STUDY INTO THE EFFECT OF CRUDE PALM OIL (CPO) AS A CUTTING FLUID ON THE TOOL WEAR AND CHIP FORMATION DURING LATHE CUTTING OPERATION

By

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CERTIFICATION OF APPROVAL

Study into the Effect of Crude Palm Oil (CPO) as a Cutting Fluid on the Tool Wear and Chip Formation during Lathe Cutting Operation

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A project dissertation submitted to the

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Approved by,

____

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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in the project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(RIMA RAFIZA A. MALIK)

ABSTRACT

For several years, cutting fluids have been serving manufacturers by providing lubrication and coolant in the machining sector. Its extensive use has commonly viewed as a requirement to enhance high productivity and high quality machining operations. A growing concern for the adverse environmental impact of using cutting fluids has enlighten the eyes of manufacturers in machining industries to shift their trend towards other potential alternative solutions that can replace the commercial cutting fluids. Vegetable oil is anticipated to have high potentials as it offers better lubricity properties and an added advantage of biodegradability characteristics.

This report highlights the overall progress of the project from problem identification until upon completion. The objective of this project is to study the effect of Crude Palm Oil (CPO) as cutting fluid to the tool wear and chip formation in lathe cutting operation. Literature review and researches were done in related to the project objective. Experiments of plain turning sample workpiece namely AISI 304 grade stainless steel by conventional lathe machine was conducted as a mean to investigate the effect of CPO to the two variables aforementioned. The results obtained were compared with two other experiment conditions, namely control (dry) and commercial (*Solkut* cutting fluid). The growth in the flank wear of the tool was inspected and the chip formation was examined accordingly.

Upon completion of the project, the results obtained reveal a positive contribution from CPO and the performance was encouraging. However, the results was still inadequate to support the claim that CPO is possible to become a cutting fluid as there are many other factors that need to be taken as consideration. Nevertheless, the author believes that this project has the opportunity for work expansion. With the performance shown by CPO, it is promising enough to promote future endeavors and further development towards preserving the environment.

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ABBREVIATIONS AND NOMENCLATURES

CPO – Crude palm oil

BUE – Build up edge

SEM – Scanning electron microscope

MQL – Minimum Quantity Lubrication

ISO – International Standards Organization

MRR – Material Removal Rate

Vc – Cutting velocity

So – feed rate

d.o.c – depth of cut

CHAPTER 1

INTRODUCTION

1.1 Project Background

This project evaluates the potentiality of using crude palm oil (CPO) as a cutting fluid in turning operation in terms of its effect to the flank wear and on the chip formation resulted from the operation. The results obtained from the experiment of evaluating CPO will be compared to the results of using *Solkut*[1] cutting fluid and dry machining. The characteristics and properties of CPO that is related will be used to develop the methodology for testing. The sample material used is AISI-304 stainless steel. Specific actions taken and results obtained are explained later in sections of the report.

1.2 Background of Study

In general, the most common machining process nowadays is the material removal process. In the process, the material of the workpiece will be removed layer by layer using a power driven machine with a sharp cutting tool and producing chips to form the desired shape and cavities until the final geometry is achieved. Some of the common cutting process is turning, whereby a workpiece is rotated and a cutting tool removes a layer of material as it moves parallel to the axis of the workpiece.

Figure 1: Example of turning process [1]

[1] A brand of commercial cutting fluid available in the laboratory used by the author

The factors that influence the cutting process can be divided into two categories:

1. Independent variables; it is specified by user.
2. Dependent variables; it is influenced by any changes in independent variables.

Table 1: Some of independent and dependent variables in cutting operation [2]

Independent Variables	Dependent Variables
Tool materials and coating	Force, torque and energy dissipated
Tool shape, surface finish and sharpness	Temperature rise
Workpiece material and condition	Surface finish and integrity of workpiece
Cutting speed, feed and depth of cut	Types of chip formation
Cutting fluid	Tool wear and failure

The variables listed in **Table 1** determine the machinability of the material, which is usually defined in terms of four factors:

1. Surface finish and surface integrity of the machined part
2. Tool life
3. Force and power required
4. The level of difficulty in chip control

One of the problems faced by the machining industry in its productivity and operation management is controlling temperature in the cutting zone. In production machining of steel, for example, inherently generates high cutting zone temperature which not only decreases the tool life, but also impairs the quality of the products.

Cutting fluid was then introduced to encounter this problem. The cutting fluid application in the machining process does not only provide lubrication and cooling to solve the temperature rising problem, but also flushes the chips away from the cutting zone to increase the surface quality of the product and avoid interruption in the cutting process. Nowadays the applications of cutting fluids have become common in the machining industry to ease in the manufacturing process.

1.3 Problem Statement

1.3.1 Problem Identification

Despite their widespread use, cutting fluid creates significant health and environmental hazards throughout their life cycle. Some of the research done shows that respiration and skin problems were the main side effects of using metalworking fluids, one of cutting fluids in machining [3]. According to the National Institute of Occupational, Safety and Health (NIOSH, 1983), it is estimated that 1.2 million workers are potentially exposed to the hazardous/chronic toxicology effects of metalworking fluids [3]. It is reported that European Union alone consumes approximately 320000 tonnes per year of metalworking fluid of mineral based of which, at least two-thirds need to be disposed [4]. It has also revealed that about 80% of all occupational diseases of machine operators were due to skin contact with cutting fluids [4].

1.3.2 Significance of the Project

Due to the ecological, economical and occupational hazards, industries are pointing their vision to replace the commercial cutting fluids with other alternatives. Vegetable oil is foreseen to be promising alternative for replacing commercial cutting fluid [3, 4], based on these factors:

- Nontoxic to the environment and biologically inert and do not produce significant organic disease
- A renewable and sustainable resources since it is an agriculture product which can be produced by planting
- Low health and safety risk as no report on chronic symptom due to exposure of vegetable oil to human [3]
- Biodegradability characteristics which ease the disposal process and preserve the environment

1.4 Objective and Scope of Study

Due to the problem, crude palm oil, being one of vegetable oil has open its way for many researchers including the author to investigate its potential and performance in the machining processes as Malaysia is one of the largest palm oil producers in the world.

The objective of this project is to study the effect of crude palm oil (CPO) as a cutting fluid during lathe operation based on two variables:

1. Tool flank wear
2. Types of chip formation

The scope of study in this project involves:

- Research on the characteristics of CPO and lathe cutting operation (machine tools, cutting parameters) related to the project in various sources such as articles, books, journals and internet resources.
- Benchmarking studies and evaluation on similar projects done from other people.
- Develop the analysis technique or methodology for experimenting CPO in the lathe operation and taking into accounts of project constraints such as time, cost and assumptions or limitations for the experiment to be conducted.
- Conduct the experiment and collecting data for further interpretations and analysis on the effects of CPO to types of chip formation and tool wear and failure. The data collected will be the baseline results for references of further developments.
- Conclude the experiment by reflecting back to the objective and look into some recommendations for further development of the project.

By having these scopes of study to set the work boundaries for the author, the target of working on the project with the given time frame and budget constraint is deemed sufficient. Further developments on the project will be planned based on the outcome of the project by the end of the time frame.

CHAPTER 2

LITERATURE REVIEW/THEORY

2.1 Cutting Fluids

2.1.1 Definition and Functions

Cutting fluids are fluids that are used mainly to provide cooling and lubrication in metalworking and machining process. There are many types of cutting fluids can be found, namely oils, oil-water emulsions, pastes, gel and mists. Sometimes it is being referred to as cutting fluid, cutting oil, cutting compound, coolant or lubricant. There are several categories of cutting fluid [5]:

- Straight oil – non-emulsifiable and are used in machining operations in an undiluted form, composed of base mineral or petroleum oil, often contains polar lubricants such as fats vegetable oils and esters as well as extreme pressure additives such as Chlorine and Sulphur, provide the best lubrication and poorest cooling characteristics.

- Soluble oil – form an emulsion when mixed with water, concentrate consists of a base mineral oil and emulsifier to help produce a stable emulsion, used in diluted form, widely used and the least expensive.

- Synthetic fluid – contain no petroleum or mineral oil base, formulated from alkaline inorganic and organic compound along with additives, generally used in diluted form, the best cooling performance.

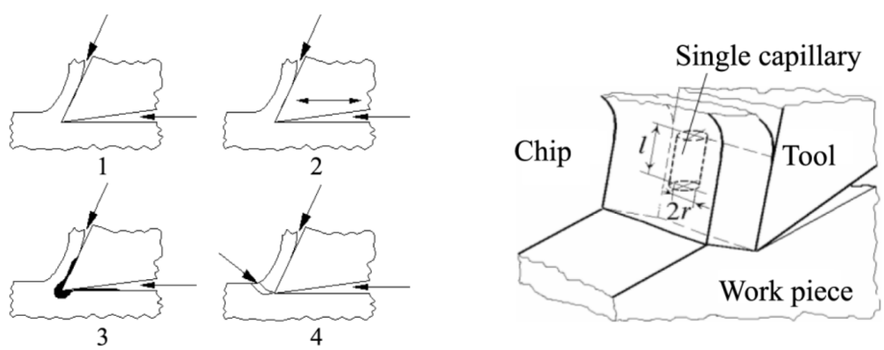
- Semi-synthetic fluid – essentially combination of synthetic and soluble oil, cost and performance lie between synthetic and soluble oil fluids.

Cutting fluids have been used extensively in machining operations to achieve the following results:

- Reduce friction and wear, thus improving tool life[2] and the surface finish of the workpiece.
- Cool the cutting zone, thus improving tool life and reducing the temperature and thermal distortion of the workpiece.
- Reduce forces and energy consumption.
- Flush away the chips from the cutting zone, and thus prevent the chips from interfering with the cutting process, particularly in operations such as drilling and tapping.
- Protect the machined surface from environmental corrosion.

2.1.2 Methods of Applying Cutting Fluids

To achieve the function as coolant and lubricant, cutting fluid reduces the contact area between the chip and tool. The better the penetration of the cutting fluid to the chip-tool interface, the higher its efficiency. **Figure 2** below show the penetration of the cutting fluid in the cutting zone.



