassin, 2009b).

7. **Optical fiber holder (Used only during cutting process):** The purpose of Optical fiber holder is to position the end of optical fiber precisely to the desired measured area.

3.3.1 Infrared detectors (Hamamatsu Photocell)

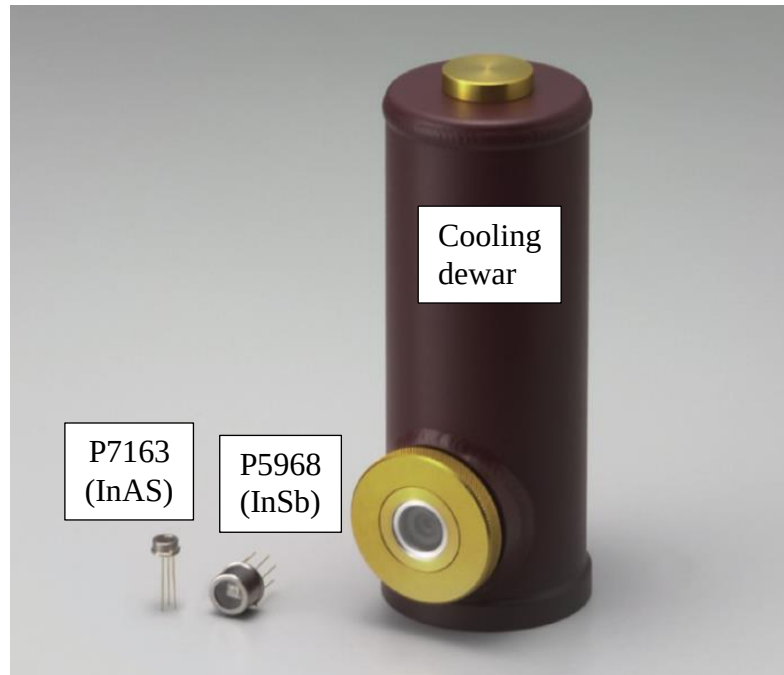


Figure 3.6: Picture of P7163 with P5968 - Hamamatsu Photocell (Hamamatsu, 2017)

P7163 - Hamamatsu photocell is an infrared detector that are equipped with InAs and InSb photovoltaic detectors. This photocell is usually placed at room temperature. Its function is to measure infrared radiation level of the targeted object. In some advanced application, it used as infrared spectrophotometer to analyse the spectrum of infrared light region passed through a material in order to identify its chemical structures. For this project, it will be used as main components in a pyrometer to detect the infrared radiation emitted from the cutting edge of tool and converts it to electrical signal.

Hamamatsu Photocells' sensitivity are heavily dependent on cooled environment to function properly. The manufacturer company, Hamamatsu designed the photocells equipped with a liquid nitrogen dewar in order to reduce noise and increase its sensitivity to infrared radiation.

The ideal surrounding environment for the experiment should be located in air-conditioned room. Unfortunately, the experiments were conducted in a normal room temperature and the location of the milling machine is installed near to non-tinted window. Furthermore, the climate of the research area is in a tropical rainforest country, Malaysia which is located in the equator belt region. The average temperature of Malaysia in a whole year is around 27~35°C. Liquid nitrogen boiling point is -198.5°C. Therefore, the liquid nitrogen will evaporate regardless to any location in the world, unless it is stored in a designated place which is lower than its boiling point. Compared to cool region in the world, rate of liquid nitrogen evaporation is significantly faster in Malaysia as shown Table 3.1.

The dewar inside the Hamamatsu InAs-InSb photocell is functioned as a storage for liquid nitrogen. Its purpose is to cooldown the photocells sensor and reduce its sensitivity to the presence of noise. The liquid nitrogen evaporate quickly due to the ambient temperature in a laboratory are hot and not air conditioned. The rate of liquid nitrogen evaporation was observed and recorded as shown in Table 3.1.

Table 3.1: Evaporation rate of liquid nitrogen inside a photocell's dewar at a UNIMAS FENG's laboratory

Volume (mL)	Temperature inside dewar (°C)	Time (minutes and seconds)	Deviation of InAs Voltage from Ground Voltage (mV)	Error Percentage (%)	Deviation of InSb Voltage from Ground Voltage (mV)	Error Percentage (%)
75.0	-170.0	0	0	0	0	0
70.0	-169.1	0.6	0.30	1.5	0.4	6.7
60.0	-160.3	1.0	0.60	3.0	0.5	8.3
55.0	-160.5	2.0	0.90	4.5	0.9	15.0
47.0	-152.0	2.4	1.6	8.0	1.0	16.7
30.0	-151.0	2.8	3.0	15.0	1.2	20.0
22.0	-140.0	4.2	6.7	33.6	2.1	35.0
9.0	-70.7	4.6	12.1	60.5	4.0	66.7
0.0	-70.2	6.0	20.0	100.0	6.0	100.0
0.0	-40.2	10.0	20.1	100.0	6.0	100.0

Therefore, during calibration process and cutting experiment, a liquid nitrogen level inside photocell's dewar are ensured to be at least 30 mL in order to run an experiment. If the dewar run out of liquid nitrogen, the signal baseline will be shifted gradually and causing a misleading in temperature measurement. It was advisable to standby a liquid nitrogen tank near to experimentation area to refill the dewar. An explanation of noise presence during signal measurement as liquid nitrogen dries up and signal conditioning method were explained in Chapter 4.

3.3.2 Temperature range of InAs and InSb photocells

In this pyrometer development, Indium Arsenide (InAs) and Indium Antimonide (InSb) developed by Hamamatsu company are used as infrared detectors and its properties are shown in Table 3.2. They are mounted in a sandwich configuration in order to ensure a single unique infrared radiation wave can pass both. The photocells were operated at temperature of -196.15 °C by using liquid nitrogen to stabilize the photodetectors. These photocells is a high speed response infrared sensor.

Spectral response is a range of signal wavelength that can be detected by photocells. Peak sensitivity is the specific signal wavelength with lowest disturbance of noise that are detected by photocells. Specific detectivity is a signal-to-noise ratio with respect to detection area and detection bandwidth. Response time is a rate of detection at one time.

Table 3.2: Properties of InAs and InSb photocells (Hamamatsu, 2017)

Cell	InAs	InSb
Spectral response (μm)	1.0 – 3.8	1.0 – 5.5
Peak sensitivity (μm) (wavelength (μm))	3.0	5.3
Specific detectivity D^* ($\text{cm} \cdot \text{Hz}^{1/2} / \text{W}$)	8.0×10^9	8.0×10^6
Response time (μs)	1	0.6
Operating Temperature (K)	77	77

The Planck's radiation law is expressed by the following expression:

$$E = \frac{2\pi hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda kT}} - 1 \right)} \quad \text{Equation 3.1}$$

In order to determine the temperature range of InAs and InSb can detect, Planck's equation was derived to Wein's Law.

Wein's Law derived that:

$$\lambda_{max} T = 2.898 \times 10^{-3} m.K \quad \text{Equation 3.2}$$

$$T_{\lambda=1.0 \mu m} = \frac{2.898 \times 10^{-3} m.K}{1.0 \times 10^{-6} m} = 2898 K \text{ or } 2624.85 ^\circ C \quad \text{Equation 3.3}$$

$$T_{\lambda=3.8 \mu m} = \frac{2.898 \times 10^{-3} m.K}{3.8 \times 10^{-6} m} = 762.6 K \text{ or } 489.48 ^\circ C \quad \text{Equation 3.4}$$

$$T = \frac{2.898 \times 10^{-3} m.K}{\lambda_{max}} \quad \text{Equation 3.5}$$

$$T_{\lambda=5.5 \mu m} = \frac{2.898 \times 10^{-3} m.K}{5.5 \times 10^{-6} m} = 526.90 K \text{ or } 253.75 ^\circ C \quad \text{Equation 3.6}$$

Therefore, the limits range of temperature that can be detected by this pyrometer is between 253.75 °C and 2624.85 °C.

3.3.3 Chalcogenide optical fiber – Flexible type

In this experimental setup, a step-index multimode chalcogenide optical fiber was used. Figure 3.7 shows the structure of step type optical fiber. Since infrared radiation is one of the electromagnetic spectrum, it travels in a straight line path until its density of path changed. The infrared light will reflect or reflect relying on the incident angle. This phenomenon is shown in Figure 3.7.

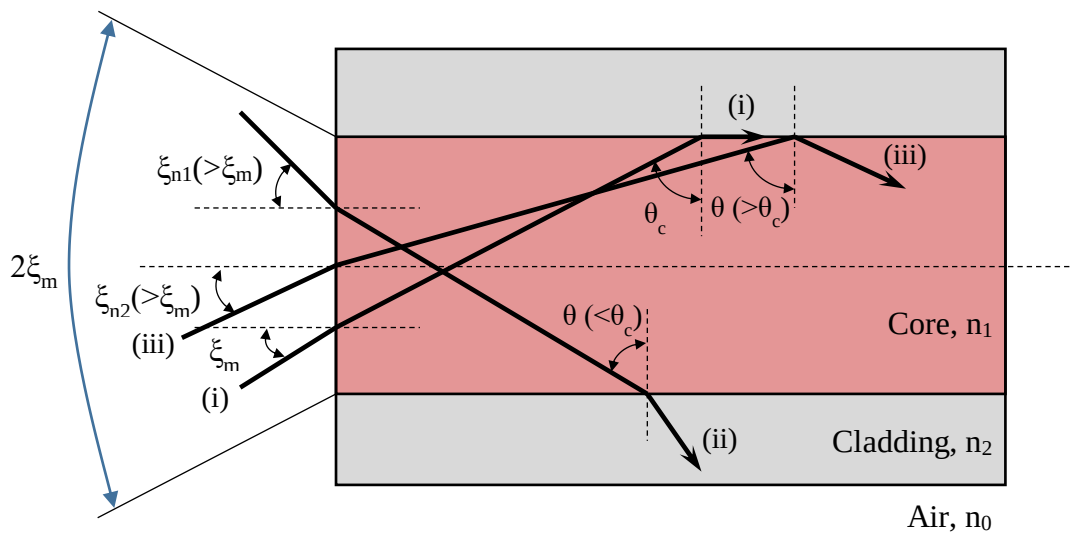


Figure 3.7: Typical path of infrared radiation at different angle in optical fiber (Yassin, 2009a)

The angle of incident radiation decides the direction of subsequent path. Critical angle is the minimum angle required by incident radiation to experiences total internal reflection inside the optical fiber. In order for the radiation to propagate along the optical fiber, the radiation must intersect at the core-cladding interfaces at an angle greater than critical angle, θ_c . As soon as the radiation enters the core, the radiation will refract at certain angle due to the differences in the density of air and core.

The critical angle is defined as the minimum angle of incident light to achieve total internal reflection. It is determined as follows:

$$\sin \theta_c = \frac{n_2}{n_1} \quad \text{Equation 3.7}$$

The relations of angles of location (i) which is between the core layer and the air can be expressed using Len's law as follows:

$$n_0 \sin \xi_m = n_1 \sin \left(\frac{\pi}{2} - \theta_c \right) \quad \text{Equation 3.8}$$

If the infrared light travel at an angle lower than the critical angle of the boundary between core and cladding, it will not convey light along the optical fiber. This is where the transmission loss will occur. The acceptance angle, ξ_m of optical fiber relies on this critical angle and this relations is mostly known as numerical aperture, NA and defined as follows:

$$n_0 \sin \xi_m = n_1 \left[1 - \left(\frac{n_2}{n_1} \right)^2 \right]^{\frac{1}{2}} = \sqrt{n_1^2 - n_2^2} = NA \quad \text{Equation 3.9}$$

A high numerical aperture indicates that the acceptance angle is wide. Therefore, the incidence light can enter the optical fiber at various angle, allowing efficient grouping of light into the fiber. However, the drawbacks of high numerical aperture will increase the number of dispersion as rays at different angles have different path lengths and therefore take different times to traverse the fiber.

Since the refractive index for the atmosphere is $n_0 = 1$, therefore the maximum acceptance angle ξ_m of the optical fiber is shown as follow,

$$\xi_m = \sin^{-1}(NA) \quad \text{Equation 3.10}$$

3.3.4 Characteristics of chalcogenide optical fiber

Spectral transmittance of chalcogenide optical fiber was shown in Figure 3.8. From Figure 3.8, the successive transmittance is ranging from 43% to 64%. In terms of transmission losses, it range about 36% to 57%. Table 3.3 gives the characteristics of the chalcogenide optical fiber.

Table 3.3: Characteristics of chalcogenide optical fiber (Art Photonics, 2014)

Specifications	Value
Core diameter, d_c	340 μm
Numerical aperture, NA	0.25 – 0.28
Core material	As_2S_3
Cladding material	As-S
Core refractive index, n_1	2.4
Cladding refractive index, n_2	2.38
Acceptance angle, ξ_m	14.48 – 16.26 °
Transmission wavelength range	1.5 – 6 μm
Operating temperature	-200 < T < 100
Maximum transmitted power, W	1 (CW)
Maximum bending radius	60 cm

This optical fiber are capable to transmit infrared radiation from wavelength region of 1.5 – 6 μm or in terms of temperature, 209 °C to 1659 °C. Severe transmission loss will occur if the infrared radiation wavelength is beyond this region (Nalwa, 2012). Under no physical damage circumstances, the transmission loss occur because of the radiation are absorbed by the chemical bonds of the core inside the optical fiber.

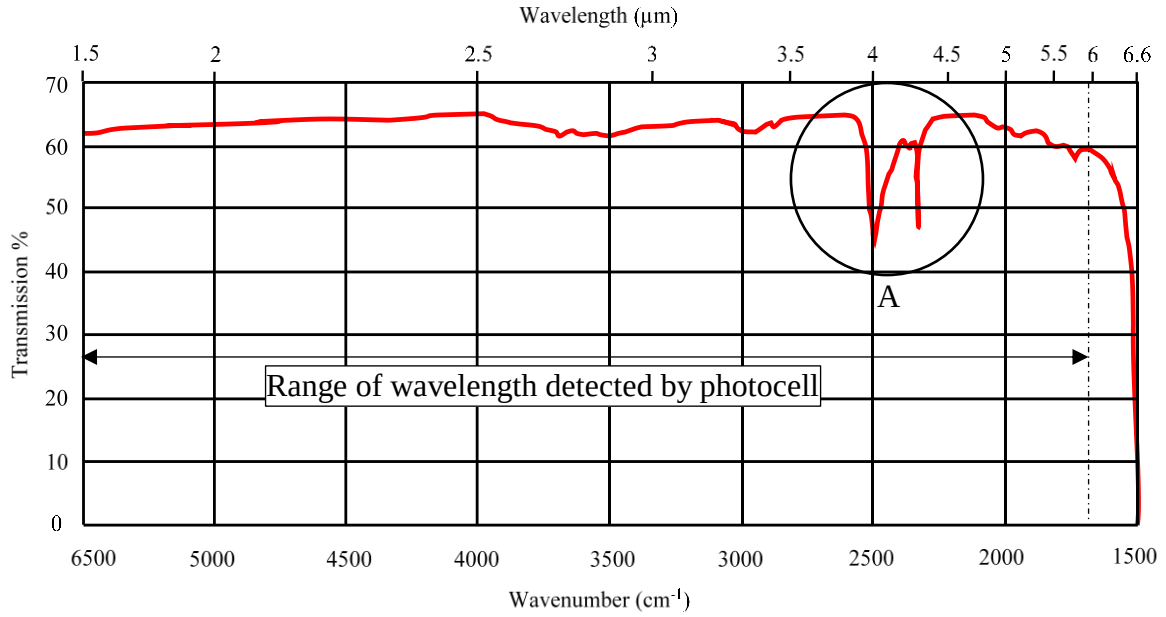


Figure 3.8: Spectral transmittance of chalcogenide optical fiber (Art Photonics, 2014)

The two fall points of transmission percentage at region circle A indicates that a portion of infrared energy is absorbed by the particular chemical bonds of As_2S_3 . In other words, the efficiency of radiation transmission will drop at certain particular wavelength. At the region A, the transmission of infrared radiation from photocell will losses around 55%. It is still considerably as moderate loss as 45 % of infrared radiation still can get through the optical fiber.

Absorption loss by Cr, Mn, Co, Fe, Ni, Cu, and V inside fiber material has been studied (Okoshi, 2012). In terms of quality, chalcogenide optical fiber have great advantages when transmitting infrared radiation (Bureau, 2014). Based on the range of wavelength detected by photocell in Figure 3.8, the transmission percentage are only drastically plummet at region A, while the rest of transmission percentage are consistent around 60 to 65%. It shows that there are almost no impurities along the optical fiber.

3.3.5 Measuring area of the optical fiber

During calibration process, it was found there are relationship between the spot diameter of optical fiber and its distance from the targeted object. The distance of optical fiber from the targeted object has its limitation as the degree of accuracy might be compromise. As reported by Ueda et al. (2001) the accuracy of single colour pyrometer are influenced by the distance of optical fiber. The temperature reading of single colour pyrometer deviate far from the actual temperature. Fortunately, the effects of optical fiber distance is disregarded when two colour pyrometer are used as stated by Ueda et al. (2001). Even the distance is apart by 10 mm, the reading are still approximately around 93% correct from its actual temperature. Therefore, the setting location of optical fiber from targeted object which is the cutting edge of tool does not influence much on the degree of accuracy of temperature measurement.

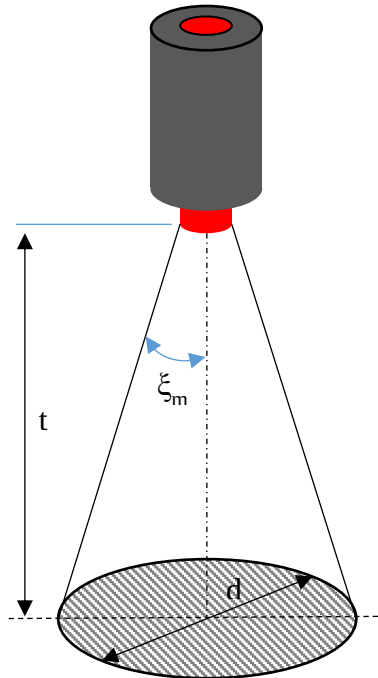


Figure 3.9: Schematic illustration of measuring area (Yassin, 2009a)

The schematic illustration of measuring area at incidence face of the optical fiber is shown Figure 3.9. Figure 3.10 describes the relationship between measuring distance, t from the object and spot diameter of the target area, d_s . Based on Figure 3.10, increasing the measuring distance will increase the diameter of target area.

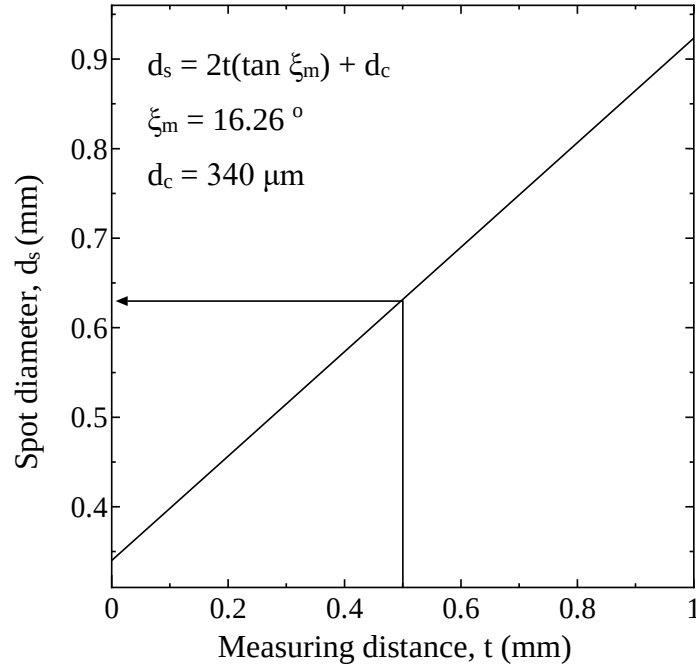


Figure 3.10: Relationship between measuring area diameter and spot diameter

From Table 3.3, the acceptance angle, ξ_m is 16.26°

By referring to Figure 3.9, a relationship between spot diameter (d_s), measuring distance (t), acceptance angle (ξ_m), and core diameter (d_c) is shown in Equation 3.11.

$$d_s = 2t(\tan \xi_m) + d_c \quad \text{Equation 3.11}$$

If measuring distance, t is 0.5 mm.