(a) The ways of cutting fluid access **(b)** The geometry model of single capillary

Notes: 1 access through capillary action 2 access through vibration action 3 access through built- up action 4 access through diffusion action

Figure 2: The cutting fluid access [6]

[2] The length of time that a tool can function properly before it begins to fail

There are several methods to apply cutting fluids in machining, mainly:

- Flooding – a flood of cutting fluid is applied on the workpiece
- Mist – cutting fluid is atomized by a jet of air and the mist is directed at the cutting zone, supplies the fluid into inaccessible area
- High pressure systems – a jet of high pressure cutting fluid is applied on the workpiece directed at the cutting zone, increase the rate of heat removal from the cutting zone
- Through the cutting tool system – cutting fluid is applied on the workpiece through the cutting tool directly to the cutting zone

2.1.3 Properties of *Solkut* Cutting Fluid

Product name : SOLKUT 2140

Description of product : Proprietary Soluble Metal Working Fluid

Physical and chemical properties [7]:

- State : Liquid
- Colour : Amber
- Odour : Mild
- Oxidising : Non-oxidising (by EC criteria)
- Solubility : Soluble in water and most organic solvents
- Viscosity : Viscous (>40cSt)
- Boiling point : >100ºC
- Flash point : 100ºC
- Autoflammability : >150ºC
- Relative density : 0.95
- pH value : 9.3
- viscosity test method: Kinematic viscosity in 10-6m^2/s at 40ºC (ISO 3104/3105)

2.1.4 In General

Cutting fluids have been used more than 100 years ago mainly to reduce the severity of the contact processes at the cutting tool-workpiece interfaces. Back in the old days, water was used as a coolant to control the temperature rise in machining due to its high thermal capacity and availability [8, 9]. Oil then was introduced to counter the drawback of water by improving higher lubricity and corrosion protection, but having lower cooling ability as the toll. These two characteristics were then combined to give a better lubrication properties as well as cooling and became known as the soluble oils.

Cutting fluids plays important role in the manufacturing costs. Historically two decades ago, cutting fluids cost is as insignificant as less than 3% of the entire cost in machining process. As time passes by, cutting fluids goes about 15% of a shop production cost [10]. The cost of cutting fluids is not only focuses on initial cost, but also on disposal cost as many states and localities have classified them as hazardous wastes. As environmental concerns are growing, many efforts have been done to develop a more environmental-friendly cutting fluids such as using biodegradable oil in machining operations.

2.2 Crude Palm Oil (CPO) in Malaysia

2.2.1 CPO Characteristics

Due to the increasing demand of environmental concerns, vegetable oils are finding their way to enter the lubricants and cutting fluids market mainly in industrial and transportation field and palm oil is one of the potential entrants.

Palm oil is derived from the pulp of the fruit of the oil palm tree. As palm oil is one of the few vegetable oils relatively high in saturated fats (polyunsaturated fats) content, it makes the readily available and inexpensive oil not suitable for lubrication purpose. Monounsaturated fatty acid oil provides optimum oxidative stability and lower temperature properties. As a result, the polyunsaturated fats can be converted to monounsaturated to produce vegetable oils with high stability and low pour points [11].

Typically the requirements for selection of a cutting fluid for a given machining operation are:

- Heat transfer performance
- Lubrication performance
- Chip flushing
- Fluid mist generation
- Fluid carry-off in chips
- Corrosion inhibition
- Fluid stability (for emulsion)

Based on these criteria, the related properties for CPO are shown in the following tables and figures when comparing with other type of oils.

Table 2: Viscosity measured for the various vegetable oil and mineral oil [11]

Oil	Viscosity 40°C cSt	Viscosity 100°C cSt	Viscosity Index
Coconut oil	27.7	6.1	175
350 Neutral mineral oil	65.6	8.4	97
Low erucic rapeseed oil	36.2	8.2	211
High oleic sunflower oil	39..9	8.6	206
Conventional soya oil	28.9	7.6	246
Palm oil	39.7	8.2	188

The above **Table 2** reveals a relatively high viscosity index[3] (VI) in palm oil when comparing to the mineral oil[4]. This indicates palm oil has lower rate of change in viscosity with temperature compared to mineral oil which can contribute to better lubricity properties.

[3] Gradient of the viscosity against the temperature in range of 40 to 100°C
[4] Common base oil for commercial cutting fluid

Table 3: Qualitative effects of fatty acid profile upon performance of base fluids for lubrication [11]

Physical Properties	Saturates - 1	Saturates - 2	Mono - LC	Polys - LC
Oil	Coconut	Palm	HO rapeseed	Soybean
Main fatty acid	50% C12:0	45% C16:0	80% C18:0	75% C18:2&18:3
Oxidative Stability	Excellent	Excellent	Very good	Very Poor
Low Temp Properties	Poor	Poor	Good	Good
Hydrolytic stability	Moderate	Moderate	Good	Good

The above **Table 3** shows a relatively high content of main fatty acid in palm oil which contributes to lubrication performance. This is due to the molecular of long and polar fatty acid chain which provides high strength lubricant films that interact strongly with metallic surfaces, thus reducing both friction and wear and greater capacity to absorb pressure [4]. **Table 3** also indicates the excellence oxidative stability as well as moderate in hydrolytic stability, but taking into account the poor properties of low temperature of palm oil.

Table 4: The common tests and % biodegradability of base fluids [11]

Biodegradable Fluids

Examples: Product	CEC L-33-A-93 (21days)	Modified Sturm. (28 days)
Mineral oil	15% - 75%	5- 50%
Synthetic esters	> 55%	> 40%
Vegetable oils	> 90%	> 70%
"Readily Biodegradable"	67% - 80%	> 60%"

There are two common tests usually conducted to measure biodegradability[5] of a substance which are CEC-L-33A-93 test (measured as the loss of extractable hydrocarbon, primary[6] biodegradation) and modified STURM test (measured as carbon dioxide production, ultimate[7] biodegradation). The above **Table 4** indicates that

[5] Defined as a substance is susceptible to biochemical breakdown by the action of micro-organisms
[6] Degradation to the minimum extent to change the identity (chemically and physically) of a substance
[7] Substance is totally converted by micro-organisms into carbon dioxide, water, mineral salts and biotic mass

vegetable oil possessed the best biodegradability compared to other base fluids based on the test results.

Table 5: Results of the flash point temperature measurement [7]

Sample	**Reading 1 (^{o}c)**	**Reading 2 (^{o}c)**	**Average (^{o}c)**
Solkut cutting fluid	89.5	88.3	**89.0**
Palm oil	121.9	110.7	**116.3**

Based on **Table 5**, palm oil has relatively higher flash point compared to *Solkut* cutting fluid. This provides the opportunities for increased rates of metal removal because of reduced smoke formation and fire hazard. Moreover, with high boiling point and greater molecular weight acquired by vegetable oil, lesser loss resulted from vaporization and misting during the machining operation.

Table 6: pH assessment of Palm Oil and *Solkut* cutting fluid [7]

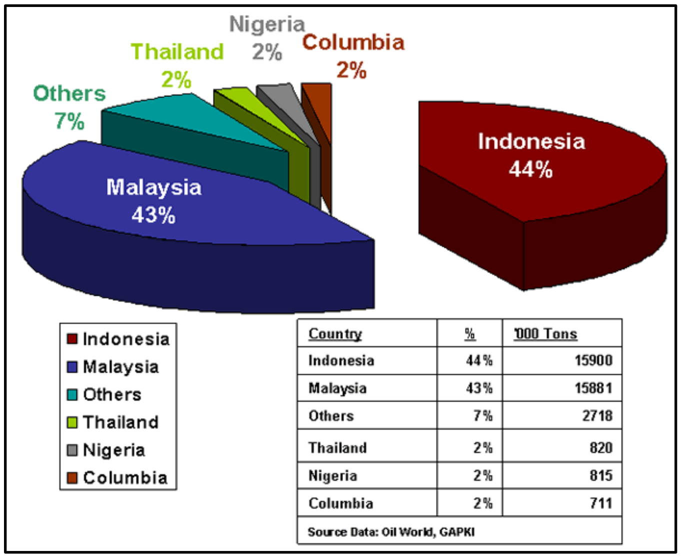
Reading	1	2	3	4	5	6	7	8	9	10	Average
Palm Oil	4.89	4.73	4.71	4.93	4.74	4.83	4.75	4.81	4.90	4.70	**4.80** acidic
Solkut cutting fluid	8.73	8.84	8.88	8.90	8.74	8.80	8.75	8.92	8.75	8.69	**8.80** alkaline

By investigation however, the palm oil is found to be acidic in nature that can be seen in **Table 6**, which leads to poor corrosion protection. Future developments can be done by adding corrosion inhibitors additives to the palm oil and enhancing its characteristics.

With many advantages that CPO can offer (high biodegradability, low pollution to environment, high flash point and high viscosity index), it can be seen that CPO has the potential to replace the commercial cutting fluid in order to preserve the environment.

2.2.2 Statistical Analysis of CPO

Palm oil has a high potential to replace the commercial cutting fluids especially in Malaysia as the country is one of the largest producer in the world [12].



Country	%	'000 Tons
Indonesia	44%	15900
Malaysia	43%	15881
Others	7%	2718
Thailand	2%	820
Nigeria	2%	815
Columbia	2%	711

Figure 3: 2006 World Palm Oil Productions [12]

The utilization of crude palm oil has been breakdown into several industries such as 80% for food industries, and 20% for non food application such as surfactants and lubricants, soap, tupperware, cosmetic, biofuel and candle/wax [13]. As Malaysia is one of the largest producers, developing the palm oil based cutting fluid would be a good prospect for the country since all the raw materials needed are easily obtained.

2.3 Tool Wear and Failure

2.3.1 Tool Wear

In metal cutting, tool wear is the dominant concern in the productivity and economy. Cost of a single tool can sometimes be insignificant, but the downtime of production line and cost to change tool can be very severe and causing shut down of the whole process. The situation that leads to tool wear:

1. High localized stresses at the tip of the tool

2. High temperatures, especially along the rake face

3. Sliding of the chip along the rake face

4. Sliding of the tool along the newly cut workpiece surface

This is a waste and less efficient to the organization and it leads to the study of factors that contribute to the longevity of tool life, which can be described in the equation below:

$$VT^n = C \text{ or } T = \left(\frac{C}{V}\right)^n$$

where V is the cutting speed, T is the tool life (time in minutes that it takes to develop a certain flank wear land, *refer **Figure 4***), *n* is an exponent (that depends on tool and workpiece materials and cutting conditions), and C is a constant. The rate of tool wear depends on:

1. Tool and workpiece materials

2. Tool geometry process parameters

3. Cutting fluids

4. Characteristic of the machine tool

Some of the types of tool wear:

1. Flank wear – occurs on the relief (flank) face of the tool, attributed to rubbing of the tool along the machined surface, causing adhesive and/or abrasive wear and high temperature.

2. Crater wear – occurs on the rake face of the tool, attributed to a diffusion mechanism, that is, the movement of atoms across the tool-chip interface.

3. Nose wear – rounding of a sharp tool, due to mechanical and thermal effects, dulls the tool, affect the chip formation, causes rubbing of the tool to the workpiece and resulting higher temperature.

4. Notching – attributed to the region where the chip is no longer in contact with the tool.

5. Plastic deformation of the tool tip – due to temperature rises in the cutting zone.

6. Chipping – small fragment from the cutting edge of the tool breaks away, due to mechanical shock and thermal fatigue.

7. Gross fracture – large fracture of chipping.

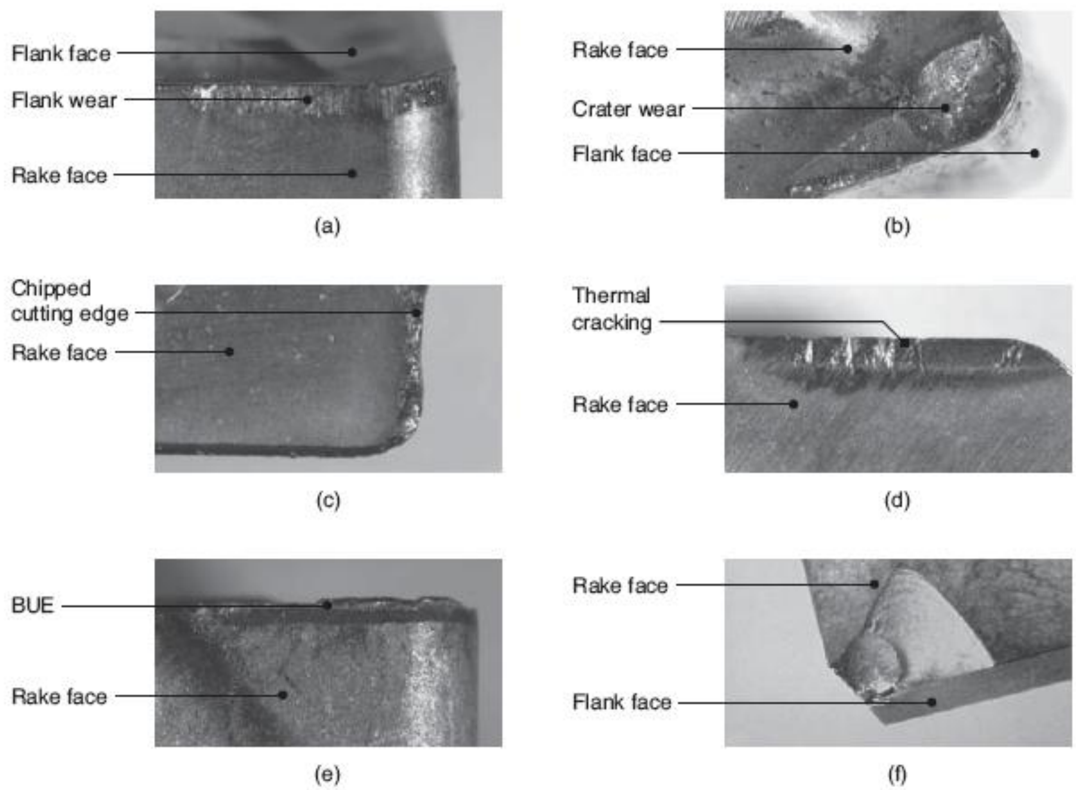


Figure 4: Types of tool wear and failure [2]

2.3.2 Effects of Vegetable Oil on Tool Wear and Failure

With the increasing concern for the adverse environmental impact of using commercial cutting fluid, the feasibility study of vegetable oil as replacement has draw huge attention among researchers around the world.

M.M.A. khan, M.A.H Mithu and N.R. Dhar [3] studied on effects of minimum quantity lubrication (MQL) on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. The experiment conditions that have been investigated were dry cutting, wet cutting using coolant brand Fuchs,model Ecocut San 220, and MQL condition using vegetable oil. The results revealed the reduced in average principal flank wear and average auxiliary flank wear under MQL condition (*refer* ***Figure 5 – 8***).

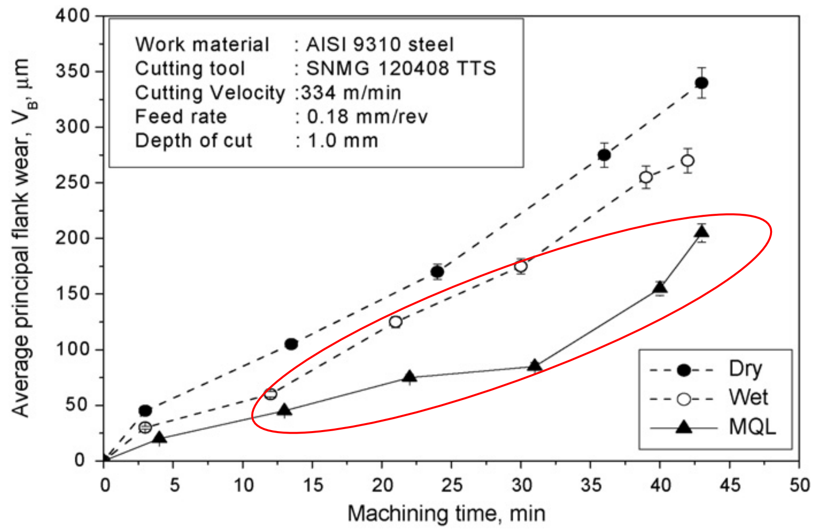


Figure 5: Growth of average principal flank wear with time under dry, wet and MQL by vegetable oil conditions at cutting velocity 334m/min [3]

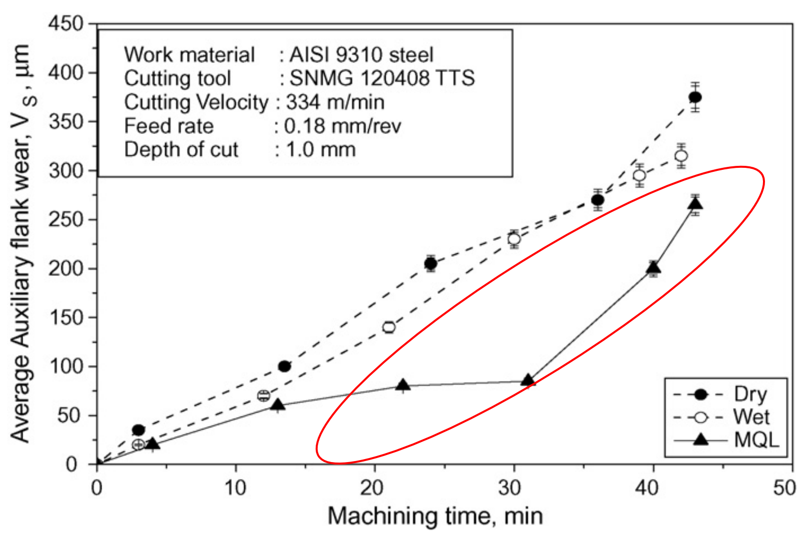
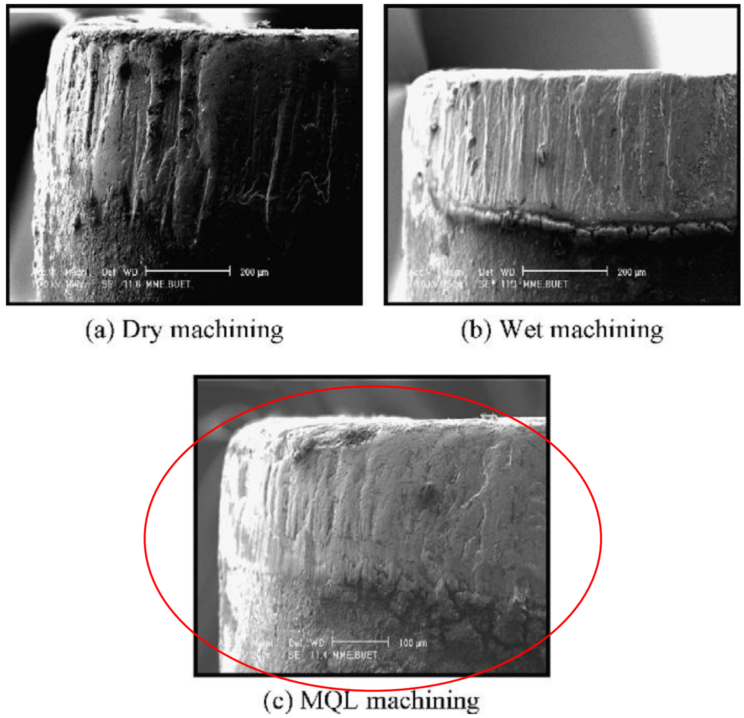
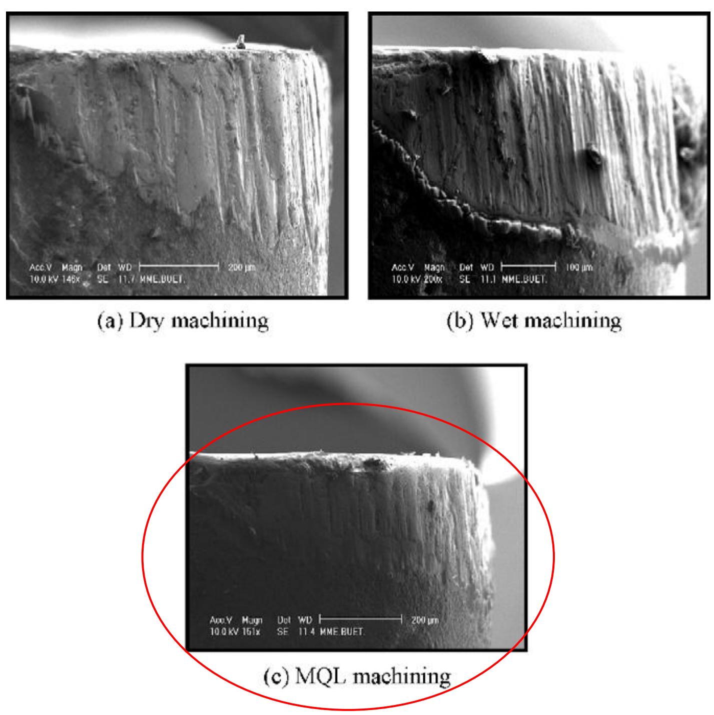