(Noted that, $t = 0.5$ mm will be chosen as a measuring distance in Chapter 4 later)

$$d_s = 2 (0.5 \text{ mm}) \tan 16.26^\circ + 0.34 \text{ mm} = 0.63 \text{ mm}.$$

It means, at measuring distance of 0.5 mm, the optical fiber can receive infrared radiation from the spot diameter of 0.63 mm.

To prevent the undesired infrared radiation such as temperature of chip or surrounding heat getting through the optical fiber, the measuring distance, t was set by 0.5 mm. 0.5 mm was chosen as its measuring distance, t because of its spot diameter, d_s which 0.68 mm are adequate to cover the major surface area of cutting edge of tool.

3.3.6 Condenser

Infrared radiation wave tends to refracted to the surroundings. The refracted waves can cause energy lost (Ahn, 2006). An energy lost will gives a less dense infrared radiation. At lower temperature, the infrared detector hard to detects infrared radiation due to low intensity of infrared radiation. In this pyrometer, BaF₂ lens is used to condense the infrared rays radiated from the optical fiber before they are accepted by the infrared detector.

Table 3.4: Specifications of BaF₂ condenser

Specifications	Value
Diameter, d_L	12.7 mm
Focal length, f	25 mm +/- 2%
Transmission range, μm	0.15 - 12
Refractive index	@ 0.265 μm , $n = 1.51217$ @ 10.3 μm , $n = 1.39636$
Density, g/cm^3	4.89
Melting point, $^\circ\text{C}$	1386

3.3.7 Amplifier

The photocell used in this pyrometer gives out a current instead a voltage. This current changed to a voltage form by differences in electric field before being captured by the digital oscilloscope as an analog signal. Unfortunately, the voltage is significantly weak as the scale range is in millivolt thus it needs an amplifier to amplify the signal. Furthermore, the voltage output is in high speed as the photocells response speed is extremely fast. Therefore, it is capable to measure cutting edge temperature of end mill tool at high speed revolution. The response performance of the conversion amplification circuit should be better than the response speed of the infrared detectors to prevent delay in signal delivery. Figure 3.11 shows the schematic diagram of amplifier for InAs and InSb photocells. InAs and InSb's output current are converted to voltage and amplify with the conversion amplification circuit as shown in Figure 3.11. Its respective response speed are shown in Table 3.5.

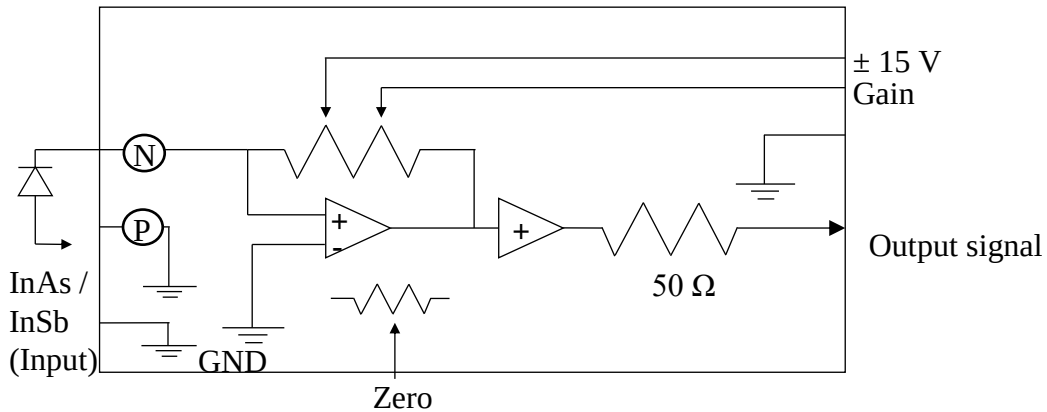


Figure 3.11: Block diagram of InAs and InSb amplifier (Hamamatsu, 2017)

Table 3.5: Technical specifications of amplifier

Parameter	C4159-01	C4159-05
Applicable detector	InSb (dewar type) (P5968-060, P5968-100)	InAs (dewar type) P7163
Frequency response	100 kHz	15 kHz
Time response	0.01 ms	0.06 ms

Based on Table 3.5, the response speed of the overall infrared detector setup is expected to reach limit at a speed of 0.01 ms despite the original response speed of photocells are 0.001 ms.

3.4 Materials and methods

3.4.1 Cutting edge temperature and cutting force measurement

Referring to previous Figure 3.2, an infrared radiation is emitted at the cutting edge of cutting tools. As infrared waves behaves like a light, it can travel through the optical fibre. Then it passes through a condenser to condense the infrared radiation before entering photocell. Infrared detectors (InAs and InSb) in the photocell captures the infrared waves and convert it to voltage output using an amplifier. Whereas cutting force from the cutting process is obtained from the dynamometer. The experimental setup is shown in Figure 3.12. Dynamometer is mfounted on the milling table as shown in Figure 3.12. The experiment is conducted by comparing cutting speeds and cutting depths with respect to its cutting edge temperature and cutting force respectively.

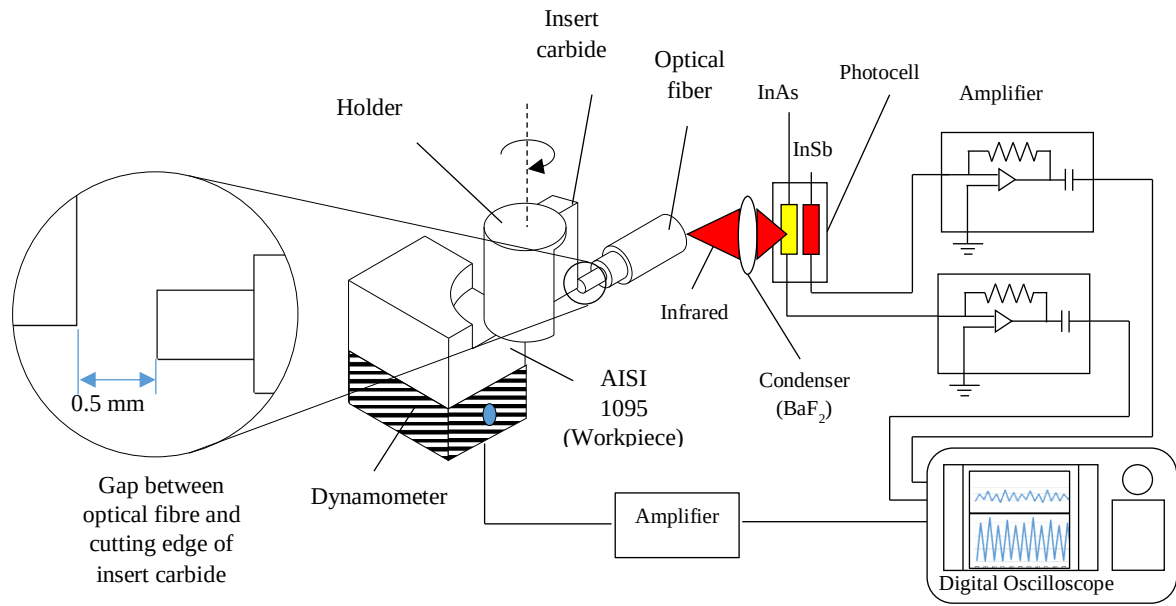


Figure 3.12: Experimental setup of cutting edge temperature and cutting force measurement

3.4.2 Preparation of workpiece

Table 3.6 shows the properties of the carbon steel AISI 1095. AISI 1095 is chosen as a workpiece material as it is commonly used in manufacturing industries. This workpiece is prepared in a shape shown in Figure 3.13.

Table 3.6: Properties of carbon steel AISI 1095

Mechanical properties	AISI 1095
Hardness, Brinell	192
Tensile strength, Ultimate (MPa)	656.7
Yield strength (MPa)	379.2
Elongation (%)	13
Reduction in area (%)	20.6
Density, ρ (kg/m ³)	7700 – 8030

Table 3.6 continued

Young's modulus, E (GPa)	190 – 210
Poisson's Ratio, ν	0.27 – 0.30
Specific heat capacity, C_p (J/Kg-K)	480
Thermal conductivity, k (W/m-K)	51.9
Chemical composition	Content
Carbon (C)	0.90 – 1.03%
Manganese (Mn)	0.30 – 0.50%
Phosphorus (P)	0.04% (Max)
Sulphur (S)	0.05% (Max)

**Figure 3.13:** Shape of AISI 1095's work material

3.4.3 Cutting tool material

The selection of cutting tool material was based on the mechanical properties of AISI 1095. For this experiment, an end milling process was selected. Therefore, end mill single flute was chosen. It is easier to observe the cutting temperature and cutting force's profile developed in the digital oscilloscope by analysing single carbide only. Insert material is made of carbide which is commonly used in the manufacturing industry to machine an AISI 1095 carbon steel. Table 3.7 shows the specification of end mill insert carbide tool.

Table 3.7: Specification of end mill insert carbide tool

Specification	Details
Cutting edge angle	90 ⁰
Toolholder material	Steel
No. of inserts	1
Insert Shape	Parallelogram
Series or model	XP-90C
Insert size type	1003
Material of Insert	Carbide coated with TiCN
Overall length	110 mm
Diameter	20 mm

3.4.4 Machined length for one cutting pass

Consecutive cutting pass was performed for this experiment to obtain the cutting profile. Theoretical calculation of machined length of the workpiece is important so that the total machined length after successive passes can be determined. The initial point of cutting process is begin when the cutting edge touches the edge of the workpiece where the distance from its center to the workpiece edge perpendicular to the feeding direction.

$$L = \sqrt{r^2 - (r - w)^2} \quad \text{Equation 3.12}$$

The cutting ends when cutting tool's centre reaches the position of the other end of workpiece edge that are perpendicular to the feeding direction. Hence the machined length (ML) in one pass is:

$$ML = L + L_1 \quad \text{Equation 3.13}$$

In this experiment, the cutting parameters are as below:

Radius of cutting tool = 10 mm

Radial depth of cut = 2 mm

Length of workpiece = 34 mm

Thus, the machined length for one cutting pass is;

$$L = \sqrt{10^2 - (10 - 2)^2} = 6 \text{ mm} \quad \text{Equation 3.14}$$

$$ML = L + L_1 = 34 \text{ mm} + 6 \text{ mm} = 40 \text{ mm} \quad \text{Equation 3.15}$$

For determination of relationship between cutting temperature, cutting force and cutting depth, the data was recorded for single cutting pass only, which is 40 mm. In order to prevent bias in data selection, each experiment are using new insert carbide.

Meanwhile, for determination of wear rate, tool wear and cutting force were measured after tenth cutting passes. Total machined length for each set of data is 400 mm. Tool wear experiment will be discussed further in chapter 4.

3.4.5 Type of milling machine used

There are two machines were used for the cutting experiment which are medium speed milling machine and high speed milling machine in order to perform the experiment ranging from 540 RPM (medium speed cutting) to 40,000 RPM (high speed cutting).

3.4.6 Medium speed milling machine



Figure 3.14: DMTG X6325 Milling machine (Vertical)

A vertical machining center was used as a milling machine for the experiment as shown in Figure 3.14 and its specification is listed in Table 3.8. The machining mode for vertical is manual meanwhile the horizontal mode is automatic.

Table 3.8: Specification of milling machine

Specifications of Model:	X6325
Table size (mm)	254×1270254×1370
Long travel (mm)	850/950
Cross travel (mm)	420
Verlical travel (mm)	420

Table 3.8 continued

T-slot no. and size	3×16
Ram travel (mm)	470
Distance from spindle to table surface(mm)	0 ~ 405
Spindle taper	R8(standard)ISO30/ISO40(optional)
Spindle travel (mm)	127
Spindle speed (rpm)	65 ~ 4500
Auto quill feed (mm/rev)	0.04/0.08/0.15
Spindle motor (kW)	2.25
Head swivel	90°
Head tilting	45°
Dimension of package (mm)	1516×1550×2080

3.4.7 High speed milling machine

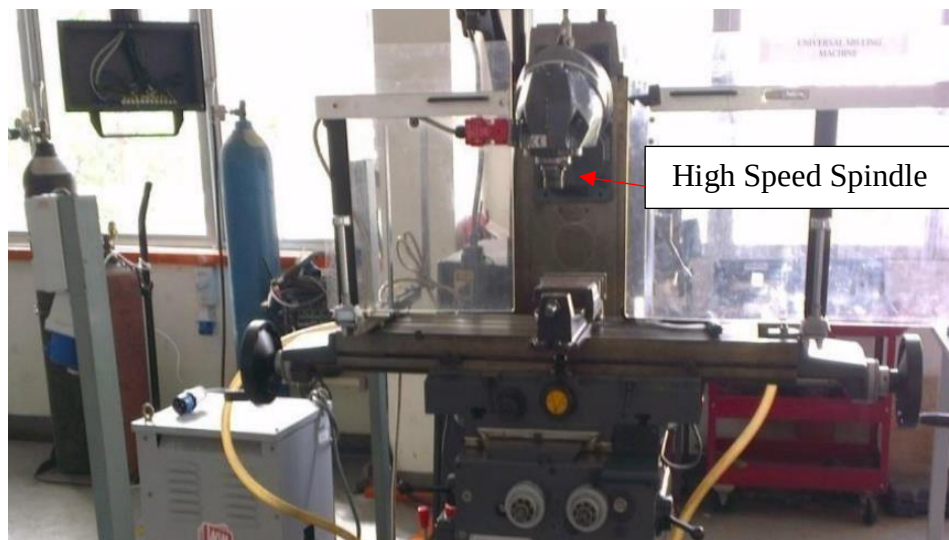


Figure 3.15: Vertical milling machine installed with High Speed Spindle



Figure 3.16: High Frequency Spindle HS-2550



Figure 3.17: Speed Controller for High Frequency Spindle HS-2550

Table 3.9: Specifications of High Speed Spindle HS-2550

Specifications	Value
RPM	5000 – 40000
Max Output (W)	410
Max Torque (NM)	0.54
Max chuck (mm)	6
Axial Runout (mm)	0.005 (max)
Accessory chuck (mm)	4 – 6
Weight (kg)	3.7

3.4.8 Digital oscilloscope

Data acquisition device used in this experiment is digital oscilloscope. For calibration process, a sample rate was set to 100 ms interval mentioned in previous chapter. The sample rate for cutting experiment need to be changed to appropriate sample rate as the cutting tooth revolution's frequency are shorter than 100 ms.

3.4.9 SPG optical microscope

The development of cutting tool wear throughout the cutting process experiment is observed through the microscope. The SPG microscope is capable to measure the flank wear at micrometer unit. It has total magnification level of 4X, 10X, 50X, and 100X.



Figure 3.18: SPG optical microscope 100X

3.4.10 Kistler dynamometer

A dynamometer was used to determine the cutting force component. This dynamometer contains a piezoelectric transducer which produces a current when a force is applied into it. The dynamometer is capable to detect force from three dimensional axis. The dynamometer was mounted on top of machining table as shown in Figure 3.19 and optical fiber holder was installed at the overarm of milling machine as shown in Figure 3.20.

Based on Figure 3.19, the 14 M8 x 1.25 threaded holes are provided on the outer surface of cover plate for the purpose of clamping the workpiece. A workpiece need to be screwed on the dynamometer to achieve good mechanical coupling so that the force sensor can detects the force applied accurately. A metal cover plate is installed in between workpiece and dynamometer for to prevent dynamometer from accidentally get damaged by cutting tools.

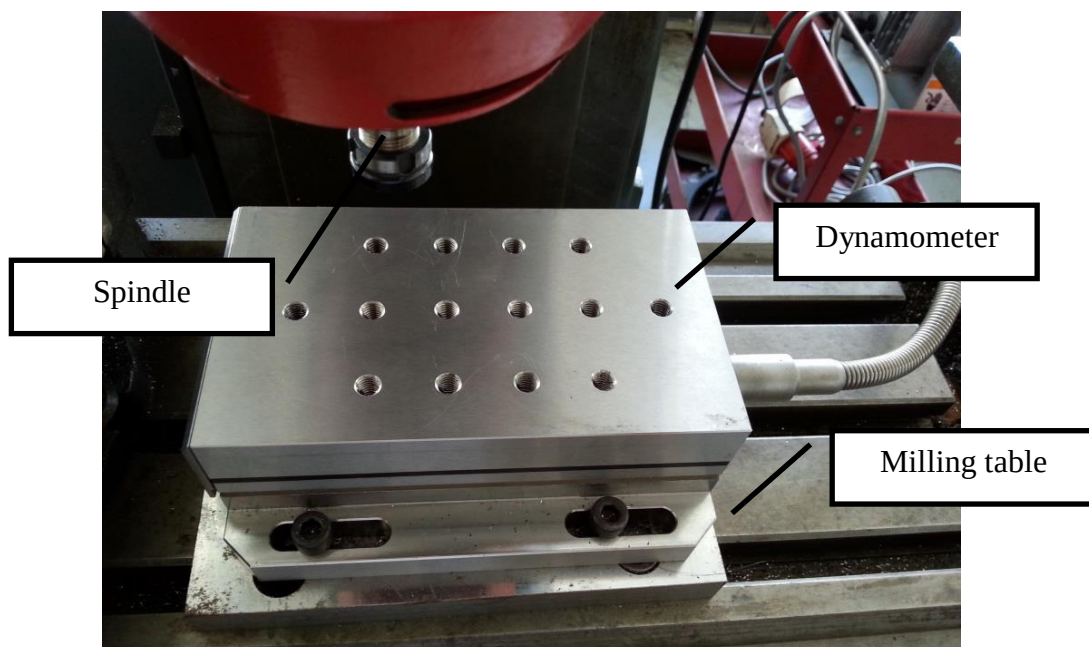


Figure 3.19: Kistler dynamometer mounted on milling table

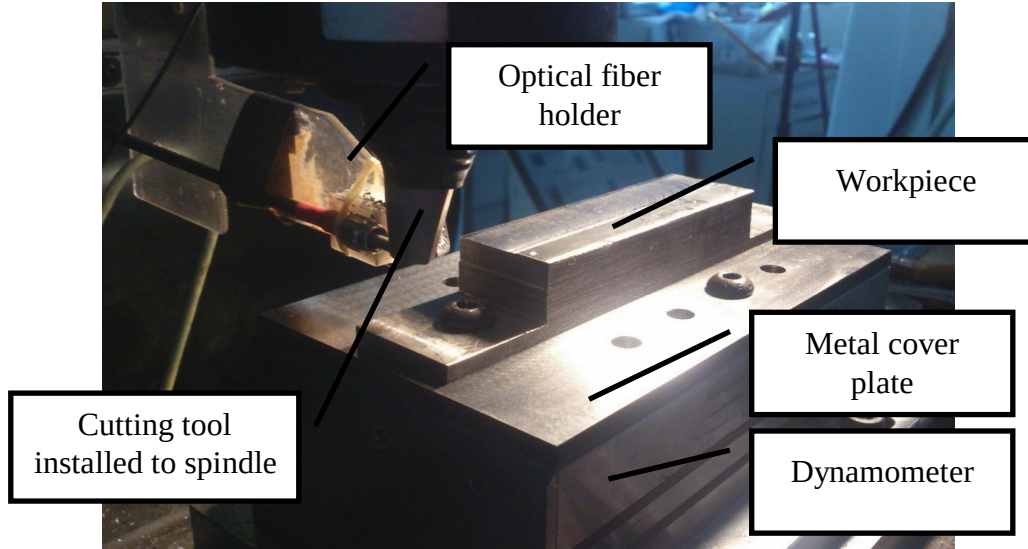


Figure 3.20: Workpiece and metal cover plate was screwed on top of dynamometer

3.4.11 Analysis of cutting parameters

Each cuts performed by cutting tools will makes a pyrometer and dynamometer to produce an electrical current, which is converted to voltage by the amplifier and recorded by digital oscilloscope. Digital oscilloscope will display a recorded voltage reading in a form of graph. Voltage reading from cutting temperature channel and cutting force channel represents cutting profile of the cutting processes. Equation 3.16 is the equation used to obtain average reading of each channel.