Figure 6: Growth of average auxiliary flank wear with time under dry, wet and MQL by vegetable oil conditions at cutting velocity 334m/min [3]



(a) Dry machining (b) Wet machining (c) MQL machining

Figure 7: SEM views of principal flank wear of the worn out insert after machining 43 min under dry, wet and MQL conditions [3]



(a) Dry machining (b) Wet machining (c) MQL machining

Figure 8: SEM views of auxiliary flank wear of the worn out insert after machining 43 min under dry, wet and MQL conditions [3]

Based on **Figure 5** and **6**, the tool has not reached its limiting value of 0.3mm [3] (according to ISO Standard 3685 for tool life testing, the cutting tool was rejected and further machining was stopped when average flank wear reaches 0.3mm) at 45 minutes in the MQL condition as compared to dry and wet machining. This shows the prolong tool life achieved when applying vegetable oil as cutting fluid and positive contributions to the overall performance of the machining process.

Other achievements have been found from other researches, showing the positive contribution of vegetable oil in this industry. M. Anthony Xavior and M. Adhitan [14] have studied on determining the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel. In the experiment conducted, the performance of coconut oil is also being compared with another two cutting fluids namely an emulsion (soluble oil) and a neat cutting oil (straight cutting oil). Coconut oil was chosen in the experiment due to its thermal and oxidative stability properties. The results shown have indicated the reduced in tool wear when using coconut oil as cutting fluid compared to soluble oil and straight cutting oil (*refer **Figure 9** and **10)***.

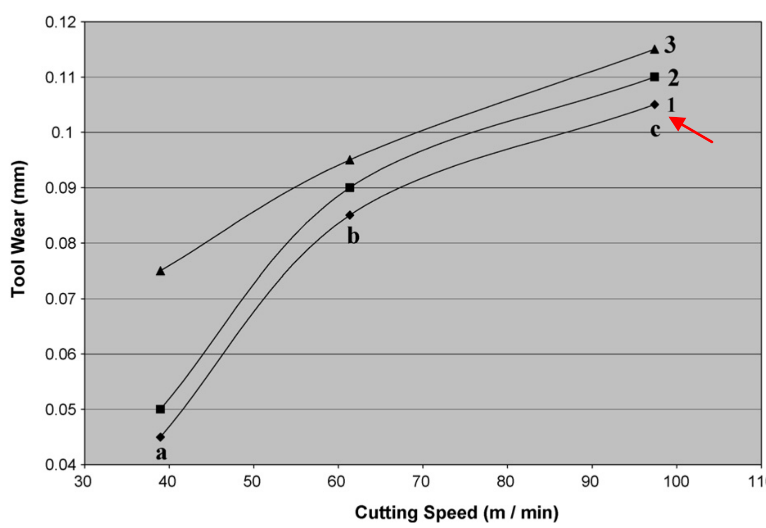


Figure 9: Cutting Speed versus Tool Wear. (1) Coconut oil, (2) Soluble oil, (3) Straight cutting oil; depth of cut (d): 0.5mm [constant]; feed rate (f): 0.2mm/rev, 0.25mm/rev, 0.28mm/rev at the three points a, b and c respectively [14]

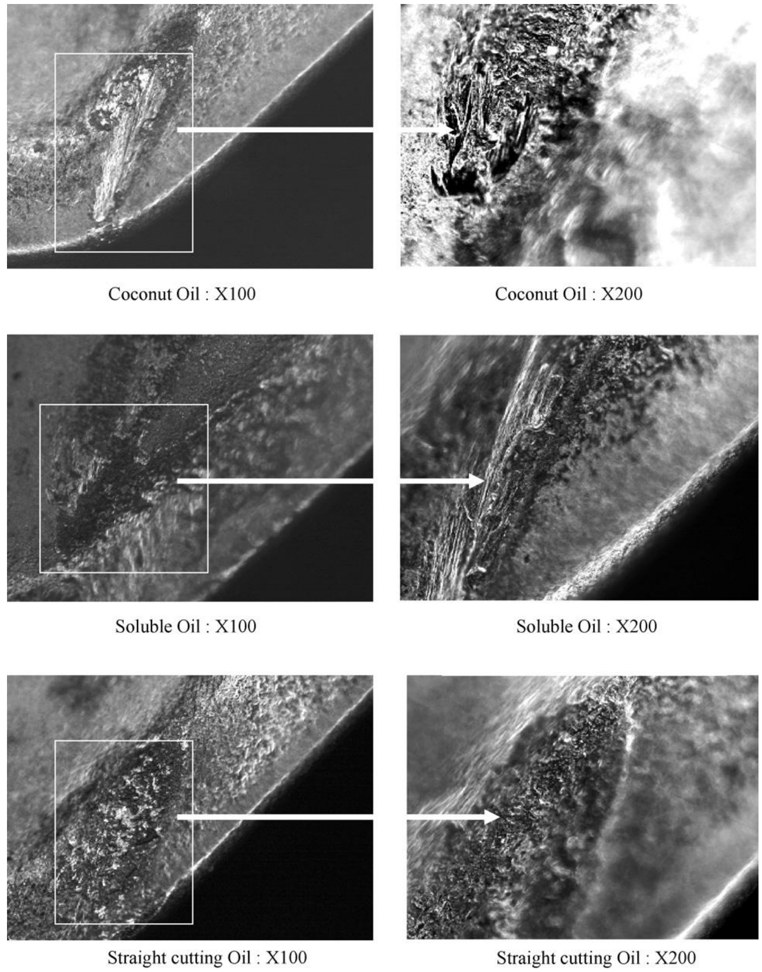


Figure 10: Microphotographs of Tool Wear. Machining condition: V_c, 38.95m/min; d, 0.5mm and f, 0.25mm/rev [14]

Apart from that, other contributions similar to the vegetable oil application in cutting fluid was done by P Vamsi Krishna, R.R. Srikant and D. Nageswara Rao [15] with their study on experimental investigation on the performance of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel. In the experiment, SAE-40 and coconut oil were taken as base lubricants and boric acid solid lubricant of 50nm particle size as suspensions. The results revealed that the combined effect of solid lubricant and vegetable leads to reduction in flank wear with 0.5% nanoboric acid particles suspensions in coconut oil compared to remaining conditions (*refer **Figure 11** and **12***).

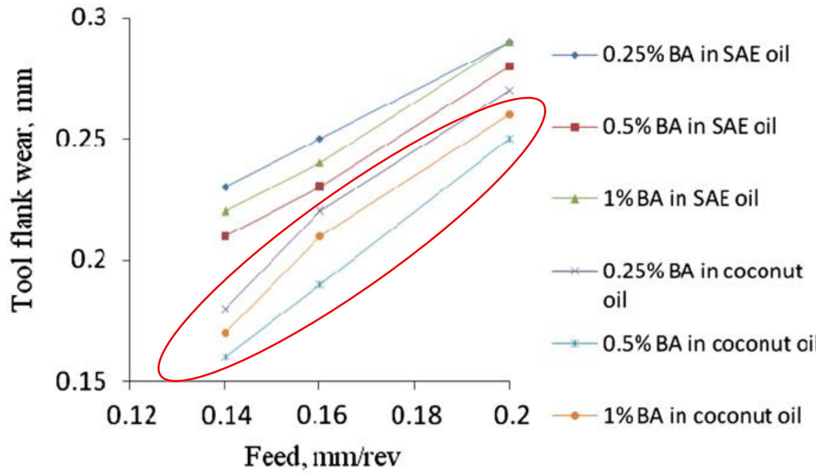


Figure 11: Variation of Tool Flank Wear with Feed (speed = 60m/min, d.o.c = 1mm, time = 15min) [15]

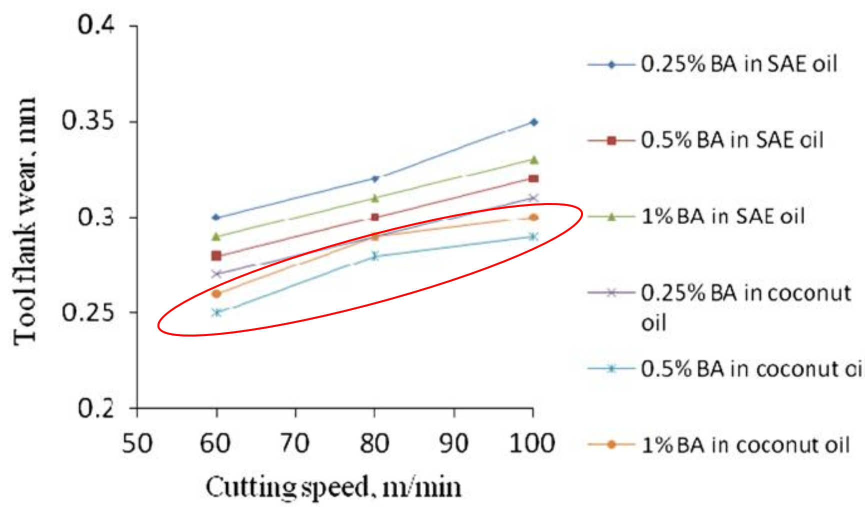


Figure 12: Variation of Tool Flank Wear with Speed (feed = 0.2mm/rev, d.o.c = 1mm, time = 15min) [15]

Another contribution found similar to the vegetable oil application in cutting fluid was done by Prof. Dr. Safian Sharif, Prof. Dr. Noordin Mohd Yusof, AP. Dr. Mohd. Hasbullah Idris, AP. Zainal Abidin Ahmad, AP. Dr. Izman Sudin, AP. Adnan Ripin and Mohd. Azrul Hisyam Mat Zin [16] with their study on feasibility of using vegetable oil in MQL during machining. In the experiment, a AISI 420 modified hardened stainless steel was end-milled with 4 different environments; dry, flood cooling with commercial cutting fluid, palm oil MQL mist, and fatty alcohol MQL mist. The results shown in **Figure 13** highlight the improvement of tool life when using palm oil compared to other conditions.

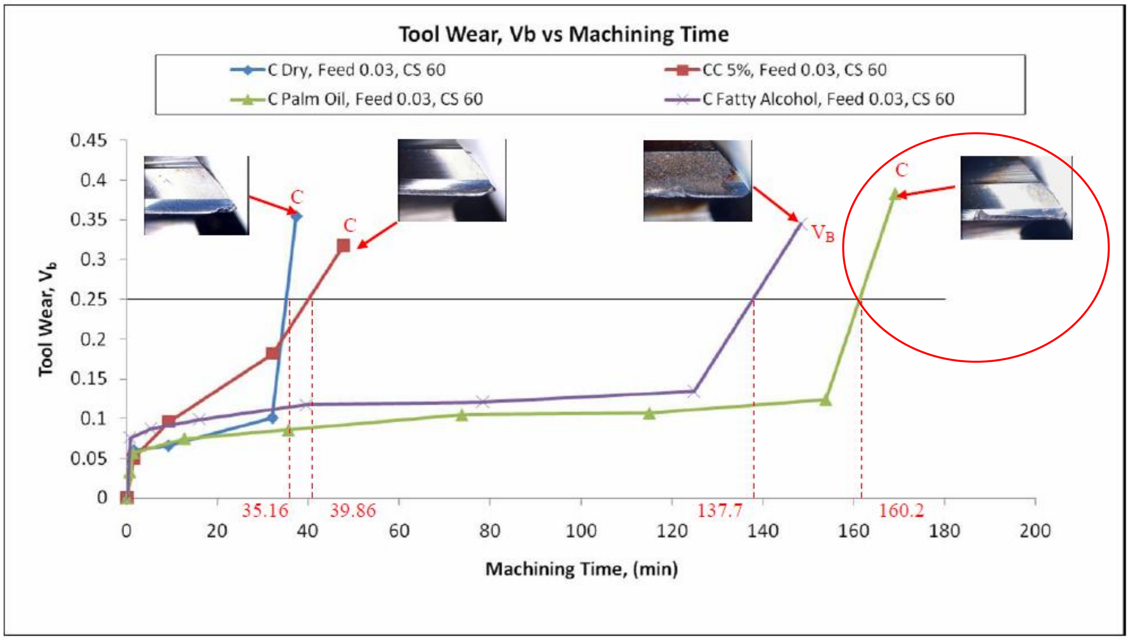


Figure 13: Tool wear when using different types of coolant condition [16]

2.4 Chip Formation

2.4.1 Definition and Types of Chip

As stated earlier in **Section 1.2**, cutting processes remove material from surface of workpiece and produce chips. Chips are produced by shearing, according to microscopic examination of chips obtained in actual machining operations. Shearing takes place along a shear zone (usually a long defined plane referred to as the shear plane) at an angle, called the shear angle.

To illustrate the chip formation, a simple model is used, referred as the M.E. Merchant Model as shown in **Figure 14**. The model is known as orthogonal cutting, as it is two dimensional and the forces involved are perpendicular to each other.

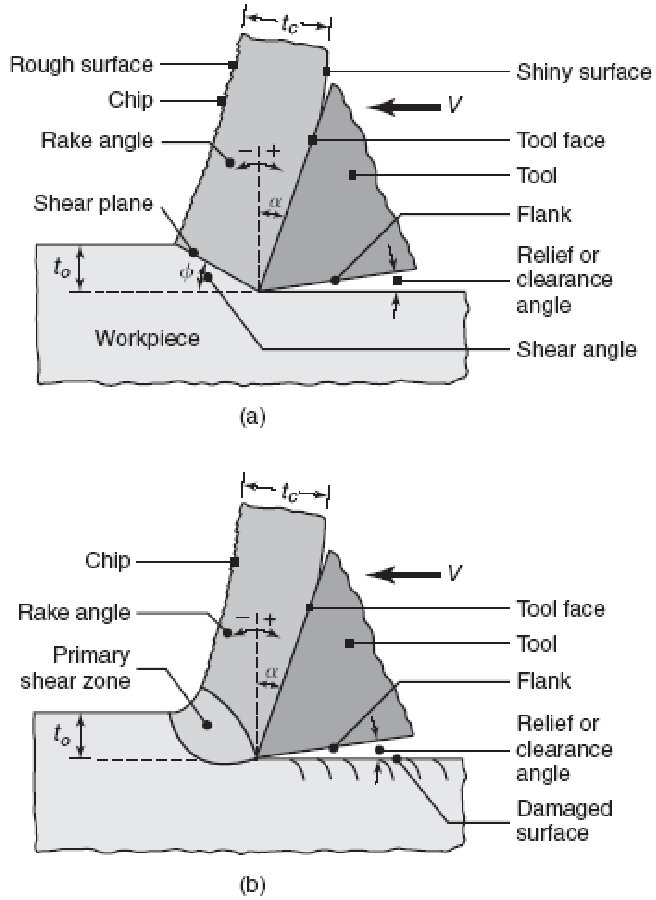


Figure 14: Orthogonal cutting: (a) with a well-defined shear plane, also known as Merchant Model; (b) without a well-defined shear plane [2]

There are four types of chip produced:

1. Continuous – formed with ductile materials, high cutting speed and/or high rake angle machining, may develop secondary shear zone due to high friction at the tool chip interface, can be solved by chip breaker or changing other parameters such as cutting speed and feed.

2. Built-up edge (BUE) – layers of materials from the workpiece that gradually deposited from the tool tip, a commonly observed in machining operation, affects

the surface finish, however, thin and stable BUE is desirable for its protecting the rake fake thus reducing tool wear.

3. Serrated or segmented – semi continuous chips with large zones of low shear strain and small zones of high shear strain, exhibits by metal with low thermal conductivity and strength that decreases sharply with temperature, for example titanium.

4. Discontinuous – segments that may be attached firmly or loosely to each other, exhibits by brittle workpiece, workpiece with hard inclusions and impurities or very low/high cutting speed in machining.

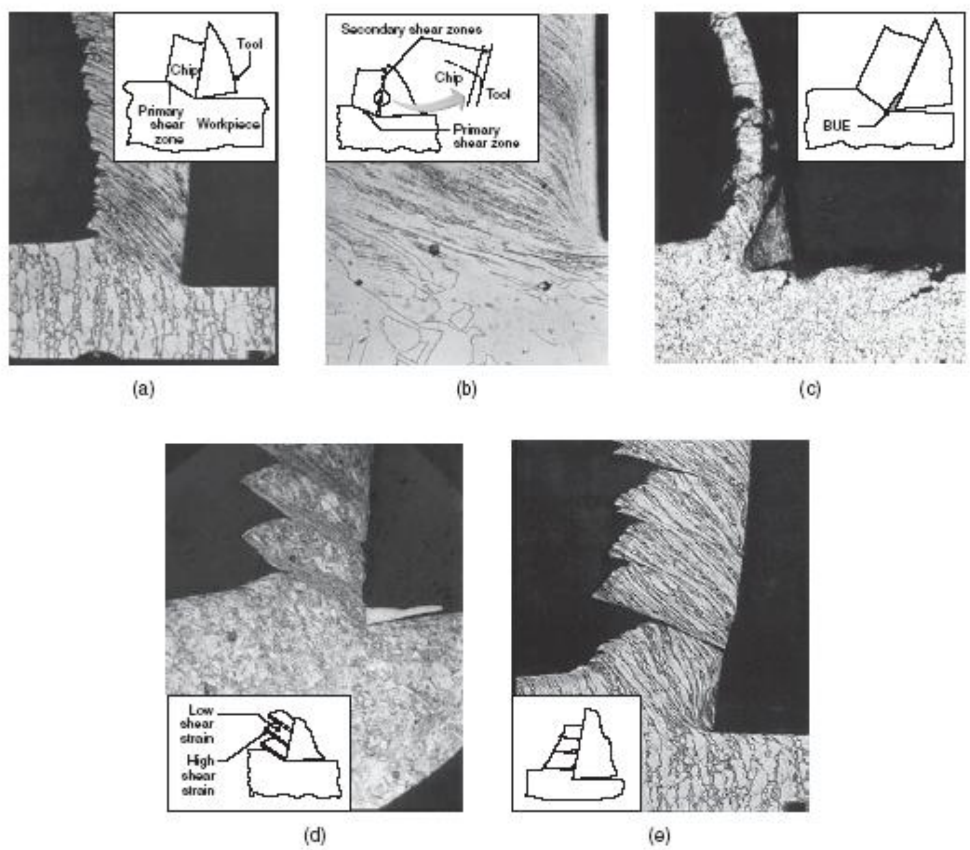


Figure 15: Types of chip produced in metal cutting [2]

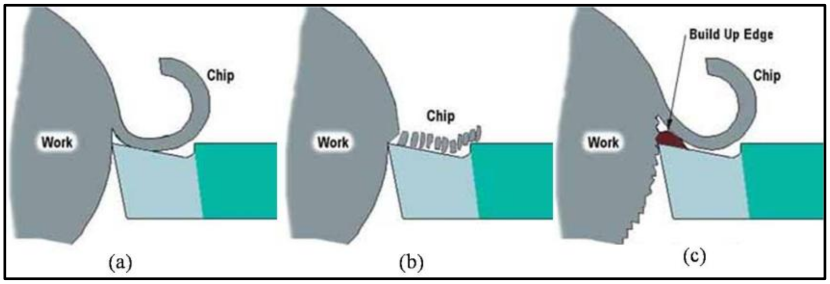


Figure 16: Types of chip formation; (a) continuous chips, (b) discontinuous chips and (c) continuous chips with Built Up Edge [17]

2.4.2 Effect of Vegetable Oil to Chip Formation

The form, color, thickness of the chips also directly and indirectly indicates the nature of chip-tool interaction influenced by the machining environment [4]. M.M.A. khan, M.A.H Mithu and N.R. Dhar [3] study on effect of MQL on chip formation have discovered that the form of continuous ductile chips did not change appreciably but their back surface appeared much brighter and smoother. This also signifies that the amount of reduction of temperature and presence of MQL application enabled favorable chip-tool interaction and elimination or even trace of built-up edge formation (*refer **Table 7***).