Average of output voltage,

$$V_{avg} = \frac{V1+V2+V3+\dots Vn}{n} \quad \text{Equation 3.16}$$

Where,

V_n = value of output taken during machining, (V)

n = number of samples

Cutting speed selection is important for this experiment. It is based on the cutting feed designed by the manufacturer, Indexa Seiki for insert carbide which is in a range of 0.1 to 0.3 mm per tooth. For consistency in parameters, 0.1 mm per tooth was selected throughout whole experiment. Cutting speed is determined by using Equation 3.17 and different table speed is shown in Table 3.10.

$$\text{Cutting speed, } V = \frac{\pi D N}{1000} \text{ (m/min)} \quad \text{Equation 3.17}$$

Where,

N = rotational speed, (rev/min)

D = diameter of cutting tool, (mm)

$$\text{Feed speed, } V_f = F_z \times Z \times N \quad \text{Equation 3.18}$$

Where,

F_z = feed per tooth, (rev/min)

Z = number of teeth

N = rotational speed (rev/min)

Take an example, for a cutting tool with 20 mm diameter revolves at 4500 rpm, the table speed should move in 460mm/min in order to achieve 0.1 mm/tooth.

Cutting tools RPM = 4500 RPM

= 75 rev/s or 0.0133 second needed for a tooth to complete revolute

Table speed = 460 mm/min

= 7.6 mm/s

Feed per tooth

= Table Speed x Cutting tools' RPM

= 7.6 mm/s x 0.0132s/tooth

= 0.1 mm/tooth

Table 3.10 shows an example of theoretical calculation for the rest of different cutting speed and table speed for medium cutting speed.

Table 3.10: Suitable table speed for different cutting speed

Manufacturer: Indexa-Seiki		Insert (s)	Table Speed(mm/min)		Actual feed/tooth	
Optimum (feed/tooth) from manufacturer	RPM, n (min ⁻¹)	z	Min.	Max.	Min.	Max.
0.10 - 0.30	550	1	55	160	0.10	0.29
	1500	1	150	430	0.10	0.29
	2200	1	230	670	0.10	0.29
	3000	1	300	870	0.10	0.29
	4500	1	460	1350	0.10	0.29

Calibration of pyrometer is based on relationship between voltage produced by pyrometer with its corresponding temperature by thermocouple. Calibration curve can be obtained by forming linear approximation polynomial correction in Equation 3.19.

$$\Delta T = \sum_{n=0}^n a_n V^n \quad \text{Equation 3.19}$$

Where,

ΔT = temperature change,

a_n = Coefficient, V^n = Voltage change

For this cutting performance experiment, carbon steel AISI 1095 was chosen as a material of workpiece. The workpiece are not limited to AISI 1095, the workpiece can be chosen from other material such titanium, wood, alloy or a rare material like TiAl6V4. Carbon steel are chosen as it is widely available and frequently used in the machining industry. Similar case are also applied to type of cutting tools. The tools can be changed with ceramic cutting tools, or diamond cutting tools.

In this experiment, the cutting experiments are divided into two main group, which are low cutting speed, and high cutting speed. The experiments subdivided into:

- i) Influences of cutting depth on cutting edge temperature and cutting force
- ii) Influences of cutting speed on cutting edge temperature and cutting force
- iii) Influences of extensive cutting length on cutting edge temperature and cutting force.

High cutting speed experiment was carried out in order to test the capability of developed pyrometer to detect cutting temperature at high cutting speed.

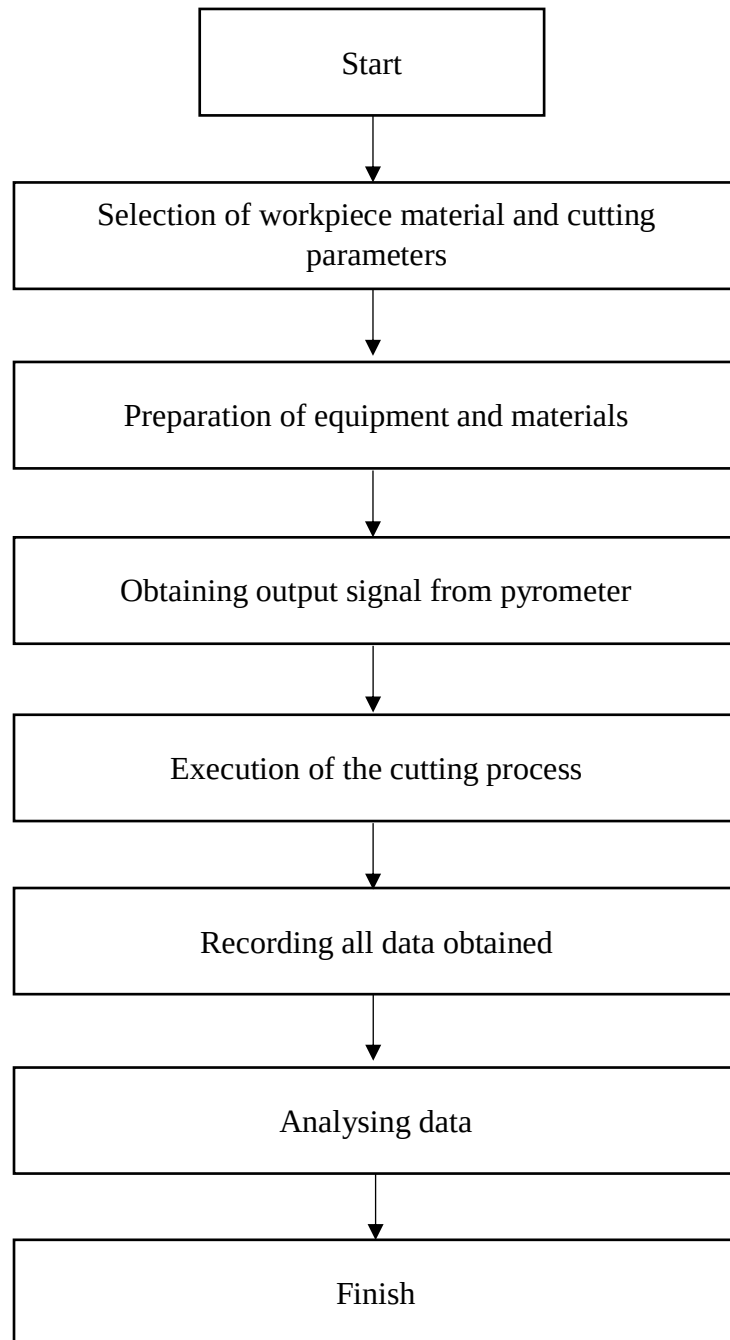


Figure 3.21: Flow chart of utilizing the developed pyrometer for cutting process experiment

3.4.12 Cutting process profile

By referring to Table 3.11, there are three main manipulated variable which are depth of cut, cutting speed and cutting length. Depth of cut are divided into two dimensions namely radial depth of cut, and axial depth of cut. Figure 3.22 shows the position of depth of cut at radial and axial distance. Cutting speed variable is dependent on tool's diameter, and spindle rotation speed as been explained in previous chapter. Meanwhile, cutting length is defined as the distance of feed done on the workpiece by the cutting tool.

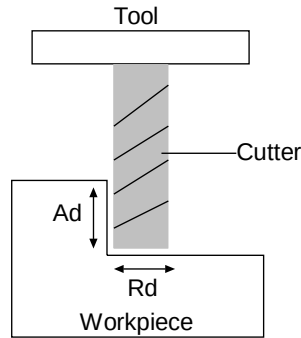


Figure 3.22: Position of radial depth of cut (R_d) and axial depth of cut (A_d)

By referring Table 3.11, cutting is done with different radial and axial depth of cut while the feed per tooth is kept at a constant value, 0.1 mm. The experiment is repeated with cutting speed at 33 m/min, 91 m/min, 142 m/min, 183 m/min, and lastly 284 m/min. This means that there were 5 sets of cutting temperature waveform and the value of $\ln A_s$ and $\ln S_b$ voltage can be obtained with the help of Xviewer software. By substituting the value of $\ln A_s/\ln S_b$ output voltage ratio into the calibration Equation 3.19, the cutting temperature can be obtained. From these 5 sets of data, the effect of cutting speed, radial and axial depth of cut towards cutting temperature can be seen. The other experiments will be explained in the next several section.

3.4.13 Cutting parameters for medium cutting speed and high cutting speed experiment

The developed pyrometer is then utilized for conducting an experiment on the effect of variable cutting speed, depth of cut and cutting length on cutting temperature, cutting force and wear mechanism.

Generally, for medium cutting speed, there are 4 sets of experiment conducted which are:

1. Study of cutting temperature and cutting force at different axial depth, A_d .
2. Study of cutting temperature and cutting force at different radial depth, R_d .
3. Study of cutting temperature and cutting force at different cutting speed.
4. Study of cutting temperature, and wear mechanism at prolonged cutting length.

Each of these experiment are carefully planned with specific parameter so that the feed per tooth are fixed at 0.1 mm. The cutting length for wear mechanism study is set to 6000 mm so that the wear are developed steadily at constant rate until it reaches irregular wear or tool failure. Feed rate is the table speed, it indicates the speed of workpieces enters the cutting process.

Table 3.11: Cutting parameters for study of cutting temperature and cutting force at different axial depth, A_d

Tool diameter	Cutter type	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R_d (mm)	A_d (mm)	Cutting length (mm)
20 mm	Indexable	1	0.1	33	55	1.0	0.2	40
				91	150		0.4	
				142	230		0.6	
				183	300		0.8	
				284	460		1.0	

Table 3.12: Cutting parameters for study of cutting temperature and cutting force at different radial depth, R_d

Tool diameter	Cutter type	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R_d (mm)	A_d (mm)	Cutting length (mm)
20 mm	Indexable	1	0.1	33	55	2.0	0.5	40
				91	150	4.0		
				142	230	6.0		
				183	300	8.0		
				284	460	10.0		

Table 3.13: Cutting parameters for study of cutting temperature and cutting force at different cutting speed

Tool diameter	Cutter type	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R_d (mm)	A_d (mm)	Cutting length (mm)
20 mm	Indexable	1	0.1	33	55	8	0.5	40
				91	150			
				142	230			
				183	300			
				284	460			

Table 3.14: Cutting parameters for study of cutting temperature, and wear mechanism at prolonged cutting length

Tool diameter	Cutter type	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R_d (mm)	A_d (mm)	Cutting length (mm)
20 mm	Indexable	1	0.1	284	460	1.0	1.0	6000

Parameters used in the previous section is chosen for medium cutting speed. In order to achieve high speed machining, the chuck and spindle of milling machine is then upgraded with by installing the high speed spindle with a high speed controller (in previous Figure

3.15 and Figure 3.16). For high cutting speed, there are 3 sets of experiment conducted which are:

1. Study of cutting temperature at different radial depth, R_d and cutting speed
2. Study of cutting force at different radial depth, R_d and cutting speed.
3. Study of machined length on flank wear rate.

A tool diameter for high speed machining is 6 mm as the chuck size of high speed spindle only can be fitted with 6 mm tool diameter. The feed per tooth is fixed constantly at 0.03 mm. The feed rate is increased in accordance with cutting speed in order to achieve 0.03 mm/tooth feed.

Table 3.15: Cutting parameters for cutting edge temperature experiment (High speed machining)

Tool diameter	Cutter type	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R_d (mm)	A_d (mm)	Cutting length (mm)
6 mm	Solid End Mill Cutter	1	0.03	188	300	1.0	1.0	40
						2.0		
						3.0		
				377	600	1.0		
						2.0		
						3.0		
				565	900	1.0		
						2.0		
						3.0		
				754	1200	1.0		
						2.0		
						3.0		

For cutting force experiment, an additional sets of data for cutting speed of 283, 471, and 660 m/min were added into the sets of high cutting speed experiment to obtain a clear trend of cutting force. Cutting force measurement for high speed machining is a tough process as only a small amount of force differences can be distinguished due to feed per

tooth is 0.03 mm, thus the chip load is extremely small and cutting energy requirement is significantly small (Neugebauer et al., 2011). The tool diameter, cutter type, number of tooth, and feed per tooth for second and third of high cutting speed experiment in Table 3.16 and Table 3.17 is fixed as same as in Table 3.15.

Table 3.16: Cutting parameters for cutting force experiment (High speed machining)

Tool diameter	Cutter type	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R _d (mm)	A _d (mm)	Cutting length (mm)
6 mm	Solid End Mill Cutter	1	0.03	183	300	0.5	1.0	40
						1.0		
						1.5		
						2.0		
				283	450	0.5		
						1.0		
						1.5		
						2.0		
				377	600	0.5		
						1.0		
						1.5		
						2.0		
				471	750	0.5		
						1.0		
						1.5		
						2.0		
				565	900	0.5		
						1.0		
						1.5		
						2.0		
				660	1050	0.5		
						1.0		
						1.5		
						2.0		
				754	1200	0.5		
						1.0		
						1.5		
						2.0		

Table 3.17: Cutting parameters for machined length experiment on flank wear (High speed machining)

Tool diameter	Cutter type	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R _d (mm)	A _d (mm)	Cutting length (mm)
6 mm	Solid End Mill Cutter	1	0.03	377	600	1.0	1.0	4500

3.4.14 Sample rate

Number of quantity of data stored over time defines sample rate of data. High revolutions of cutting tools influence a range sample rate. The highest RPM of cutting tool that was selected is 40,000 RPM which is in a minute, there are 40,000 revolution of cutting tool. For one complete revolution it takes:

Time taken for one complete revolution of cutting tool in 40,000 RPM

$$= 1/(40,000/60)$$

$$= 0.0015 \text{ seconds/revolution}$$

Which means, the digital oscilloscope should be capable to detect at 1.5 milliseconds. Unfortunately, 1.5 milliseconds are suitable only to detect cutting profile peaks meanwhile in-between peaks is not detected. The situations worsens if the digital oscilloscope unintentionally not recording the peaks data but capturing in-between peaks. Therefore, a higher sample rate was selected to cater the problems. An extreme sample rate can be achieved by installing high speed acquisition module into digital oscilloscope.

3.4.15 Signal analysis and processing

The developed pyrometer gives out an electrical signal based on the infrared radiation intensity. For this experiment, the infrared radiation source are from the rotating of cutting tools' edge. The recorded signal by digital oscilloscope was analysed quantitatively in order to find a data trend, to discover useful information, modelling a data and inducing a conclusion from the experiment. Analysing a data requires a strategic step to ensure all data are correctly processed. Figure 3.23 shows the flowchart of data analysis from pyrometer and dynamometer data.

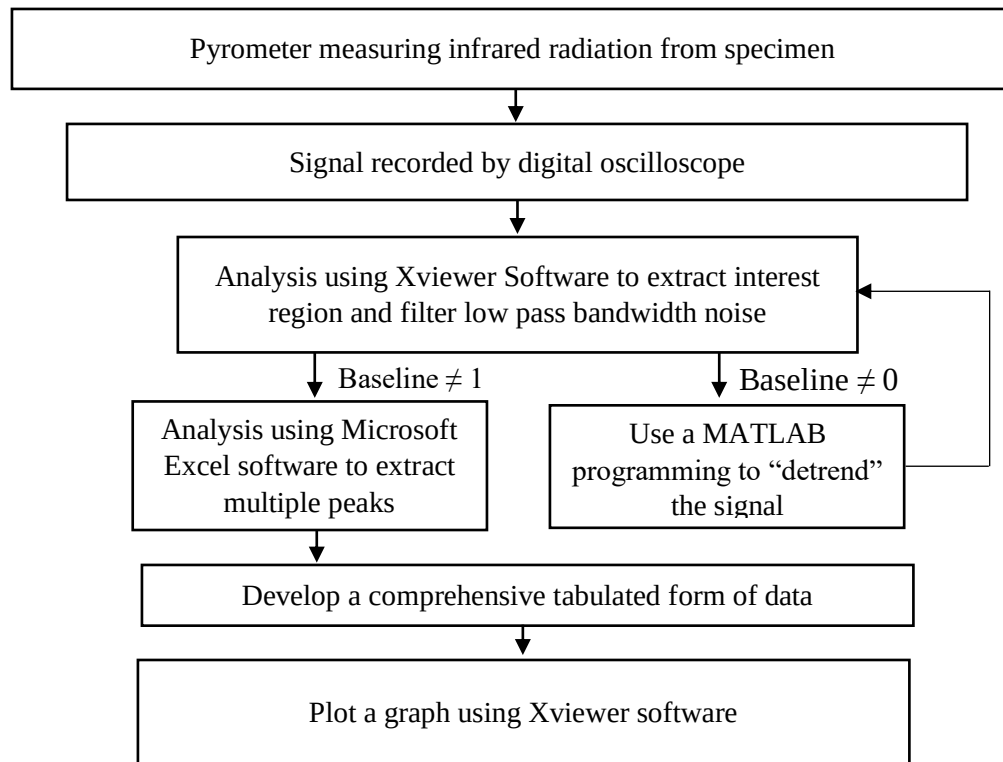


Figure 3.23: Flow of analysis of signal processing

3.4.16 Analysis software

Analysis of the data captured by digital oscilloscope was done by using computational approach. It is expected that a data recorded by digital oscilloscope is in extremely large sample where it might reach millions data, several software are used. There are three software mainly used in the analysis which are:

- 1) Xviewer
- 2) N-Graph
- 3) Microsoft Excel
- 4) Matlab

Each software has its owned unique capabilities as each software optimization for data analysis and display are different.

3.4.17 Xviewer software

Xviewer is a graphical software that provide a feature to visualize the similar graphical image displayed in the digital oscilloscope. This software is optimized by the Yokogawa manufacturer to generate a graphical waveform from millions of data in brief time. A saved data from the digital oscilloscope was transferred to Xviewer in a personal computer and analyzed. For this experiment, a several method are used to characterize the cutting profile. This software are also capable to reduce the unwanted noise that are exist in the generated waveform. As a result, an obtained signal data was filtered and more accurate.

3.4.18 Presence of erroneous in data obtained and its Solution

It is expected that the data obtained from the experiment will exhibit a signal noise which can cause an error in data value. If the signal are not condition and its baseline is not corrected, the reading of each data will be meaningless as there is no consistencies. This situation create an unreliable data of the cutting temperature and cutting force. Since the computational software recognized the voltage's value without recognizing the error, the value of the cutting temperature will skewed at a large range. The result of the analysis are possibly misleading.

Fortunately, these error can be corrected by using a smoothing technique that are commonly used in signal conditioning. A proper procedure of smoothing technique was planned as shown in Figure 3.24.

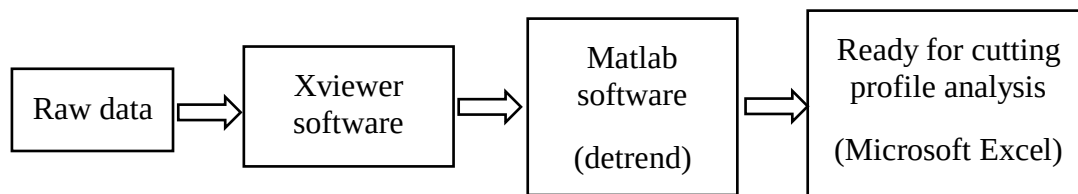


Figure 3.24: Flowchart of signal conditioning process used in this experiment

3.5 Summary

Pyrometer is successfully developed and commissioned. Both photocells sensor, InAs and InSb is working properly and capable to detects infrared emission during calibration process with high sensitivity. The data recorded by digital oscilloscope requires signal conditioning process as during commissioning, there are external noise presents and disturbs the signal level. Thus the signal recorded gave a parallax error as it was suspected

there are presence of transmission loss along the signal journey. In Chapter 4, a calibration data will be explained in detail and utilized for cutting experiment. A comprehensive signal conditioning and analysis technique will be introduced to ensure the project is reliable.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discussed about the calibration result, signal conditioning process, and performing a cutting edge temperature measurement using a developed pyrometer. An analysis of cutting profile such as the formation of peak signal and its relation to the motion of multiple successful cutting passes were also discussed in this chapter. Since the pyrometer are successfully developed, there are two sets of cutting performance experiment conducted that involve medium cutting speed and high cutting speed will be discussed. These experiments studies relationship between cutting edge temperature, cutting force, and flank wear.