Table 7: Comparison of chip shape and color at different cutting velocity, Vc and feed rate, So under dry, wet and MQL by vegetable oil conditions [3]

Feed rate, S_0 (mm/rev)	Cutting velocity V_c (m/min)	Environment					
		Dry		Wet		MQL by vegetable oil	
		Shape	Color	Shape	Color	Shape	Color
0.10	223	Ribbon	Burnt blue	Ribbon	Burnt blue	Tubular	Blue
	246	Ribbon	Burnt blue	Ribbon	Burnt blue	Tubular	Golden
	348	Ribbon	Burnt blue	Ribbon	Burnt blue	Ribbon	Blue
	483	Ribbon	Burnt blue	Ribbon	Burnt blue	Ribbon	Blue
0.13	223	Ribbon	Burnt blue	Tubular	Golden	Ribbon	Blue
	246	Ribbon	Burnt blue	Ribbon	Burnt blue	Ribbon	Blue
	348	Ribbon	Burnt blue	Ribbon	Burnt blue	Tubular	Golden
	483	Tubular	Burnt blue	Ribbon	Burnt blue	Ribbon	Blue
0.16	223	Tubular	Burnt blue	Helical	Golden	Ribbon	Golden
	246	Ribbon	Burnt blue	Ribbon	Golden	Ribbon	Golden
	348	Tubular	Burnt blue	Tubular	Golden	Tubular	Golden
	483	Ribbon	Burnt blue	Ribbon	Burnt blue	Ribbon	Blue
0.18	223	Tubular	Burnt blue	Helical	Golden	Tubular	Golden
	246	Tubular	Burnt blue	Helical	Golden	Tubular	Golden
	348	Tubular	Burnt blue	Ribbon	Golden	Tubular	Golden
	483	Ribbon	Golden	Ribbon	Golden	Tubular	Blue
Chip shape Group	 Half turn			 Tubular/helical	 Spiral	 Ribbon	

2.5 Author's contribution

Researches that have been done have discovered the promising potential of vegetable oil to perform as cutting fluid in the machining environment. This leads the author to contribute on developing the vegetable oil in the evolution of the machining industries towards eco-friendly working environment. As palm oil is one of the vegetable oil that has high potential to replace the commercial cutting fluid, the author grabs her chance to joint venture in the research of developing the environmental friendly cutting fluid to promote healthy environment through this project. Although the scope of study into the effect of palm oil on tool wear and chip formation may seem small and insignificant, the effort being channeled throughout the project is valuable to save planet Earth from catastrophic events.

Figure 17: The future of vegetable oil as cutting fluid in machining is foreseen to be highly potential

CHAPTER 3

METHODOLOGY

3.1 Project Flow

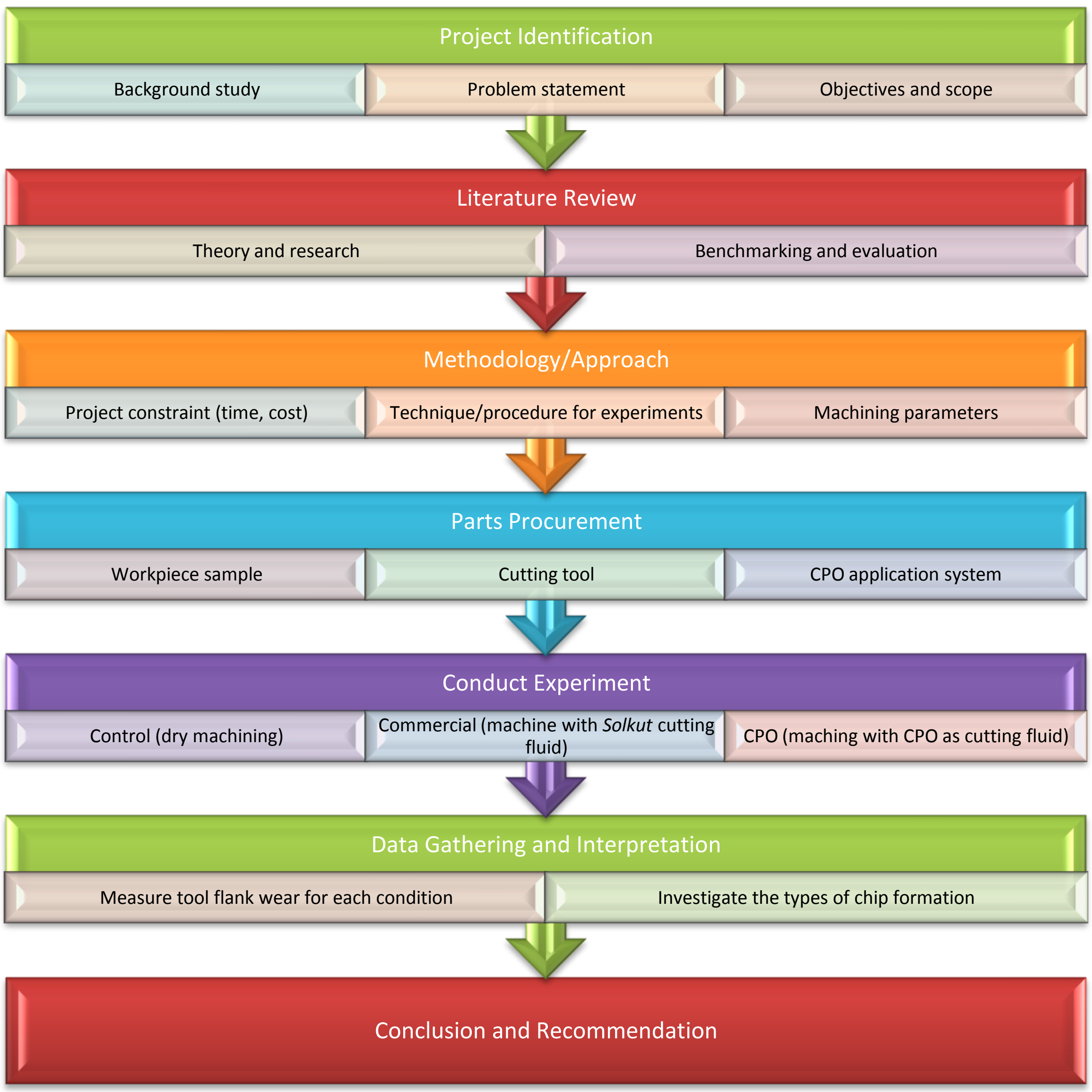


Figure 18: The overall project flow

3.2 Experimental Conditions

Experiments were carried out by plain turning a 50mm diameter and 200mm long rod of AISI Grade 304 Stainless Steel in the lathe machine at different experiment conditions. This material is chosen mainly due to good corrosion resistance as CPO was found to be acidic (*refer* ***Table 6***). These experiments will be conducted to investigate the effect of using CPO as cutting fluid to tool wear and chip formation in the lathe cutting operation. The machining parameters are listed in **Table 8**. The ranges of process parameters were selected based on the tool manufacturer's recommendation and industrial practices (*refer* ***APPENDIX 3-1****)*. In each run, further machining was stopped when average flank wear reaches 0.3mm in accordance with ISO Standard 3685 for tool life testing [3].

Table 8: Experimental conditions for the project

Machine tool	Lathe machine, Excel 1340 1.5 HP
Workpiece material	AISI Grade 304 Stainless Steel Composition: (C-0.08%, Cr-20%, Ni-10.5%, Mn-2%, Si- 0.75%, P-0.045%, S-0.03%, N-0.10% (*for material properties refer* ***APPENDIX 3-2)***
Workpiece size	Ø50 x 200 mm
Cutting insert	Mitsubishi US735 model, carbide, TiN C.V.D. coated layer
Tool holder	PCLNR 2525-M12 model, negative 80º rhombic inserts
Process parameters: Depth of cut, DOC Cutting speed, V Feed, F	 0.5 mm (constant) 50 and 100m/min 0.067 mm/rev (constant)
Experiment environment	1. Control – cutting without any cutting fluid 2. Commercial – cutting with *SOLKUT 2140* cutting fluid 3. CPO – cutting with CPO as cutting fluid
Recycling	1. Control – null 2. Commercial – yes, through the machine recycling system 3. CPO – no
ISO Standard 3685: tool life testing rejection criteria [3]	1. Average flank wear ≥ 0.3mm 2. Maximum flank wear ≥ 0.4mm 3. Nose wear ≥ 0.3 mm 4. Notching at the depth of cut line ≥ 0.6mm 5. Excessive chipping (flanking) or catastrophic fracture of cutting edge ≥ 1.6µm

3.3 List of Equipment Used

Table 9 shows the list of equipments that were used throughout commencing the project.

Table 9: List of equipment used

Equipment	Function
Excel conventional lathe machine	• To conduct turning operation for the testing of CPO in the experiments.
3D Non-contact Measuring Machine	• To measure the tool flank wear • To examine the type of chip formation

Figure 19: Excel conventional lathe machine

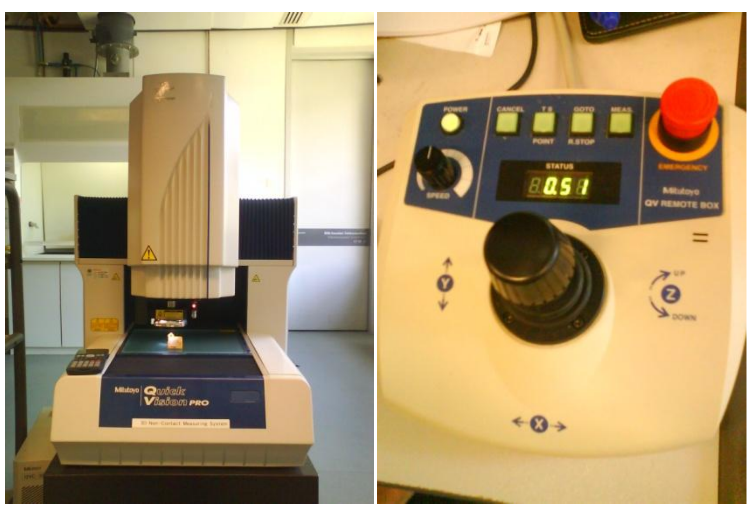


Figure 20: 3D Non-contact measuring machine

3.4 Experiment Procedures

As listed in **Table 8**, the experiment will be conducted in three different environments with variable cutting speed as shown in **Figure 21**. The results for control condition will be used as datum or reference to compare with commercial and CPO condition.

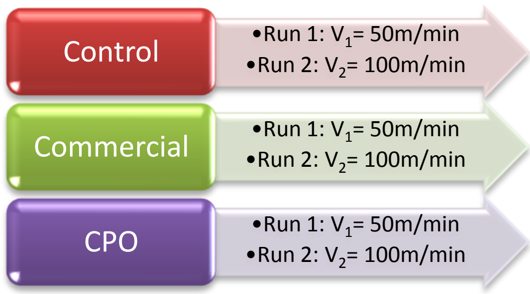


Figure 21: Three experiment environments

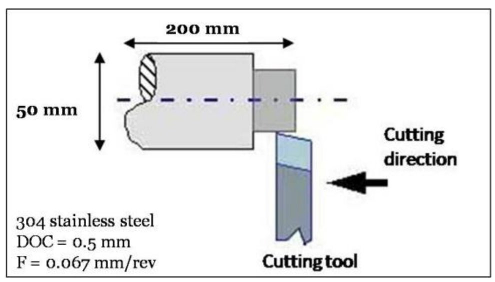


Figure 22: Process of turning in the experiments

For each experiment, the material preparation that needs to be conducted:

- Measure diameter of sample to calculate machine spindle speed
- Filtering the CPO before filling it into the reservoir tank
- New insert tool specimen will be used for each run
- Prepare the net for collecting chips

To calculate machine spindle speed, N the equation below was used:

$$V = \pi D_o N$$

where V= cutting speed, m/min (in this case is 50 and 100m/min for every condition)

D_o= initial diameter before machining, m

The general steps for the experiment to be conducted:

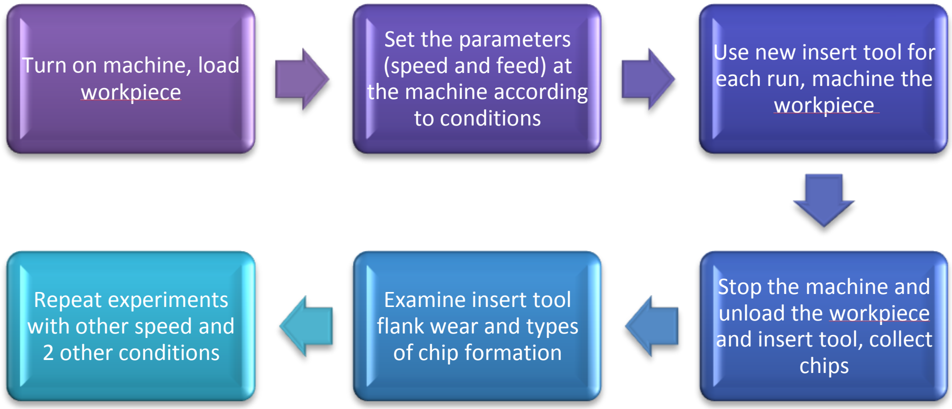


Figure 23: The General Steps for conducting experiment

The CPO is being applied on the workpiece by the system that has been designed and fabricated (shown in **Figure 24).** Average flow rate of CPO applied was 4800ml/hr and considered as flood application when compared to MQL flow rate of 100ml/hr [3].

Figure 24: CPO application system

Figure 25: Image taken during conducting control (dry), commercial (*Solkut*) and CPO conditions

3.4.1 Tool Wear Measurement

The machine used to measure the tool wear is a 3D non-contact measurement machine manufactured by Mitutoyo, modeled 3D QVPAK Quick Vision. The machine is able to obtain a clear view of the tool flank wear and chip formation with up to two times (2x) magnification (0.00481mm/pixel) of an image captured.

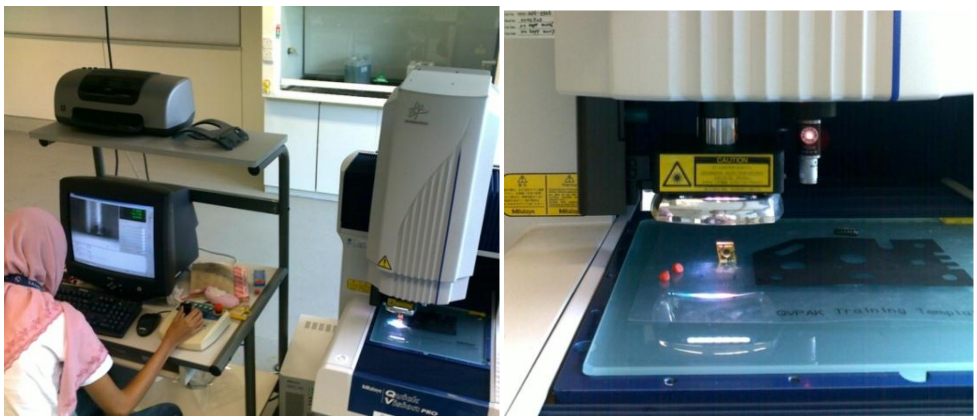


Figure 26: The measuring machine to inspect tool wear and chip formation

The following **Figure 27** shows the measurement of flank wear, V_b and crater wear, K_T at the tool dimension and shows the actual image taken to indicate flank and crater wear at the tool.

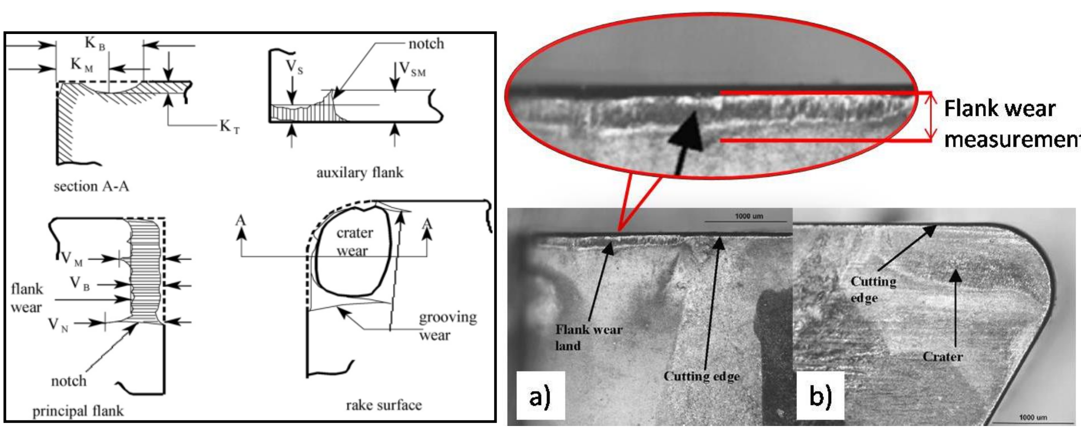


Figure 27: (top) Geometry and major features of wear in turning tools [3] and (bottom) Photographs of (a) limited rake-surface crater, and (b) clear flank-surface wear land after 45s of machining at higher cutting speed (400m/min) under dry condition with flat faced CVD tools (50x) [8]

3.5 Project Milestone

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic														
2	Project Identification and Planning														
3	Preliminary Research Work														
4	Submission of Preliminary Report				●										
5	Project Work:														
	• Further research and study														
	• Literature review														
	• Benchmarking studies														
6	Submission of Progress Report								●						
7	Seminar (compulsory)								●						
8	Project work continues:														
	• Defining project constraints and criteria to be evaluated														
	• Developing the analysis technique														
9	Submission of Interim Report Final Draft														●
10	Oral Presentation								During study week						

continued from previous															
No	**Detail/Week**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**
11	Project work continues:	■	■	■											
	• Machines familiarization & training	■	■												
	• Dummy test (dry run)		■	■											
12	Submission of Progress Report 1				●										
13	Project work continues:				■	■	■								
	• Control experiment				■	■	■								
	• Commercial experiment					■	■	■							
14	Submission of Progress Report 1								●						
15	Seminar (compulsory)								●						
16	Project work continues:							■	■	■	■	■	■	■	■
	• CPO experiment							■	■	■					
	• Data preparation & interpretation										■	■	■		
17	Poster Exhibition											●			
18	Submission of Dissertation Final Draft														●
19	Oral Presentation							During study week							
20	Submission of Dissertation (hard bound)							7 days after oral presentation							

● Milestone ■ Process

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Work Completed

The project has finally come to an end and the target and planning in the milestone have been achieved so far:

- Completion of 2 speed for control (dry), commercial (*Solkut*) and CPO conditions in turning operation
- The results for the completed experiments were tabulated, plotted
- Further interpretations on the results with respect to the effect on tool wear and chip formation
- Concluding the project and suggesting recommendations for future developments

4.2 Data Gathering and Analysis

In each of the experiment, the tool flank wear were being measured and the chip sample was collected to investigate the effect of CPO when comparing with other conditions. Two different speeds were conducted which were 50m/min and 100m/min. For the case of 50m/min, the tool flank wear was measured by the 5 minutes interval time to compare the rate of flank wear growth in each condition. By referring **Table 8**, the machining stop when flank wear is ≅ 0.3mm in accordance to ISO Standard 3685 for single point tool life testing. As for the case of 100m/min, only the final flank wear were measured after machining with the same accumulated time with 50m/min to inspect the effect of CPO with different speed. This was due to project time constraint since both machines were not located at the same building and therefore was not relevant to continue.