4.2 Pyrometer calibration results

The signals recorded by digital oscilloscope are then transferred to Xviewer software to measure the voltage ratio of InAs to InSb. Its corresponding temperature of insert carbide are also compared with signal produced by photocells. Figure 4.1 shows the graph of InAs, InSb, and thermocouple temperature with respect to time. Meanwhile Figure 4.2 and Figure 4.3 shows a portion of InAs and InSb data that were zoomed in.

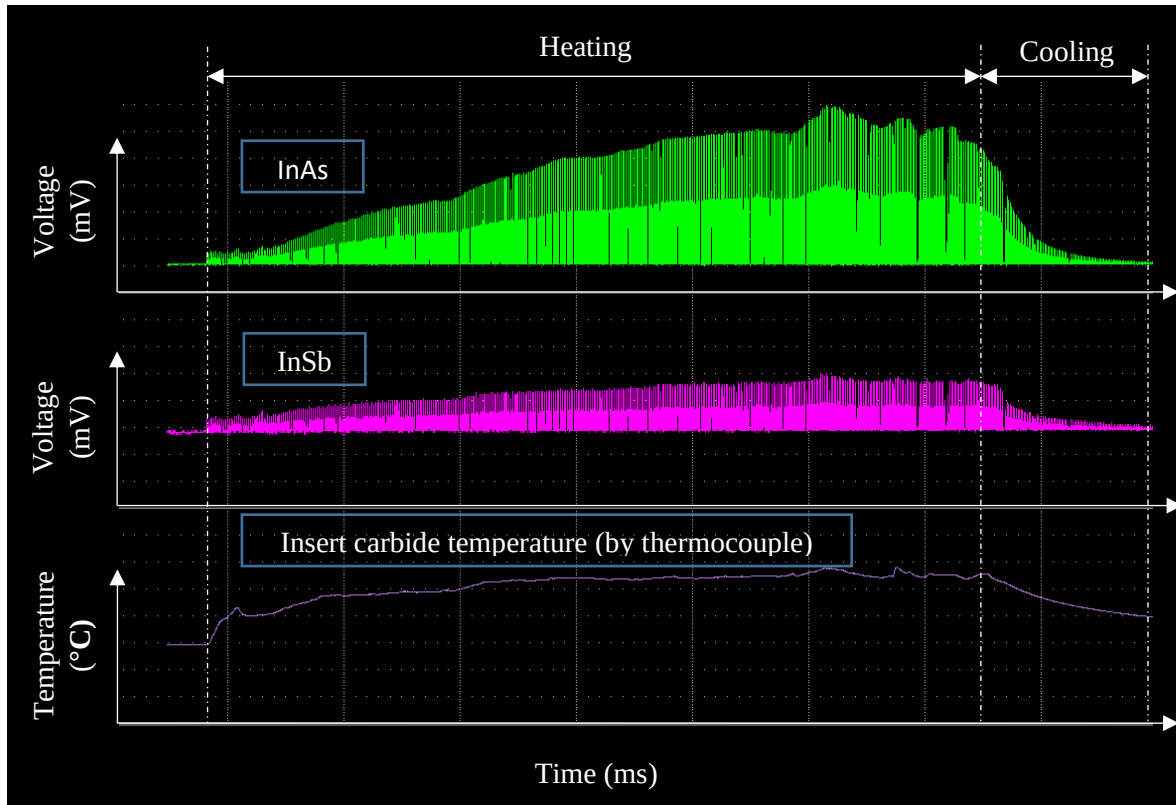


Figure 4.1: InAs, InSb and temperature of insert carbide displayed by digital oscilloscope

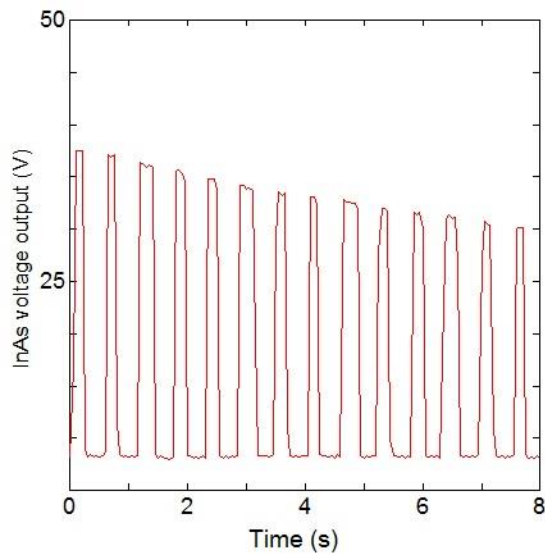


Figure 4.2: Temperature calibration profile from InAs during cool down

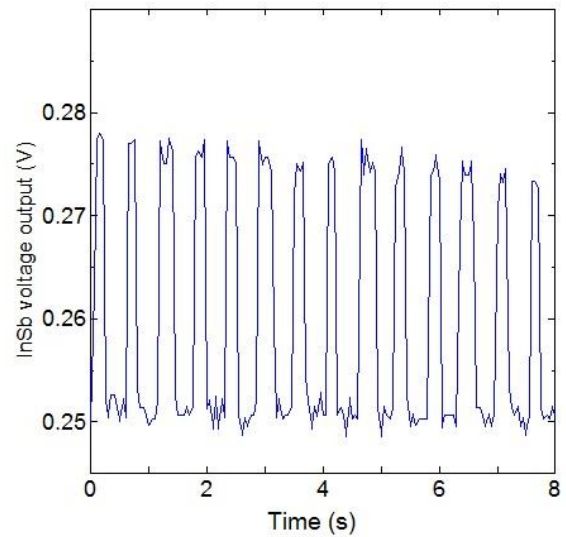


Figure 4.3: Temperature calibration profile from InSb during cool down

The ratio of InAs to InSb voltage are then plotted with respect to the temperature of insert carbide as shown in Figure 4.4. During calibration process, the insert carbide are heated using a butane torch. The highest temperature achieved of heated carbide is 910 °C. Thus, a calibration curve and its calibration equation are formed as shown below. Noted that this equation have similar form with previous Equation 3.19 mentioned in Chapter 3.

$$y = e^{5.258}x^{0.419} \text{ (where } y \text{ is temperature and } x \text{ is InAs/InSb ratio)} \quad \text{Equation 4.1}$$

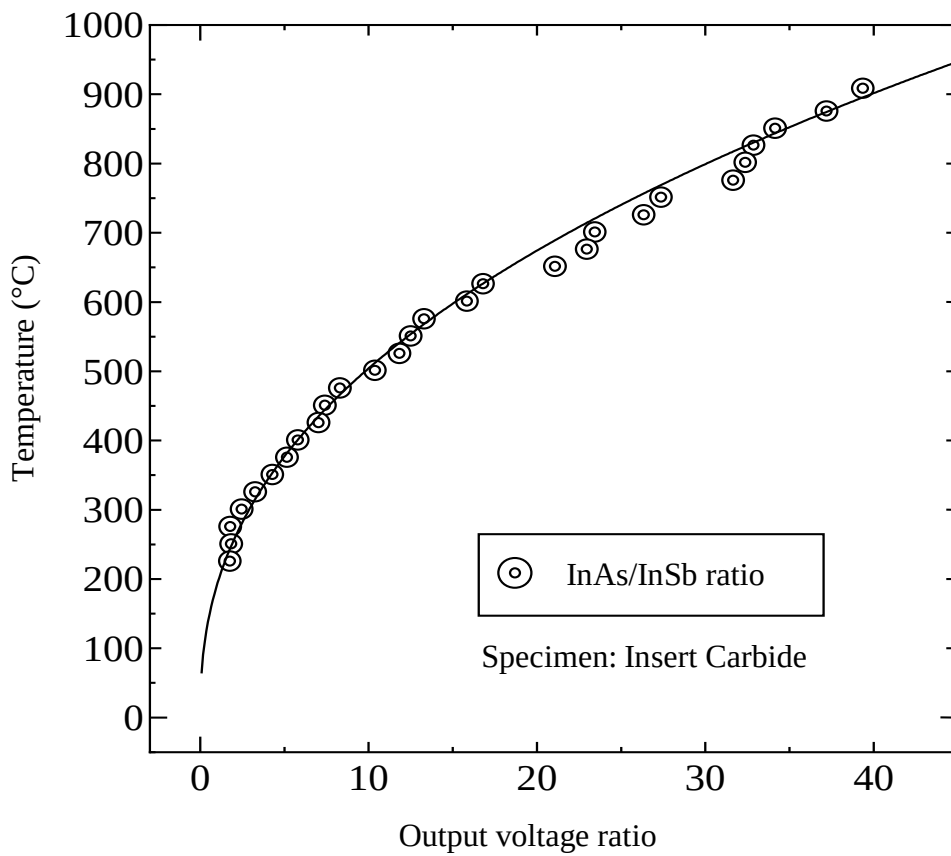


Figure 4.4: Graph of calibration curve

4.3 Results and discussion (Cutting profile analysis)

4.3.1 Xviewer: Extracting data

Technical analysis of an experiment should be nonbiased and contain an ample set of sample data to support a hypothesis. A biased set of data will caused a misleading conclusion postulated from the experiment. In this experiment, a signal produced by the pyrometer are not in stable reading. Certain wave peaks are significantly higher than its adjacent peaks.

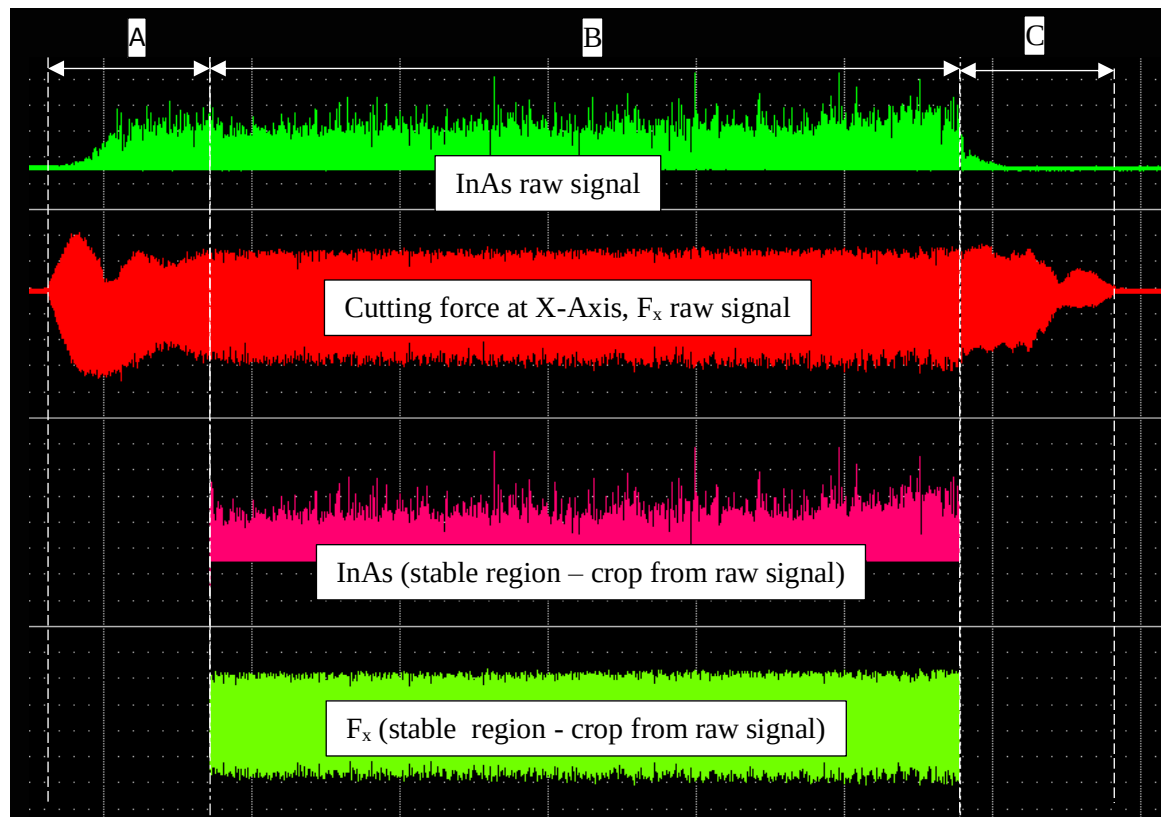


Figure 4.5: Reading of InAs photocell and Cutting Force (X-Axis)

In Figure 4.5, it is noticeably can be observed that the InAs raw voltage reading are fluctuating over the cutting process. Meanwhile, the cutting forces recorded by the dynamometer shows a consistency in trend. Referring to Figure 4.5, the data output from the

pyrometer and dynamometer can be divided into three main region which are initial cut (A), middle cut (B), and post middle cut (C). Region A is called as initial cut because the tool diameter are partially engage into the workpiece. Meanwhile, region B is where tool's diameter completely in contact with workpiece during cutting. Region C is called post middle cut as the cutting temperature starts to deplete, but the cutting force still exist. This is due to the cutting temperature produced at region C is too low for the pyrometer to detect the infrared eventhough the cutting process still ongoing. The fluctuating reading of cutting force at the C region are also originates from the residual vibration from the region B.

For the purpose of this experiment analysis, region A and C are not the main interest and region B will become the focus in the analysis as the reading are considerably stable.

4.3.2 Xviewer: Analysis of waveform based on peak-to-peak

For this experiment, a peak-to-peak between each successive cut are measured. The peak of the waveform resembles a maximum radiant energy detected by pyrometer after each cutting edge passes through the tip of an optical fiber. A screenshot of signal data loaded on Xviewer software are shown in Figure 4.6. Based on Figure 4.6, cursor 1 and cursor 2 is placed on each successive adjacent peak. By using analysis tool provided in Xviewer software, it is possible to obtain time gap between adjacent peak and its voltage value. Analysis tools that are used are 'Measure Waveform Parameter' and 'Measure Vertical and Horizontal Cursor'

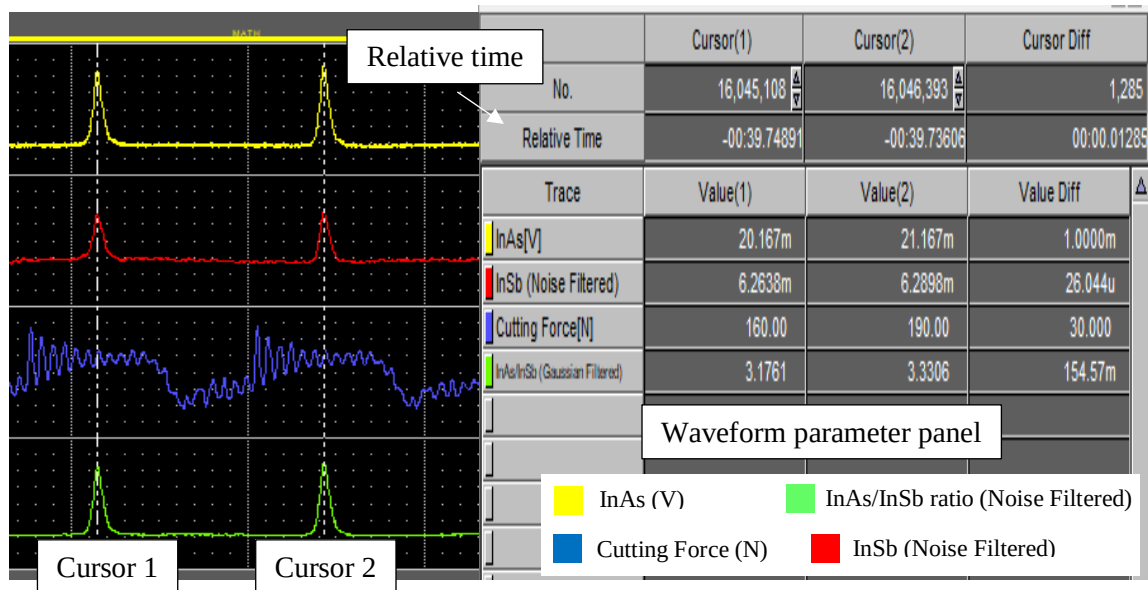


Figure 4.6: Measuring time relative between each peaks of data from pyrometer and dynamometer

These tools are used to measure the difference of time between cutting edge temperature and cutting force. The time are relatively to distance of cut and angle of tool rotation as explained in Section 4.3.14.

4.3.3 Systematic error in data: linear and nonlinear baseline waveform

A photocell used in the experiment is vulnerable to presence of noise. This is due to the high sensitivity of photocell and poor noise shield of internal wiring. Unstable current input will also affects the output signal of the photocells. These situations contribute to linear offset error as shown in Figure 4.7 and nonlinear offset error phenomenon of the ground voltage value of the output as shown in Figure 4.8. Linear offset error is exist due to the cooling effect of liquid nitrogen photocells's dewar is evaporates overtime. Meanwhile, nonlinear offset error might be from internal sources such as electrical motor and mechanical vibration of milling machine. Since the photocells connected by electronic circuit, thus the circuit inside the photocells are susceptible to pink noise which usually occur at low pass

bandwidth. Pink noise is unavoidable as the source are coming from external sources such as radio signal, radiation, and outer space.

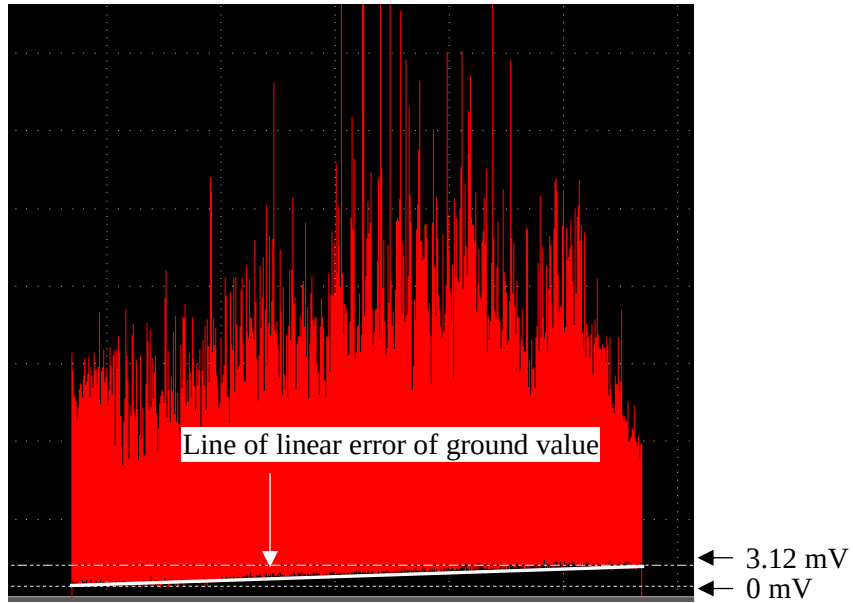


Figure 4.7: Linear ground value of InAs from the cutting experiment of 283 m/min

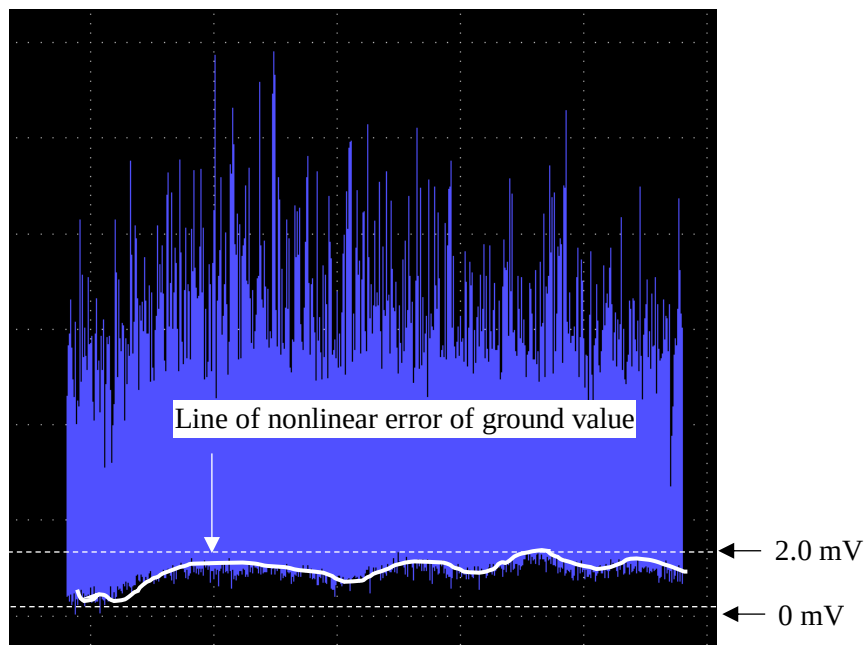


Figure 4.8: Nonlinear ground value of InSb from the cutting experiment of 283 m/min

4.3.4 Random error in Data: Flicker noise

From the conducted experiment, a noise can clearly be seen from both InAs and InSb sensor as shown in Figure 4.9. These noises is categorized as high frequency noise as the noise are oscillates at microseconds ranged.

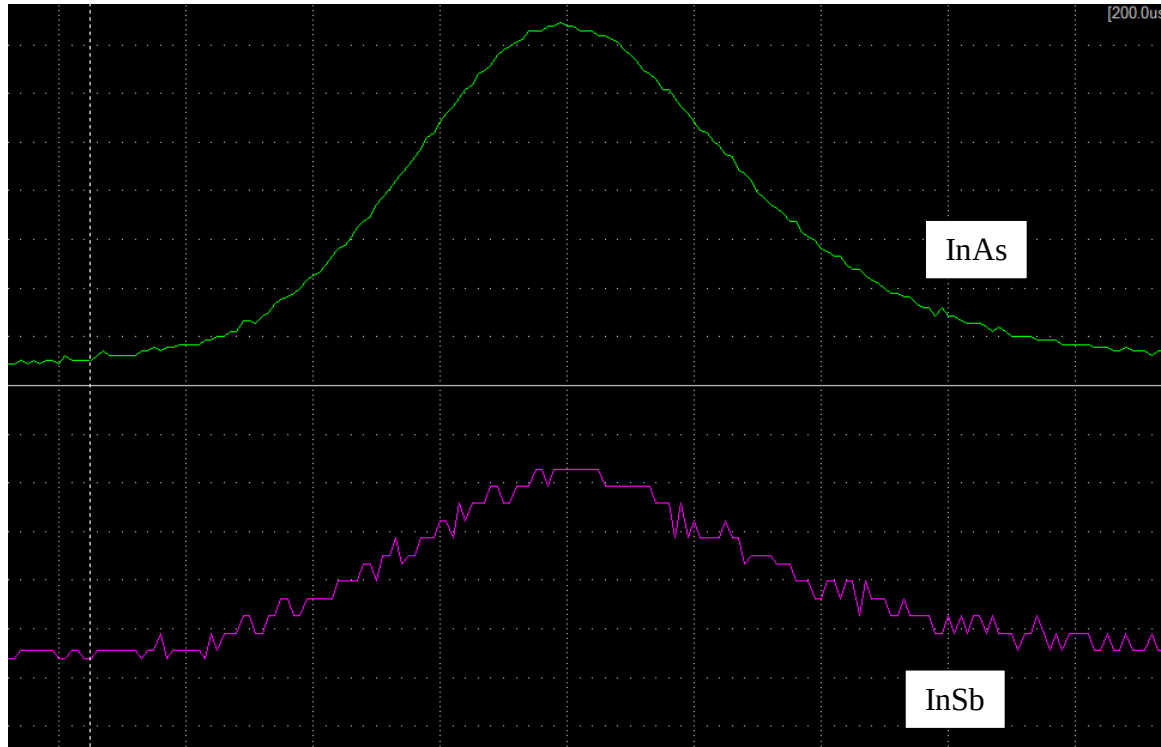


Figure 4.9: Jagged signal recorded by digital oscilloscope

4.3.5 Signal conditioning by Gaussian filter method

InAs and InSb photocells are susceptible to low and high bandwidth noise. Possible sources of high bandwidth noise in the factory are the vibrations from milling machine, rotary equipment, electromagnetic equipment and surging electrical power outlet while source of low bandwidth noise are from unconditioned power source. In this experimental setup, an Uninterruptible Power Supply (UPS) unit is installed to reduce high bandwidth

noise. The UPS contains a 1:1 ratio transformer and a backup battery to condition a power source. A signal from InAs and InSb detector cells have been conditioned further by Gaussian filter method to reduce low and high bandwidth noise (Figure 4.10 and Figure 4.11). Reducing the low bandwidth noise can increase the accuracy of the recorded data. InSb detector cells have higher sensitivity to noise than InAs due to its specific detectivity is lower than InAs. The signal recorded by dynamometer is clean and consistent. Therefore signal conditioning for dynamometer's signal are not required.

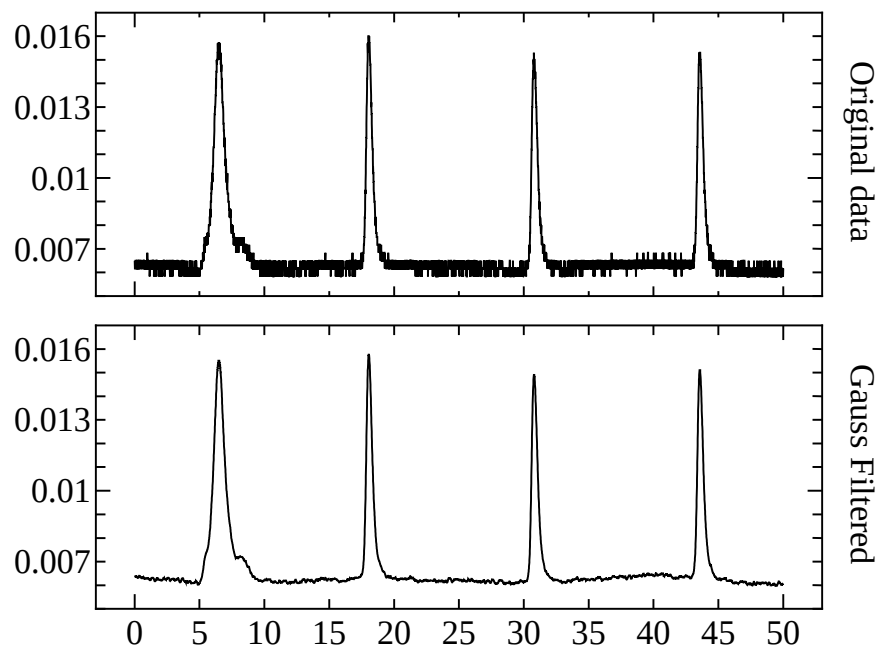


Figure 4.10: Output wave from InAs photocell

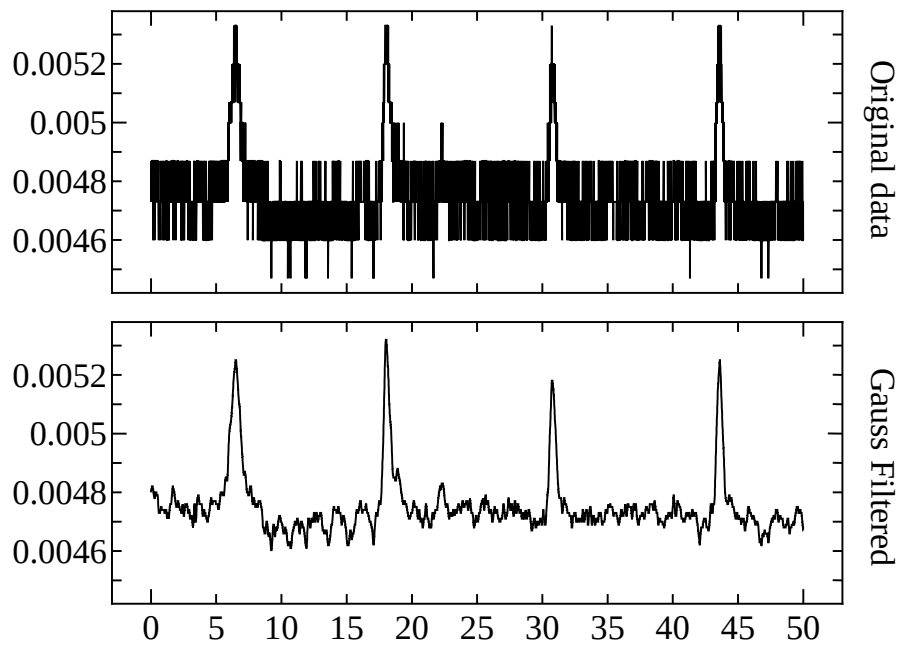


Figure 4.11: Output wave from InSb photocell

Figure 4.10 and Figure 4.11 shows the typical output waves of two-colour pyrometer during cutting experiment. The unfiltered data is drawn in the upper figure of each Figure 4.10 and Figure 4.11. Each pulse represents a heat passed through an optical fiber. The heat is emitted from the cutting edge of insert carbide. Photocells accept infrared waves based on its respective spectral response as discussed in Chapter 2. The period between each pulse is 11.7 ms. Each pulse represents one revolution of the cutting edge. By dividing voltage output from InAs (Figure 4.10) to InSb (Figure 4.11), voltage ratio is obtained. This voltage is converted to a temperature scale by referring to the calibration curve from previous Figure 4.4.

4.3.6 Detrend a Linear Baseline Error by using Matlab software

By referring to Section 4.3.3, those baseline systematic error can be corrected by using a numerical programming approach from Matlab software. Linear error of ground value was corrected by using a simple programming as shown below:

Matlab Scripts	Description
InAs = csvread('InAs from 95 WDF.csv')	→ Load a spreadsheet file
dt_InAs_Linear = detrend(dt_InAs_LinearError)	→ Detrend the baseline

4.3.7 Detrend a Non-Linear Baseline Error by using Matlab software

For non-linear error, it requires special technique to extract the nature of waveform trend. The baseline trend correction for each signal data was corrected by finding the fit line of the data trend. Following is the programming script used to detrend the baseline of InAs signal.

Matlab Scripts	Description
InAs = csvread('InAs WDF.csv')	→ Load a spreadsheet file
x = (1:length(InAs))'	→ Define the length of x-axis
polynum = 20	→ Define the degree of polynomial
[p,s,mu] = polyfit(x,InAs,polynum);	→ Set each parameter with corresponding data
f_y = polyval(p,x,[],mu)	→ Forming an equation to trace wavy baseline
dt_InAs= InAs - f_y	→ Removing wavy baseline from loaded file

Figure 4.12 shows the raw data of InAs signal that are zoomed in until the profile of cutting temperature pattern can be clearly seen. A baseline is drawn to visualize that the base error is exist in the data. This error affects the true peak value of cutting temperature profile.

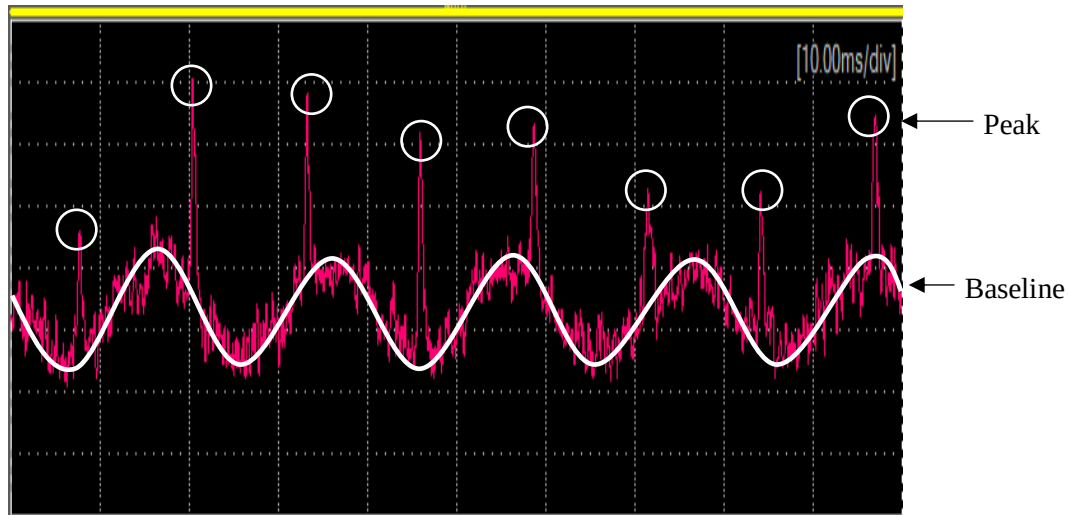


Figure 4.12: InAs waveform in Xviewer software

Figure 4.13 consists of three graphs of A, B and C. Graph A is the original data loaded into the Matlab software. Noted that the data is raw and unconditioned. Data of Graph A was imported from Xviewer software by linking both software using Microsoft Access Database software. Graph B is a process of drawing a harmonics wave line that are traced from the Graph A. The process of obtaining harmonics wave is possible by iteration of polynomial degree from number 1 until 50. A degree number of 20 is matched with the frequency of baseline harmonics wave and the amplitude. Graph C is a process of removing the non-linear baseline by subtracting the original data, Graph A with harmonics wave obtained from Graph B. As a result, a consistent baseline was obtained and thus systematic error is eliminated. The processed data can be interpreted further to determine the peak-to-peak value.

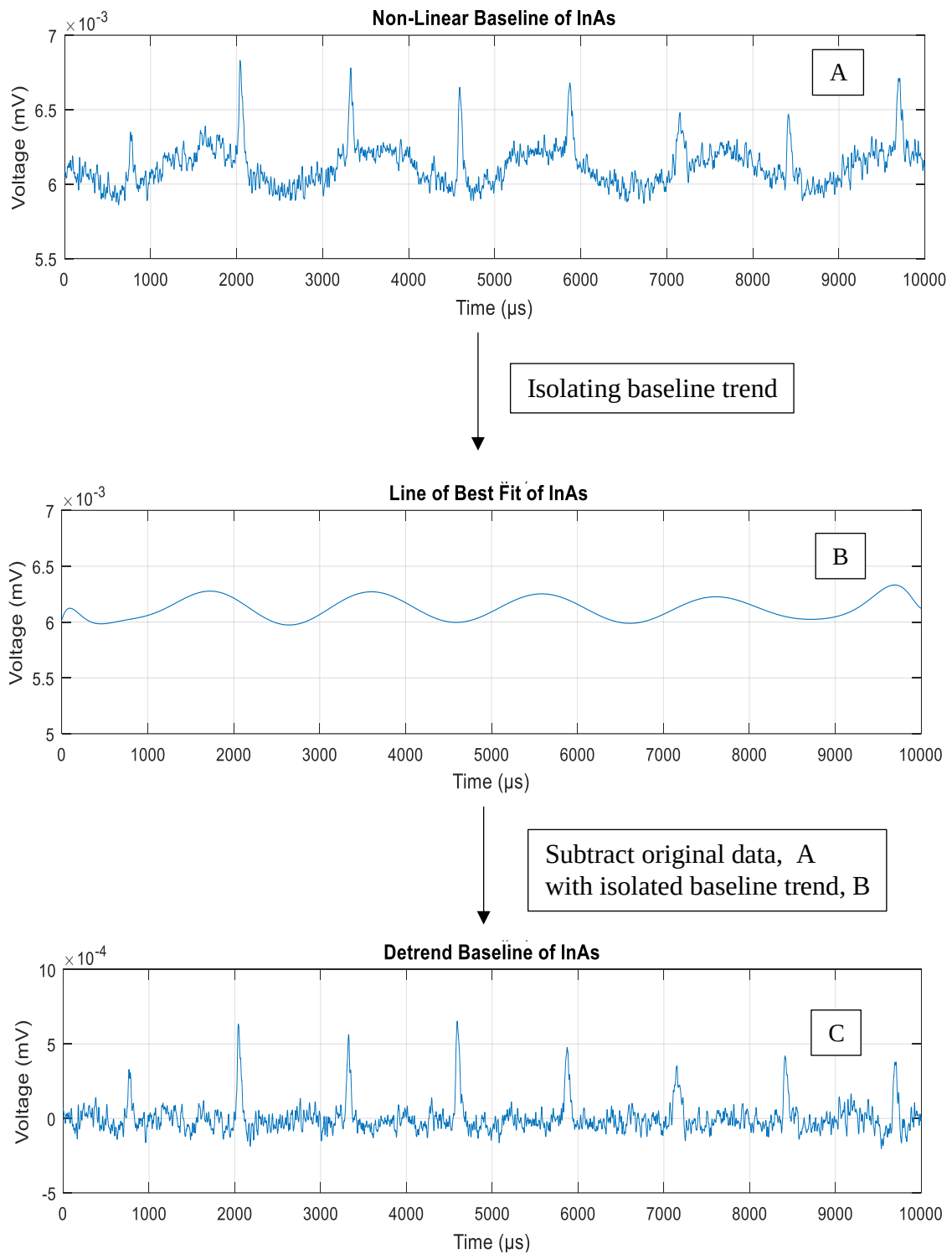


Figure 4.13: Data processing in Matlab

4.3.8 Extracting peaks value by using Microsoft Excel

The signal can be analysed after the process of signal conditioning and detrending data using Xviewer and Matlab respectively. Spreadsheet software are useful to filter the specific data from the photocells. Figure 4.14 shows the step taken in Microsoft Excel in extracting the peaks value.

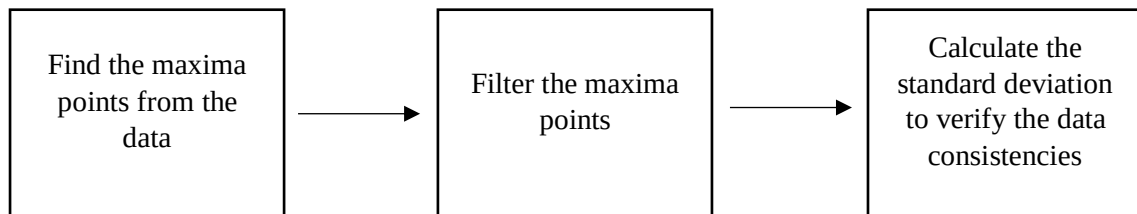


Figure 4.14: Steps in extracting peaks value

4.3.9 Maxima points of waveform

A signal recorded by digital oscilloscope was saved in a single entry data, which means each single data are recorded for one particular time. When it is plotted by Xviewer software, the data are seen like in a waveform. Basically, a waveform formed in Xviewer have critical points which is a repetitive local maxima. The local maxima point are called as a peak waveform as shown Figure 4.16. Measuring local maxima points for cutting experiments manually is time consuming, as each cutting experiments will produce approximately 20 million data. Time taken to extract the voltage value of each peak can be shorten by understanding the mechanism of critical point formation based on maxima and minima trend.

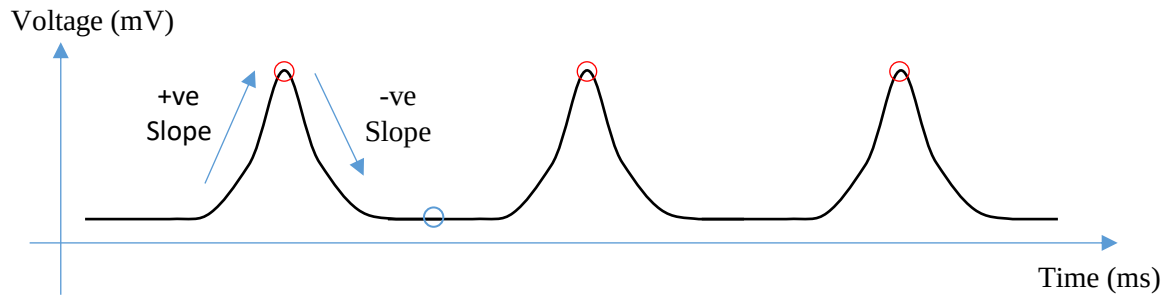


Figure 4.15: Illustration of typical signal generated by pyrometer

Type of waveform signal shown in Figure 4.15 is a unidirectional waveform. It is simplified waveform drawn based on actual cutting data. Based on Figure 4.15 example, there are three consecutive peaks. As the cutting edge of insert entering the spot diameter of optical fiber as illustrated in Figure 4.18, the reading of the voltage output from photocells starts to increase as the heat sources approaching the center of optical fiber's spot diameter. The increasing voltage will gives positive changes over time thus giving positive gradient or slope. As it reaches at top of the peaks, the gradient stays zero for a short brief of moment. The voltage onward begins to decrease over time and gives negative slope. Changes of gradient at short moment from positive to negative resembles existences of peak value.

Assuming that the waveform is in a function form, which is:

$$y = f(x) \quad \text{Equation 4.2}$$

By deriving it, it become Equation 4.3

$$dy/dx = f'(x) \quad \text{Equation 4.3}$$

dy/dx indicates the gradient at a particular point where if its positive value, it shows incline slope while negative value shows decline slope.

Of course, second derivatives of the function gives the characteristics of the local maxima and minima point.

$$d^2y/dx^2 = f''(x) \quad \text{Equation 4.4}$$

Unfortunately, using derivative method to identify the maxima point is not practical as the data is not in a form of harmonics wave where the peaks value are not constant.

In order to solve this problem, another method was created which is multiplication between gradient exist before and after maxima point. This method is based on gradient function of dy/dx .

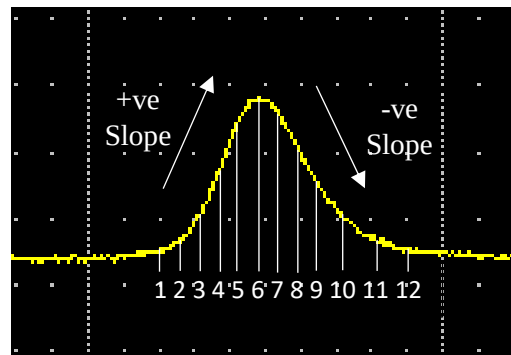


Figure 4.16: Slope change from positive to negative at maxima points (Xviewer software)

Slope at location 2 was identified by calculation of gradient between location 1 and 2:

$$\nabla_{1,2} = (4.203 - 4.173)/(0.02-0.01) = 2.983$$

The next adjacent slope multiplication is the multiplication of gradient between location 2 and 3 and so forth, in pair. If it is positive value, there is no changes in gradient. Thus, no peak presents. Meanwhile, negative value indicates a present of peak, as there are changes in gradient. Table 4.1 is a computed data of waves signal by using Microsoft Excel software to identify the present of peaks and its value.

Table 4.1: Computed data of each signal data produced by photocell

Location	Time (ms)	Voltage ratio	Slope	Adjacent slope multiplication	Indicators
1	0.01	4.173007	-N/A-	-N/A-	-N/A-
2	0.02	4.202834	2.9827	7.01918791	Positive
3	0.03	4.226367	2.3533	4.08344616	Positive
4	0.04	4.243719	1.7352	1.96736976	Positive
5	0.05	4.255057	1.1338	0.62778506	Positive
6	0.06	4.260594	0.5537	-0.00193795	Negative
7	0.07	4.260559	-0.0035	0.0018767	Positive
8	0.08	4.255197	-0.5362	0.5608652	Positive
9	0.09	4.244737	-1.046	1.6043548	Positive
10	0.1	4.229399	-1.5338	3.0691338	Positive
11	0.11	4.209389	-2.001	4.8946461	Positive
12	0.12	4.184928	-2.4461	-N/A-	-N/A-

Based on Table 4.1, the peak was found at location 6. The voltage ratio of location 6 is converted to temperature reading by using the Equation 4.1. This method are then used for the rest approximately thousands peaks of waveform to obtain the true average cutting temperature for each experiment.

4.3.10 Filtering peak value

Filtering peak process is followed after the detrending process. The voltage ratio value was identified by utilizing a ‘conditional formatting’ tools in the Microsoft Excel. A cell with negative value is then colored with blue color. A data is then filtered using ‘sort and filter’ to extract the blue colored cell. By processing a million data from each cutting experiment, Microsoft Excel are capable to extract thousands of peak with ease.

E	F	G	H	I	J	K	L	M
InSb	InAs Tr	InSb True	Ratio	Difference In	Trend InAs			
8469729	0.02652	0.001476158	17.96526591	4.127E-05	-1.2381E-11			
8469729	0.024816	0.001399581	17.73112882	1.562E-05	-3.50044E-10			
8469729	0.027351	0.001474927	18.54376589	3.183E-05	-3.08433E-10			
8469729	0.027778	0.001558521	17.8235975	2.522E-05	-4.68335E-10			
8469729	0.025697	0	Custom AutoFilter					
8469729	0.01897	0	Show rows where:					
8469729	0.022496	0	Trend InAs					
8469729	0.033277	0	is less than					
8469729	0.029745	0	And Or					
8469729	0.020729	0						
8469729	0.020008	0	Use ? to represent any single character					
8469729	0.006142	0	Use * to represent any series of characters					
8469729	0.019922	0						
8469729	0.029079	0						
8469729	0.019677	0						
8469729	0.025536	0.00149138	17.12213587	8.7E-07	-3.73839E-11			
8469729	0.029818	0.001667971	17.87675625	3.932E-05	-4.56505E-10			
8469729	0.019365	0.001063209	18.21348484	1.695E-05	-2.2391E-10			

Figure 4.17: AutoFilter tool in Microsoft Excel

4.3.11 Average and standard deviation of cutting temperature

Thousands of peak that were found using Microsoft Excel is then computed from Excel by finding average value of InAs-InSb voltage ratio. A simple function command was used to analyse the cutting temperature as shown below.

For cutting experiment of tools rotating at 4500 RPM with $A_d = 0.5$ mm, $R_d = 10$ mm, the average voltage ratio is,

AVERAGE(H2:H795)

=19.07825

Furthermore, another function command to find standard deviation of voltage ratio are also used. To find standard deviation, the function used in cell is,

STDEV.P(H2:H795)

=0.89172

Standard deviation of 0.89172 resembles the deviation among the particular data are extremely small, and therefore the data analysis are reliable.

4.3.12 Comparison of analysis result between specific peak and overall peak

Based on the discussion from previous section, the gathered reading of thousands peaks can be used for analysis of cutting temperature. There are significant differences of cutting edge temperature influenced by number of data samples. Table 4.2 shows the comparison of different number of data sample and its influenced on its standard deviation.

Table 4.2: Comparison between numbers of data sample of waveform peaks

Experiment	Analysis method	Number of sample	Voltage ratio	Standard deviation	Cutting edge temperature	Differences
Cutting speed = 283 m/min; Rd = 6 mm; Ad = 0.5 mm	Manually (Specific)	10	16.710	1.673	238.32	22.58 %
	Spreadsheet (Overall)	777	17.012	1.029	194.41	

Referring to Table 4.2, the standard deviation of each analysis method giving a different value where by measuring peak manually from Xviewer software gives 1.673. Meanwhile, by using additional software which are Microsoft Excel and Matlab softwares, the value is 1.029. Since, standard deviation resembles the distance of each data to the median of grouped data, it indicates that the lower value of standard deviation gives a better accuracy of data analysis which is the dispersion is small. Even though the voltage ratio differ by 0.302, the differences of temperature are significantly different once it was substituted into calibration Equation 4.1. The differences are 22.58%.

4.3.13 Effects of number of sample of waveform peaks on analysis

Since the number of signal recorded by digital oscilloscope as high as millions of data therefore, the number of waveform peaks were expected to thousands in number. There are two ways to measure the waveform peaks which are by manually or by developing a programming. If by manually, each peak will be measured by subtracting the peak value at position C shown in Figure 4.20 with the base value of waveform of position A or B. There is a drawback using a manual method. It is possible to measure all peaks but it is time consuming. Thus there is high possibility that the rest of other peaks' value are neglected and only hundredths of peak are taken into account for one cutting experiment. The number of sample greatly is affect the reading of cutting edge temperature and its standard deviation.

In order to solve this problem, the programming method was used as been mentioned in previous section. An explanation on peak trend formation and its relationship between cutting force, cutting temperature (in a form of voltage ratio) and position of cutting tool was explained in the next section.

4.3.14 Peak trend formation

Each impulse produced by InAs and InSb voltage ratio is produced by cutting edge's heat passed through an optical fiber. The heat is produced by work done required by cutting tool to cut the workpiece and to overcome frictional force interaction between tools, chip and workpiece. Infrared waves is radiated from the hot surfaces of cutting edge tool. Formation of output waves is visualized in Figure 4.20. A peak is slowly developed when radiated cutting edge moving in front of optical fiber. The peak trend is in sequential order with cutting force based on its feed path angle (Figure 4.20(a)). Theoretically, the difference of position angle between dynamometer input and photocells input is by 66.4° (Figure 4.19(b)). From the actual experiment (Figure 4.20), the position of cutting force impulse and cutting edge temperature impulse is differed by 65.72° . The differences occur is due to the deceleration of cutting tool when the cutting edge cuts through position A to B (Figure 4.20(a) and Figure 4.20(b)). Once cutting tool passed through position B, the cutting tool regains back to its constant angular velocity. Another possible reason is the tip of optical fiber vibrates due to cutting force when accepting the infrared radiation. The cutting force source is produced from cutting feed from position A to B. Position B to C is the gap between cutting feed end and optical fiber.

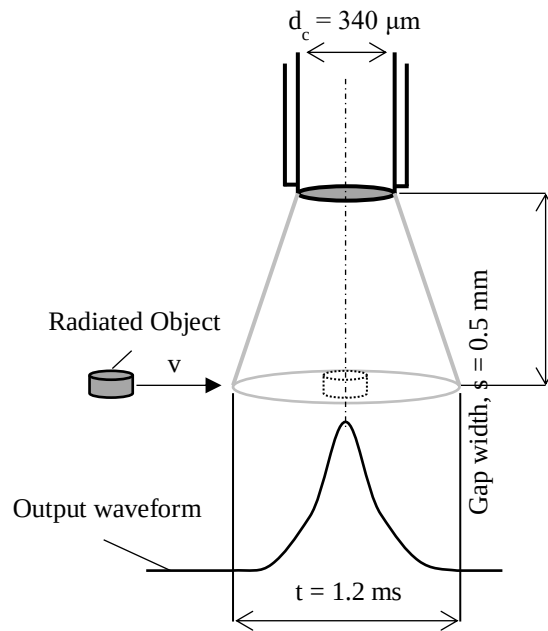


Figure 4.18: Formation of output waveform when cutting edge passed through optical fiber

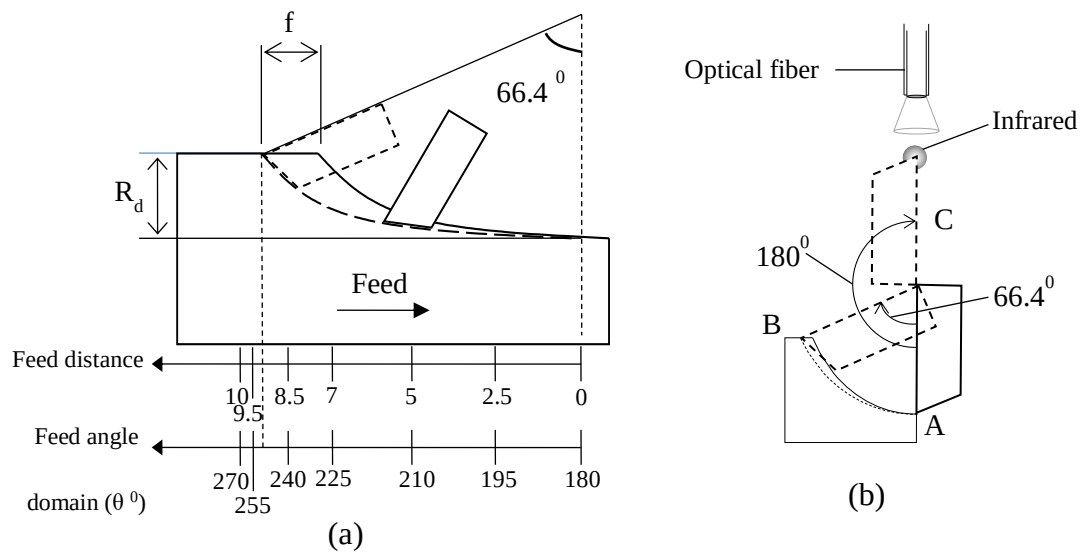


Figure 4.19: (a) Theoretical position of cutting feed at cutting speed of 283 m/min at $R_d = 6 \text{ mm}$ and $A_d = 0.5 \text{ mm}$; (b) Top view of theoretical position

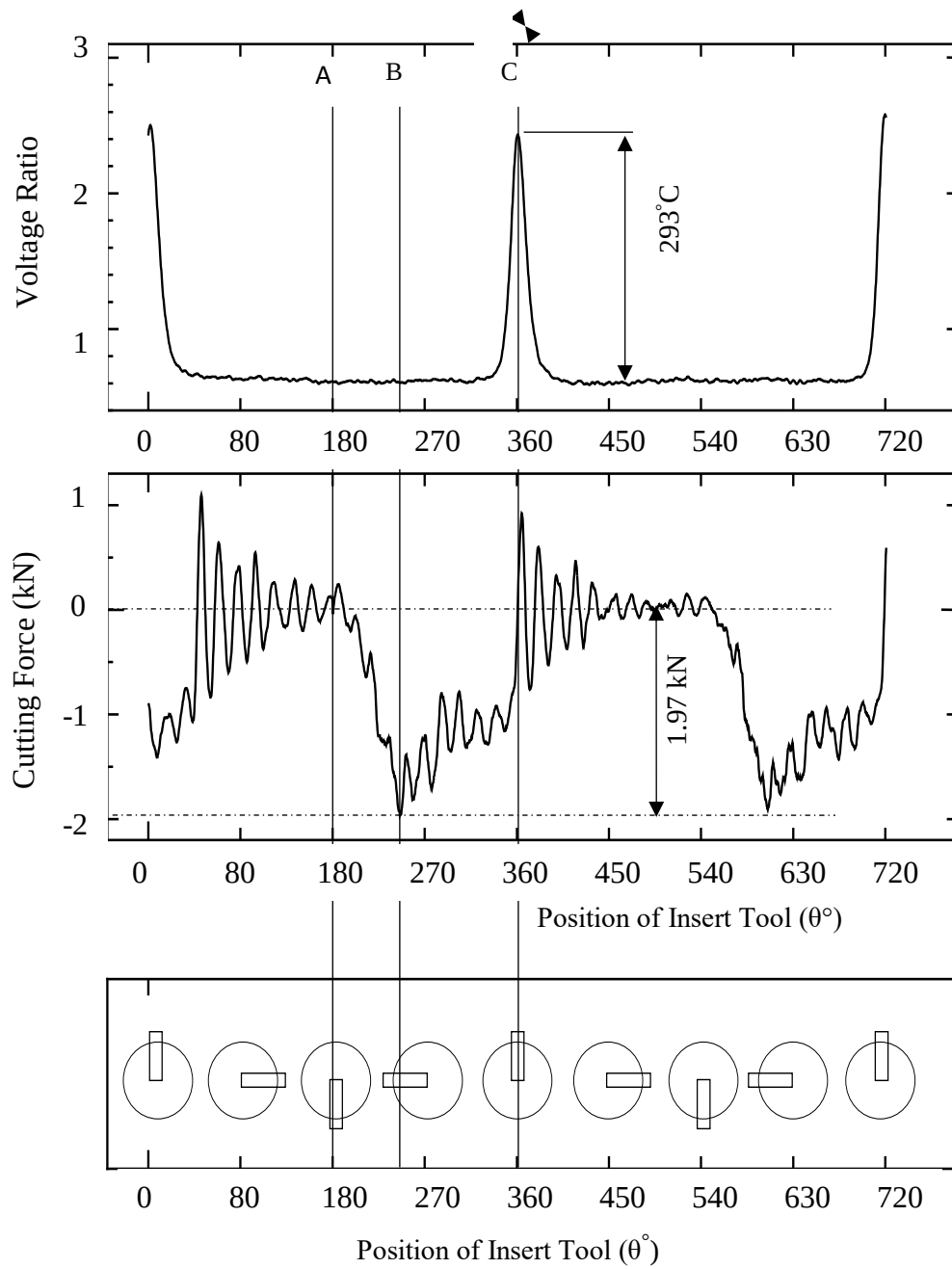


Figure 4.20: Optical fiber received infrared radiation differ by 180° from initial cut's contact

4.3.15 Systematic environmental error

Hamamatsu Photocells' sensitivity are heavily dependent on cooled environment to function properly. The manufacturer company, Hamamatsu designed the photocells equipped with a liquid nitrogen dewar in order to reduce the noise and increase its sensitivity to infrared radiation. The ideal surrounding environment for the experiment should be located in air-conditioned room. Unfortunately, the experiments were conducted in a normal room temperature and the location of the milling machine is installed near to non-tinted window. Furthermore, the climate of the research area is in a tropical rainforest country, Malaysia that is located in the equator belt region. The average temperature of Malaysia in a whole year is around 27~28°C. Liquid nitrogen boiling point is -198.5°C. Therefore, the liquid nitrogen will evaporate regardless to any location in the world, unless it is stored in a designated place which is lower than its boiling point. Compared to cool region in the world, rate of liquid nitrogen evaporation is significantly faster in Malaysia.

4.3.16 Systematic instrumental error

Once the liquid nitrogen begins to evaporate, the baseline of the signal will shift additively as discussed in Section 4.3.3. The shift occurred due to specific detectivity of the InAs and InSb photocells are reduced because of cooling temperature is increase. InAs and InSb are a type of photovoltaic sensor that detects infrared radiation at narrower spectral response. Benefits of narrow spectral response is the sensor are capable to detect small changes in temperature. The sensor are capable to distinguish the infrared radiation from different wavelength. If the temperature of InAs and InSb is not cooled down, the sensor will experiences a thermally-induced noise. The presents of thermally induced noise will cause inaccuracy of the signal recorded. Therefore, a cooled condition of photovoltaic sensor will

minimized the thermally induced noise signal significantly lower than the signal from the measured temperature. The result is, the specific detectivity will also decrease as the cooling temperature of sensor increase. The decrease in specific detectivity will cause signal to noise ratio approaching to one. The signal to noise ratio of one means the magnitude of signal and noise are almost identical.

4.4 Results and discussion (Cutting performance of AISI 1095)

Result is divided into two groups, which are medium cutting speed and high cutting speed. As mentioned before in Chapter 3, there are two types of milling machine used in the experiments, which are milling machine with medium speed spindle and another milling machine with high speed spindle. The main purpose of the experiment is to study the relationships between cutting speed, depth of cut, cutting length, cutting temperature, cutting force, and tool wear.

4.4.1 Medium cutting speed (33 to 284 m/min): Cutting temperature and cutting force at different cutting speed and depth of cut

Figure 4.21 shows the effects of different size of axial depth of cut towards cutting edge temperature and cutting force. Similar trends can be seen on Figure 4.22 where the increments of radial depth of cut leads to the increase of cutting edge temperature and cutting force. Noted that the cutting edge temperature for radial depth of cut experiment is higher than axial depth of cut even though the feed rate for both is fixed at 0.1 mm. This is due to the material removal rate (MRR) of radial depth of cut is higher than axial depth of cut

experiment as shown in Table 4.3 and Table 4.4. Meanwhile the cutting force for axial depth of cut experiment and radial depth of cut experiment is around the same range.

Table 4.3: Material removal rate, MRR of axial depth of cut experiments

Tool diameter	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R _d (mm)	A _d (mm)	Cutting length (mm)	Material removal rate, MRR (mm ³ /min)
20 mm	1	0.1	33	55	1	0.2	40	11
			91	150		0.4		60
			142	230		0.6		138
			183	300		0.8		240
			284	460		1		460

Table 4.4: Material removal rate, MRR of axial depth of cut experiments

Tool diameter	Number of tooth	Feed per tooth (mm)	Cutting speed (m/min)	Feed rate (mm/min)	R _d (mm)	A _d (mm)	Cutting length (mm)	Material Removal Rate, MRR (mm ³ /min)
20 mm	1	0.1	33	55	2	0.5	40	55
			91	150	4			300
			142	230	6			690
			183	300	8			1200
			284	460	10			2300

Figure 4.21 and Figure 4.22 shows the cutting temperature and cutting force against different axial depth of cut and radial depth of cut. It is not advisable to increase the radial depth of cut at the same length of the radius of the cutting tool which is 20 mm as it may damage the delicate speed spindle.

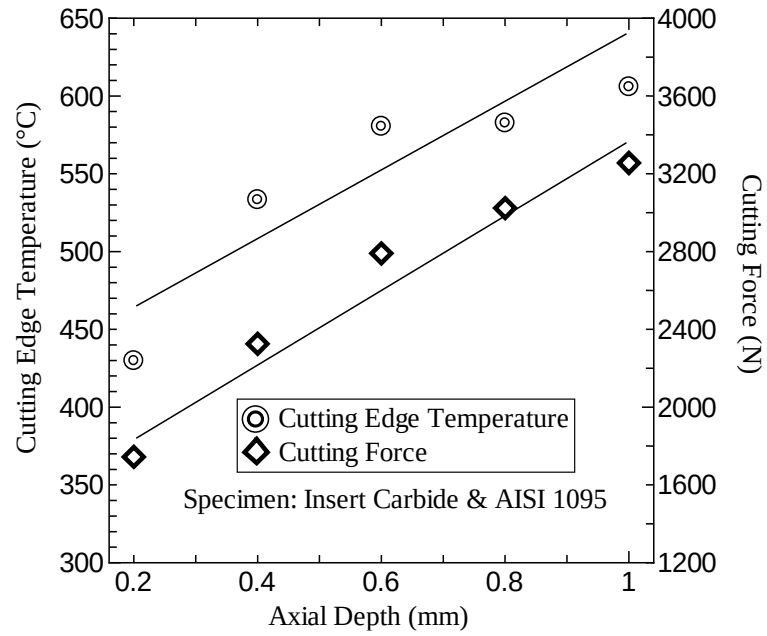


Figure 4.21: Axial depth of cut, cutting edge temperature and cutting force

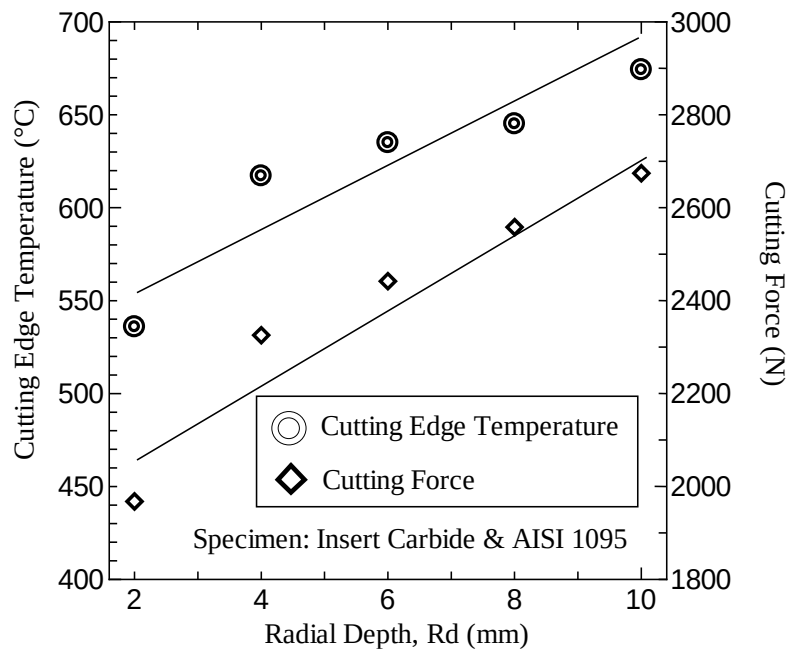


Figure 4.22: Radial depth of cut, cutting edge temperature and cutting force

The increment of cutting speed have a direct impacts on the rising of cutting edge temperature as shown in Figure 4.23. This is due to overall cutting energy is increased when the cutting speed increased. Meanwhile the cutting force decreased as the cutting speed increase. This trend correlates with the formula of cutting energy in Chapter 2 where the increment of cutting speed have reverse effect on cutting force. This is mainly due to the thermal softening of work material as the cutting temperature increases.

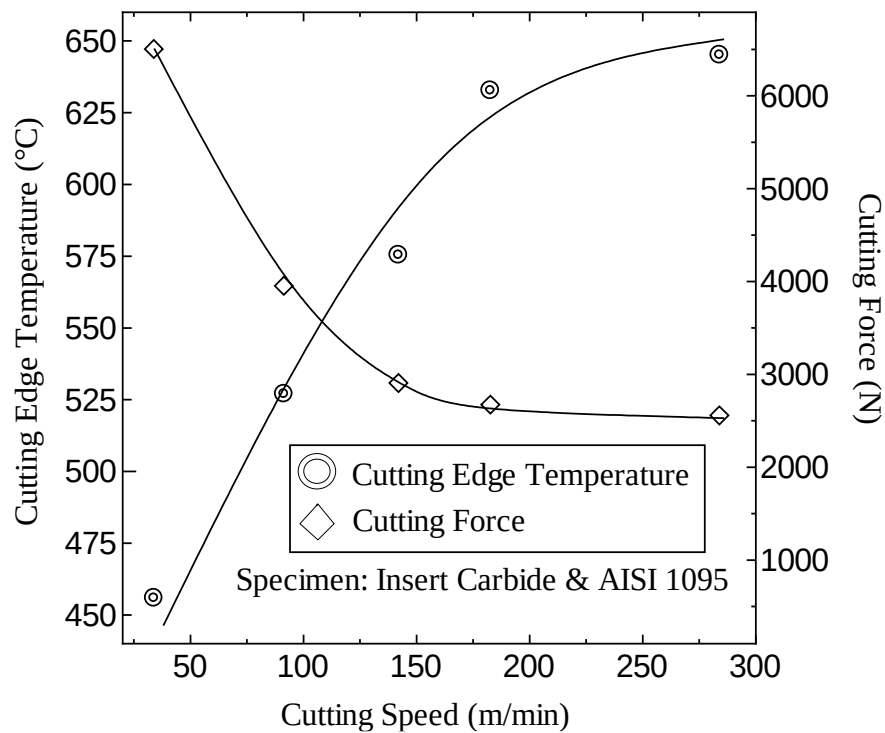


Figure 4.23: Cutting speed (33 to 284 m/min) affects cutting edge temperature and cutting force

4.4.2 Medium cutting speed (284 mm/min): Impacts of wear on cutting edge temperature and cutting force

A standard, ISO 3685:1993 of measuring flank wear on tool wear was referred as a guideline to identify the type of wear and method of suitable measurement. Flank wear size were measured from the bottom flat surface of the cutting tool. The prolonged use of cutting tool has increased the width of flank wear at the contact point of flank face and the workpiece's machined surface. The flank wear is measured based on steady wear developed over the cutting edge surface of tool. Figure 4.24 shows the development of flank wear after consecutive cutting length. The influence of flank wear on cutting edge temperature is shown in Figure 4.25 which indicates significant effects.

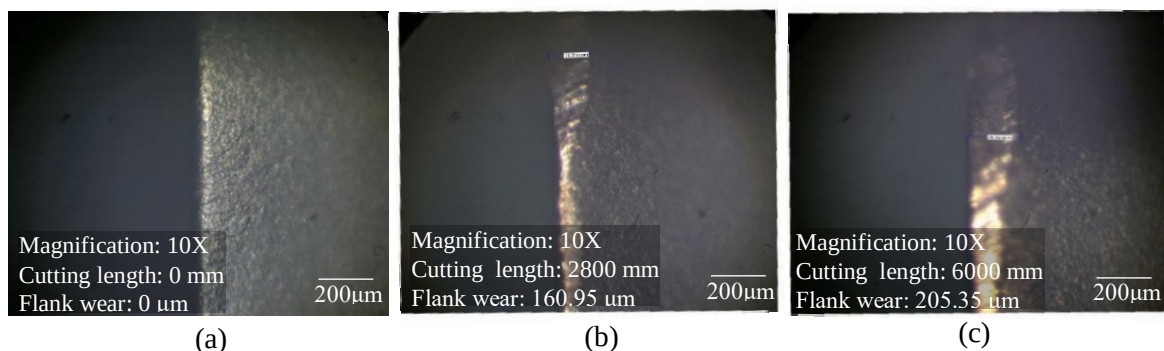


Figure 4.24: Flank wear's width at cutting length of (a) 0 mm, (b) 2800 mm and (c) 6000 mm at cutting speed of 284 m/min

Flank wear contributes to the development of cutting forces and increase the total area of abrasion. Increment of abrasive forces incites more thermal energy to be developed. Thus, these thermal energy escapes to surrounding in the form of infrared radiation. It is supported by a trend shown in Figure 4.26 where cutting force increases together with a growth of flank wear's width. The ununiformed chipping (Figure 24(b) and Figure 24(c)) at the flank face of insert carbide was caused by abrasive friction between insert's flank face

and workpiece's machined surface. As a conclusion, increment of flank wear has increased abrasive force in total cutting force and cutting edge temperature.

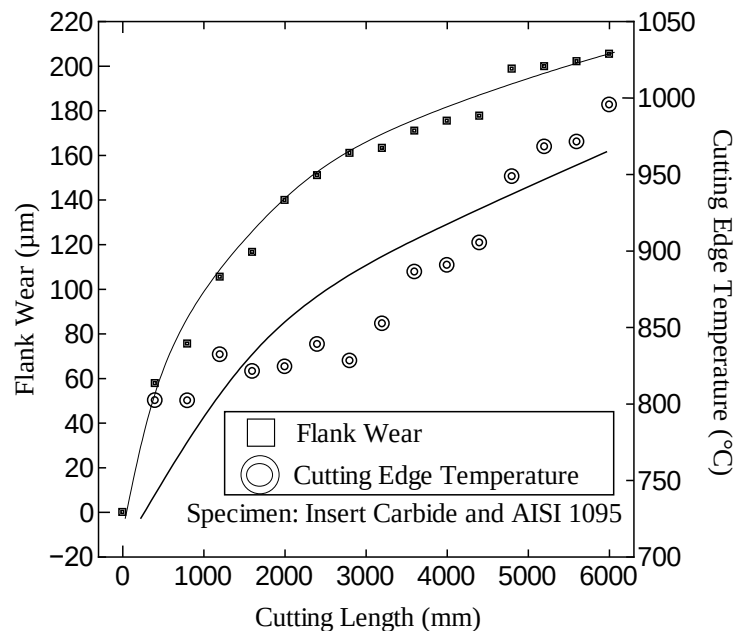


Figure 4.25: Influence of flank wear on cutting edge temperature (Medium speed machining)

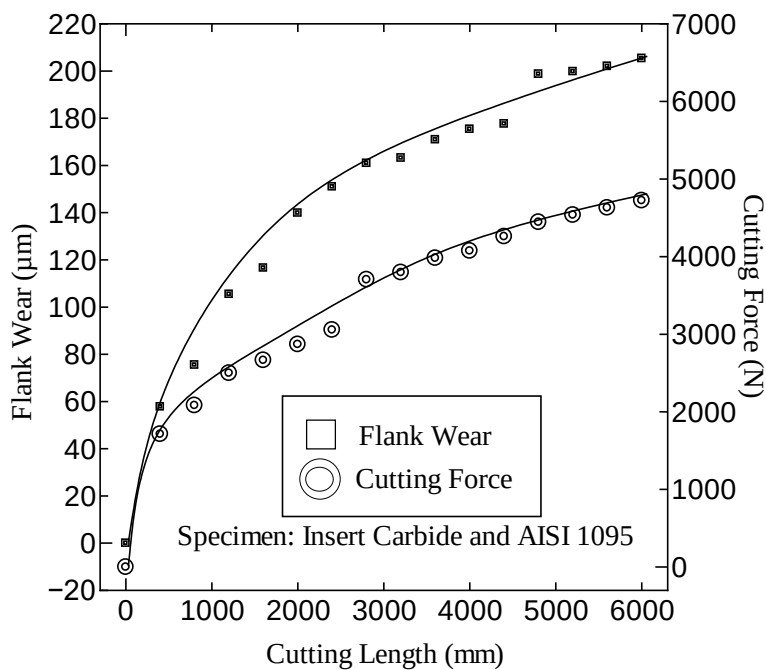


Figure 4.26: Influence of cutting length on flank wear development and cutting force (Medium speed machining)

4.4.3 High cutting speed (183 to 754 m/min): Cutting temperature and cutting force at different cutting speed and depth of cut

Based on Figure 4.27, for cutting speed at 188 m/min, although a significant temperature rise of 17% can be seen as R_d is increased from 1 mm to 2 mm, the temperature change is not very apparent when R_d is set to 3 mm which is an increase of only 6%.

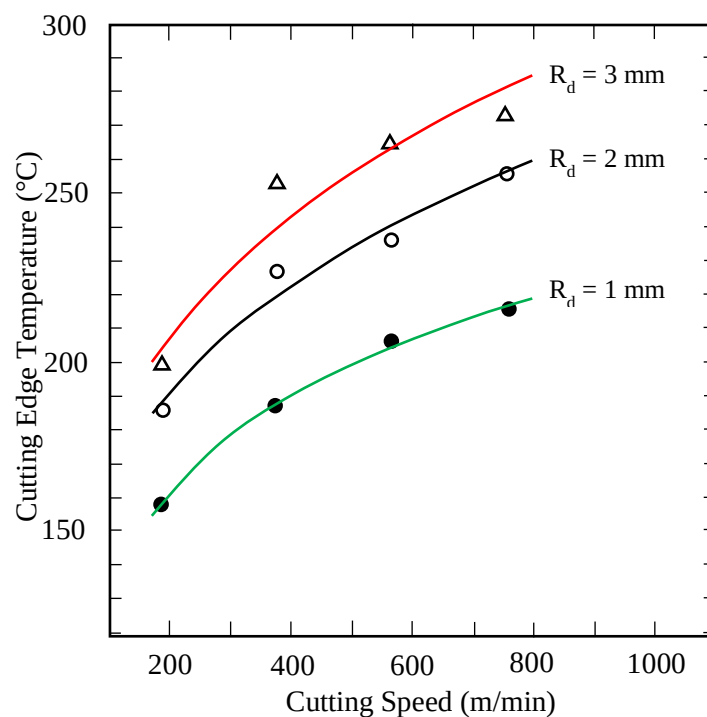


Figure 4.27: Effects of cutting speed on cutting temperature at different radial depth of cut

The same cases can be seen at Figure 4.29. This is the result of time delay between each cut which gives extra time for the heat energy from the cutting tool to spread to the surrounding. As the cutting speed increase, the temperature change is very apparent as the heat accumulates over time at the cutting tool. Meanwhile, trend of cutting force as the cutting speed increases is decreasing as shown in Figure 4.28. The result of the experiment still agrees to the theory as discussed by Trajcevski (2009).

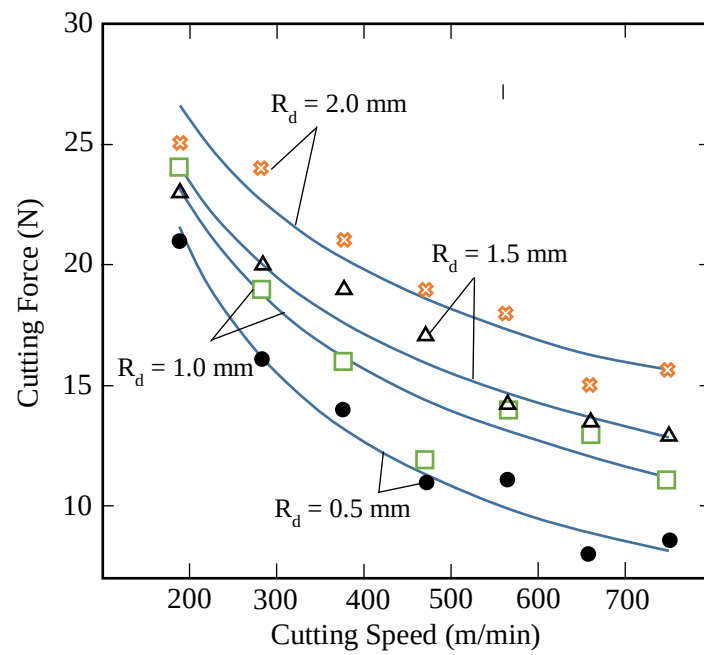


Figure 4.28: Effects of cutting speed on cutting force at different radial depth of cut

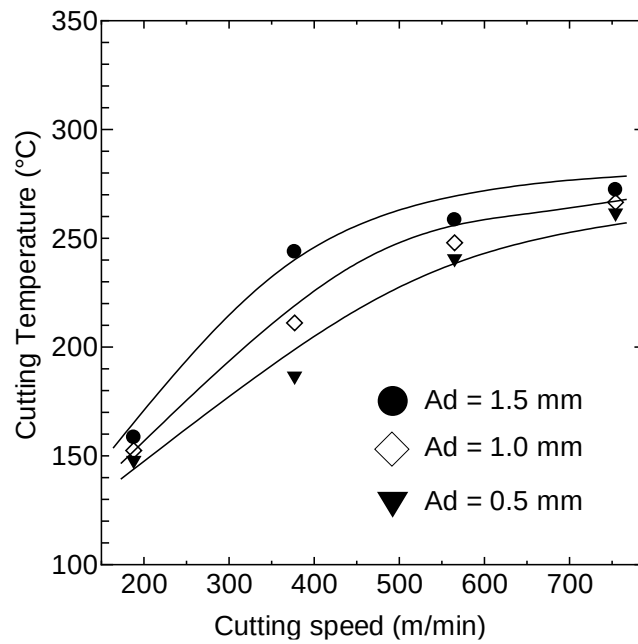


Figure 4.29: Effects of cutting speed on cutting temperature

The increase in temperature when radial depth of cut is increased is due to the higher plastic deformation which occurs at the primary and secondary deformation zone. According to Trent and Wright (2000), heat is produced due to the combined shear and friction action from the sticking and sliding friction sections. The rise in temperature also occurs at the tertiary deformation zone as a result of work done in overcoming frictional force at the rubbing contact between the tool flank face and the newly machined surface of the work piece.

Depth of cut in milling process has a significant impact on the cutting edge temperature and cutting force. As the material removal rate (MRR) increased, cutting edge temperature and cutting force are also increased. This is due to effective work done, which is increased when the depth of cut increases.

In a conclusion, the cutting edge temperature increases as the cutting speed increase meanwhile, cutting force decrease with cutting speed. Thermal effects have the significant cause in decreasing trend of cutting force. The friction in the cutting tool-workpiece and cutting tool-chip interfaces are resisting overtime and dissipates as thermal energy as discussed by Ye et al. (2011). The increasing cutting edge temperature has softened the mechanical strength of the workpiece's feed. As a result, work done required to cut a single pass in high cutting speed is less than in medium cutting speed.

4.4.4 High cutting speed (Cutting speed of 377 m/min): Impacts of wear on cutting force

Figure 4.30 shows the initial condition of solid end mill cutter before the cutting process begins for high cutting speed experiment. The cutting edge is still visible and intact. The image was taken from the flank surface by using optical microscope at total magnification level of 50X. Figure 4.31 shows the tool experiences catastrophic wear or chipping after 3600 mm distance of cutting length.

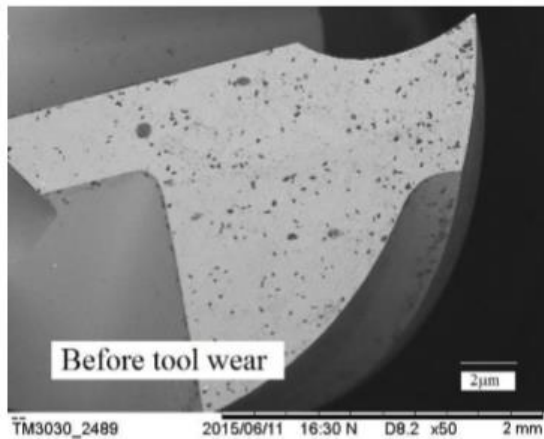


Figure 4.30: A view from flank surface of solid end mill cutter before cutting process.

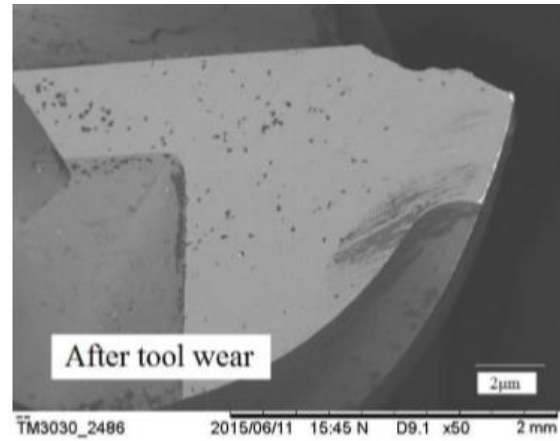


Figure 4.31: Solid end mill cutter experiences tool wear after cutting process

The wear is measured in micro meter (μm) unit. In this experiment, flank wear was measured. Image of flank wear developed for each cutting pass was captured and viewed using VISS Pro software. In this software, the wear was measured using point to point method as shown in Figure 4.33. As chipping starts to developed after 3600 mm cutting length, an imaginary line perpendicular to the measuring line will be drawn so that there will be appoint of reference when taking the measurement. The distance between the points will be the value of the tool wear.



Figure 4.32: Tool edge on new cutting tool (Before cutting process).

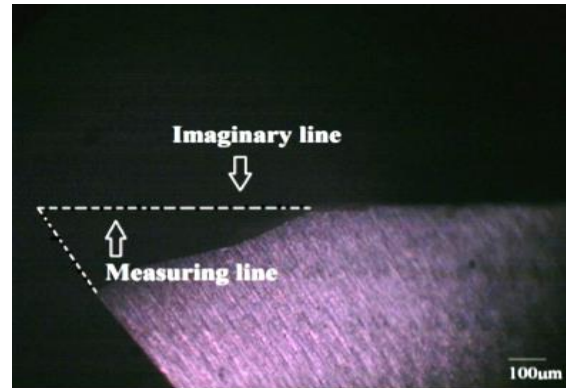


Figure 4.33: Imaginary line drawn according to original tool edge to measure tool wear.

Figure 4.34 show the graph of flank wear against machined length of the workpiece. Based on the experiment, the dominant tool wear are flank wear and chipping. Damage observed on the rake surface, such as crater wear, was quite limited. At the beginning of cutting process from 0 mm until 1200 mm of machined length, the flank wears grow steadily. Flank wear did not increase steeply due to the coating of the cutting tool that is still intact that hinders the flank wear to happen. From 1200 mm to 1600 mm of machined length, flank wear started to increase rapidly. There is 251% of increase of flank wear from 1200 mm to 2000 mm because at this point, chipping started to happen. From 2000 mm to 3600 mm length of machined length, flank wears increase steadily. Then from 3600 mm to 4400 mm of machined length, there is an increase in the flank wear by 9%. At this point, the flank wears is very visible and affect the cutting performance. 424 µm of flank wear is recorded at 4400 mm of machined length.

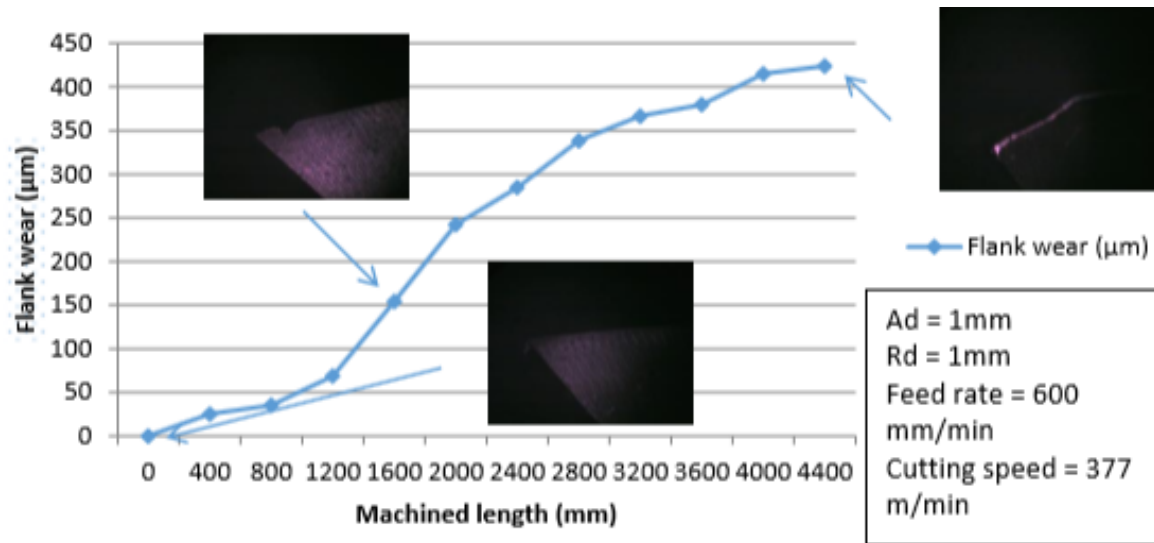


Figure 4.34: Machined length against flank wear (High speed machining)

Figure 4.35 show the three stages of flank wear in increasing machined length in this experiment. Theoretically, the wear occurred rapidly during the initial stage, gradually increased in the second stage and greatly increased at the final stage (Sulaiman et al., 2014). In initial wear region, increasing size of flank wear with increasing machined length is caused by micro cracking, surface oxidation and carbon loss layer. Small contact area and high contact pressure will result in sudden spike at this stage. The first region is for the break in period where the flank wear initially increases rapidly and then gradually reduces to a constant rate. However, the coatings of the end mill hinder the wear to increase steeply in the first 1200 mm of the cutting length. Based on the experiment, an increase in cutting speed tends to accelerate coating layer to decrease, which exposes tool substrate to the extremely high temperature environment. Hence, several obvious thermal cracks, thermal fatigue and chemical reaction at high temperature quickly bring the cutting tool edge to catastrophic failure. This theory is the same as research done by Hou et al. (2014).

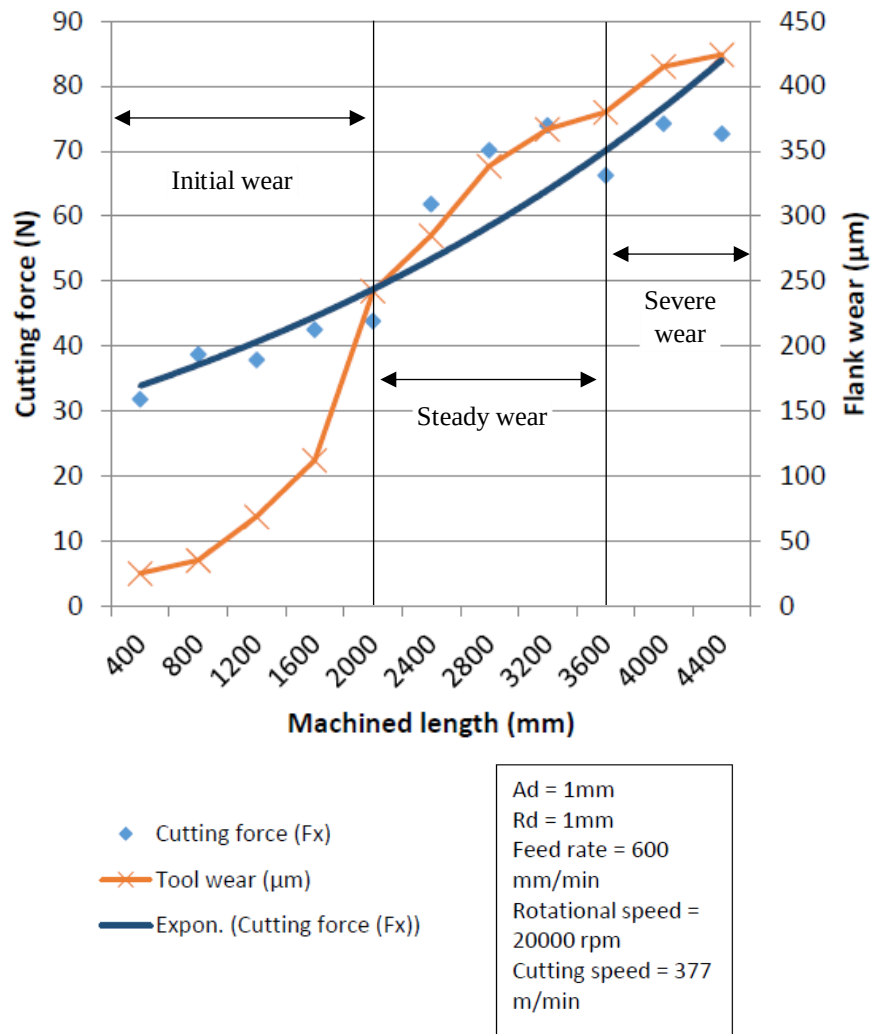


Figure 4.35: Machined length against cutting force and tool wear (High speed machining)

4.5 Summary

In this chapter, a study of cutting conditions on cutting edge temperature and cutting forces was carried out experimentally. The effect of cutting speed, depth of cut, and flank wear on cutting edge temperature were examined. The main results were analysed as follows:

1. Experimental method of using bichromatic pyrometer with an optical fiber to measure an infrared radiation is developed, in which it is capable to detect intermittent infrared radiation emission from the heat source.
2. A simple experiment on determination of cutting edge temperature of end mill tool is successfully implemented. In order to proof that the cutting edge temperature is from the machining process, a dynamometer is used to compare a peak of cutting force and peak of cutting temperature for each successive cut based on flute's rotation cycle.
3. Using the developed pyrometer, the cutting edge temperature of cutting tool is measured during milling process. In the cutting of AISI 1095, the cutting edge temperature is approximately 293.49 °C and cutting force is 1.97 kN at a cutting speed of 283 m/min in climb milling direction.
4. The number of sample data used in the analysis plays an important role in the determination of cutting edge temperature. Even though the voltage ratio differ by 0.302, the differences in cutting edge temperature are huge.
5. The developed pyrometer is expected to measure an infrared radiation at a rate of 0.01 ms. Theoretically, it can measure up to 6000000 RPM or 10000 Hz or 0.01 ms. To test the capability of high speed transient reading rate of temperature by a pyrometer, a high speed cutting experiment up to 40,000 RPM is carried out.
6. Increasing depth of cut gives an increasing cutting edge temperature. It is due to work done required to remove additional MRR that are increasing.

7. Higher cutting speed gives a decreasing cutting force and increasing cutting edge temperature. This condition is caused by the workpiece's mechanical strength is softened by heat interaction between cutting tool, chip and workpiece's machined surface while cutting edge temperature increase due to total friction increase at cutting tool-chip's interface and cutting tool-workpiece's interface.
8. Existence of progressing flank wear affects both cutting edge temperature and cutting force progressively. The ununiformed chipping had cause increase in the friction total area and increasing thermal energy. It also affects the cutting pressure to be reduced significantly resulting in cutting force increase.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 General Conclusion

This research mainly focuses on the development of a pyrometer that can measure an infrared emission radiated from the cutting edge of cutting tool. There were four major goals of these study. One of this is to study novel method for measuring cutting edge temperature at high cutting speed. By doing so, the design and specifications of developed pyrometer can meet the expected requirements.

The second objective is to adapt principle of infrared radiation in measuring cutting edge temperature at high cutting speed for improving machining performance. The purpose of second objective is utilizing the infrared radiation level radiated from cutting edge of tool as a temperature measurement apart from using current conventional method, which is thermocouple technique. Besides that, it is convenient to use infrared radiation technique as it is non-contact measurement.

The next objective is to characterize temperature profile of cutting edge at high cutting speed. Since the developed pyrometer have excellent transients speed, it is possible to characterize temperature profile and analyze it by observing the waveform signal produced by photocells as recorded by digital oscilloscope. The last objective is to evaluate cutting tool performance during wear formation.

5.2 Development of temperature measurement device for cutting edge at high speed

Generally, this study focus on development of pyrometer and applying it on the milling machine as a cutting edge temperature measurement device as well as assessing the cutting tool performance by using infrared radiation approach. By using the developed pyrometer, a cutting experiment is performed in order to determine the capability of the pyrometer as well as studies the relationship between cutting temperature, cutting force and flank wear. This pyrometer is developed using a InAs-InSb photocells, optical fiber, and digital oscilloscope. Meanwhile for a cutting experiment, it involves a high and low speed vertical milling machine, insert carbide, and AISI 1095 carbon steel as a work piece. The cutting experiment is conducted with fixed parameters such as feed per tooth, depth of cut, dry cut, and tool wear measurement. During initial phase of development of pyrometer, a calibration process is carried out by comparing temperature reading between K-type thermocouple temperature reading and photocells. Calibration process is implemented before performing the actual cutting experiment. The result of the calibration process is an equation is formed where it govern the relationship between photocells' electrical signal output and correspond temperature.

5.3 Study of cutting profile analysis during machining process

The pyrometer development is also extended to the analysis of characterized cutting profile. Characterization of cutting profile is important to determine the signal noise and study the formation of signal peak during machining process. It is found that, the position of optical fiber plays an important role in determining the cutting temperature. The delay of temperature reading from the actual cutting temperature is between 0.05 seconds (at 540

RPM) to 0.00075 seconds (at 40,000 RPM) or in other words the measured cutting temperature is delayed by an angle of 180° .

The significant contribution of pyrometer in measuring cutting temperature is its ability to measure temperature at high transient speed compared to thermocouple. The pyrometer is capable to detect temperature changes at a span of 0.01 ms theoretically. Since, the laboratory only equipped with high speed milling machine up to 40,000 RPM, thus, to date, the pyrometer is tested only with temperature reading a rate of 1.5 ms.

5.4 Assessment of cutting performance of machining a carbon steel, AISI 1095

Since the cutting profile analysis is carried out, the study is extended to the study of cutting performance of machining a workpiece by observing the cutting temperature trend. It was found that the cutting temperature trend is mainly influenced by cutting speed, depth of cut, feed rate, and tool wear that are developed along the machining process. The conducted study concluded that, increment depth of cut increases the cutting temperature and cutting force due to material removal rate (MRR) is increased. As the cutting speed increases, the cutting temperature increased as well but cutting force is decreased because of thermal material softening effect of the workpiece surface as the cutting temperature increased significantly. During extensive cutting length, flank wear have direct effect on the cutting temperature and cutting force as the total friction at the flank surface increases.

During the study, it was found that there are limitations of dynamometer as measurement devices of cutting profile. During high cutting speed experiments of chip load 0.03 mm, the dynamometer is barely able to detect the cutting profile of milling process. Meanwhile the pyrometer is able to detect the cutting profile with ease.

5.5 Recommendations

5.5.1 Optical fiber holder

In the present study, a cutting temperature is measure using a flexible optical fiber. It is positioned by using magnetic tool holder which can gives excellent stability but it lacks in flexibility and accuracy. Therefore, there might be a possibility for optical fiber to get a scratch from the sharp surface of cutting tool's edge if the magnetic tool holder loses it stability. For more safety, better design of optical fiber holder is recommended.

5.5.2 Location of optical fiber

The conducted experiment is only determine cutting temperature of tool after a cutting tool's edge cuts the workpiece. Therefore there are heat lost after a workpiece cut. It is expected that the actual cutting temperature during contact cut is higher than this. For a more precise cutting temperature, embedding the optical fiber inside a workpiece is recommended.

5.5.3 Alternative cooling system other than liquid nitrogen

Main drawbacks of using a developed pyrometer in this research comes from the cooling mechanism of photocells. As been mentioned in previous chapter, the photocells used is equipped with a Dewar to store a liquid nitrogen. In a future of pyrometer development, it is expected that a next researcher will use a photocells equipped with Peltier system which currently available in a market. This is due to inefficiency of refilling a liquid nitrogen every time during a cutting experiment. Furthermore, the price of liquid nitrogen is not cheap and it requires a special tank to store it only for several weeks.

5.6 Future Research and Applications

A developed pyrometer can also be integrated with a controller for CNC machine. By inventing so, the wear of cutting tool can be minimized as pyrometer can become a heat controller to prevent cutting tools from reaching a melting point thus reducing the wear level. A developed pyrometer is capable to detects a cutting temperature both non-conductive and conductive material without direct contact. Therefore, it can be used for other research application such as determination of cutting temperature of ceramic tools, diamond tools, grinder temperature, non-conductive workpiece such as wood, and propeller jet temperature. The usage of the developed pyrometer is not limited to subtractive manufacturing, it also can be used for other additive manufacturing or metal forming, such as metal stamping, or metal bonding as long it produces an infrared waves that can be utilized to mapping the heat generation.

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APPENDIX

Publications and Awards

- 1) Kiprawi, M. A., Yassin, A., Shazali, S. T. S., Islam, M. S. and Said, M. A. M. (2016). *Study of Cutting Edge Temperature and Cutting Force of End Mill Tool in High Speed Machining. The 9th International UNIMAS STEM Engineering Conference (ENCON 2016) “Innovative Solutions for Engineering and Technology Challenges”*. Universiti Malaysia Sarawak. Kota Samarahan, Sarawak.
- 2) Kiprawi, M. A., Yassin, A., Shazali, S. T. S., Islam, M. S. and Said, M. A. M. (2017). Study of Cutting Edge Temperature and Cutting Force of End Mill Tool in High Speed Machining. *In MATEC Web of Conferences*, 87(1), 02030.
- 3) Kiprawi, M. A., Yassin, A., Kamaruddin, A. M. N. A., Shazali, S. T. S., Islam, M. S. and Said, M. A. M. (2017). *Assessment of cutting profile of AISI 1095 by using infrared radiation approach. The 10th International UNIMAS STEM Engineering Conference (ENCON 2017) “Gearing Towards a Greener Future”*. Universiti Malaysia Sarawak. Kota Samarahan, Sarawak.
- 4) Kiprawi, M. A., Yassin, A., Kamaruddin, A. M. N. A., Shazali, S. T. S., Islam, M. S. and Said, M. A. M. (2019). Assessment of cutting profile of AISI 1095 by using infrared radiation approach. *International Journal of Engineering and Technology*, 7(3.18), 79-82.

- 5) Kiprawi, M. A., Yassin, A., Kamaruddin, A. M. N. A., Shazali, S. T. S., Islam, M. S. and Said, M. A. M. (2017). Development of a Cutting Edge Temperature Measurement Device of End Mill Tool by Infrared Radiation Technique. UNIMAS Silver Jubilee Conference 2017 (USJC) “Transforming Community Towards a Sustainable and Globalised Society”. Universiti Malaysia Sarawak.
- 6) Kiprawi, M. A., Yassin, A., Kamaruddin, A. M. N. A., Shazali, S. T. S., Islam, M. S. and Said, M. A. M. (2019). Development of a Cutting Edge Temperature Measurement Device of End Mill Tool by Infrared Radiation Technique. *Journal of Mechanical Engineering and Sciences*, 13(1), 4661-4678.

Awards

- 1) Bronze Medal, “Measuring Cutting Edge Temperature Measurement of High Speed Machining using Infrared Radiation Technique.”, MTE 2018.
- 2) Gold, “Development of Pyrometer for Milling Machine”, InTEX 2017.