4.2.1 Tool Flank Wear

Table 10 below shows the results of the tool flank wear measured in the experiment based on measurement point shown in **Figure 28**.

Table 10: Flank wear measurement results from the experiments

				Flank wear at cutting time (mm)					
Tool	**cond.**	**V**	**Point**	**0 min**	**5 min**	**10 min**	**15 min**	**20 min**	**25 min**
1	**Commercial (with *Solkut* 2140)**	**50**	**pf1**	0.000	0.008	0.019	0.028	0.032	0.048
			pf2	0.000	0.032	0.056	0.075	0.079	0.106
			pr1	0.000	0.044	0.178	0.181	0.188	0.192
		100	**pf1**	0.000					0.043
			pf2	0.000					0.043
			pr1	0.000					0.048
2	**CPO (with CPO as cutting fluid)**	**50**	**pf1**	0.000	0.034	0.043	0.048	0.058	0.063
			pf2	0.000	0.048	0.063	0.091	0.101	0.106
			pr1	0.000	0.067	0.072	0.077	0.086	0.111
		100	**pf1**	0.000					0.043
			pf2	0.000					0.087
			pr1	0.000					0.082

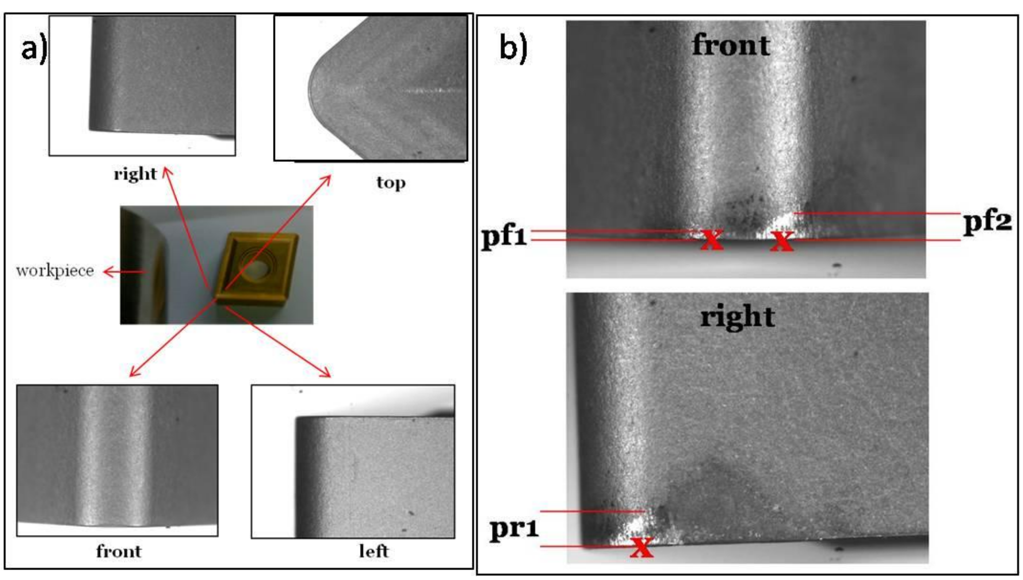


Figure 28: (a) Parts nomenclature and (b) Point measurement of flank wear (2x magnifications)

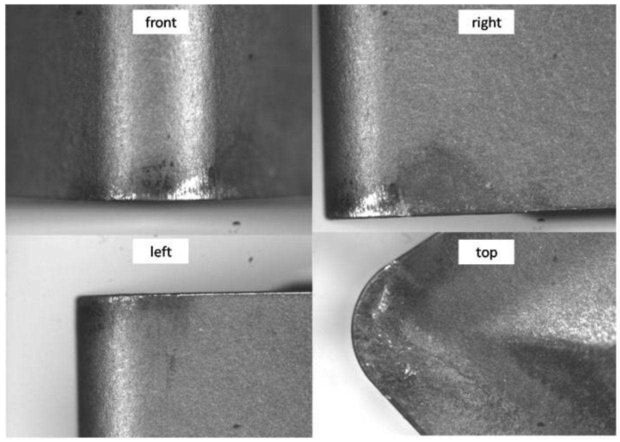


Figure 29: Tool after 25 minutes machining (condition: control, 50 m/min) with 2x magnification

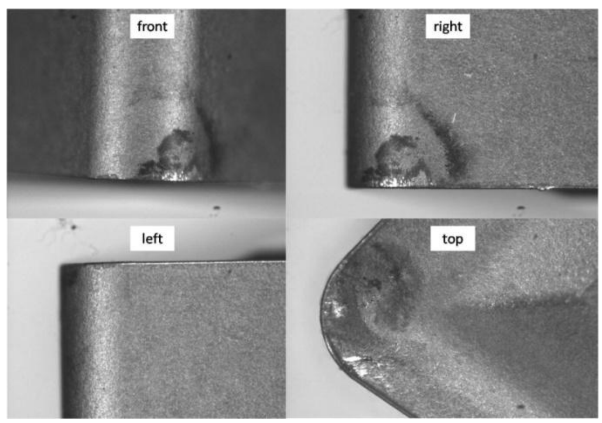


Figure 30: Tool after 25 minutes machining (condition: commercial, 50m/min) with 2x magnification

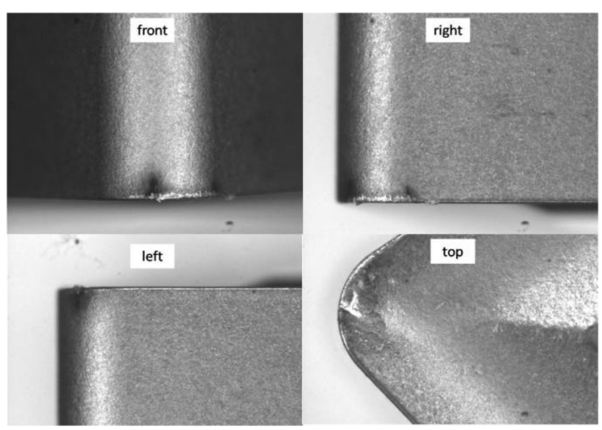


Figure 31: Tool after 25 minutes machining (condition: CPO, 50m/min) with 2x magnification

Based on **Table 10** and **Figure 29 - 31**, for the first point of measurement which is pf1, it reveals the growth trend for all conditions were not so similar along the machining time. It can be seen that in the first 5 minutes of machining, the growth of flank wear measured in CPO condition was higher than commercial condition. But as the machining time increases, the growth of flank wear measured in CPO condition was considerably less.

At this area of the tool, commercial condition did the best in decreasing the growth of flank wear compared to other conditions. The growth of flank wear observed was steadily lower than CPO conditions. Pictorial results can be referred at **APPENDIX 4-1 – 4-3.**

Based on **Table 10** and **Figure 29 - 31**, for second point of measurement which is pf2, it shows the growth trend for CPO and commercial. At this area of the tool, CPO and commercial reacted similar in decreasing the growth of flank wear. Pictorial results can be referred at **APPENDIX 4-1 – 4-3.**

Based on **Table 10** and **Figure 29 - 31**, for third point of measurement which is pf1, it shows clearly the growth trend for all conditions were very much similar along the machining time. Except for CPO, the growth for commercial conditions shoots drastically on the first 10 minutes and then gradually increasing. The flank wear measured in CPO condition was significantly less than the other conditions.

At this area of the tool, CPO did the best in decreasing the growth of flank wear compared to the other conditions. Each condition followed the same trend along the machining time. Pictorial results can be referred at **APPENDIX 4-1 – 4-3.**

Based on the results in **Table 10**, it can be seen that CPO did has a potential on reducing the tool flank wear in machining process. At some area of the tool, CPO outperforming all the conditions by having the lowest flank wear measured.

The cause behind reduction in flank wear may reasonably be attributed by the high viscosity of CPO which enables reduction of friction between tool and workpiece interface. Due to this, easy removal of heat developed at the interface which caused the reduction of temperature at the cutting zone. The polar heads of the molecules in CPO could have been a great chemical affinity for metal surfaces and attach themselves to the metal like magnets. And as a result, a dense, homogeneous alignment of CPO molecules, perpendicular along the metal surface that creates a thick, strong and durable film layer of lubricant. Thus, with decreasing friction between the tool and workpiece, tool flank wear is also reduced.

Figure 29 – 31 shows the image taken under 3D Non-contact measuring machine with 2 times magnification. Looking at the front and right part of the tool, it can be seen clearly that CPO contributed to the reduction of flank wear to the tool and was considerably balanced throughout the flank face. Burn marks in commercial condition however, can be seen clearly possibly due to the cooling effect.

From **Table 10** it also shows the results of flank wear measured for both speed, 50m/min and 100m/min. It reveals that tool flank wear decreases when cutting speed increases from 50m/min to 100m/min for all measurement point of the tool. The cause could have been at low cutting speed, the machining process is generally unstable, particularly at the beginning of the cut. This is due to higher friction between the interfaces, irregular break-in wear[8] of fresh cutting edges, chances of built-up edge formation and fluctuation in cutting forces. All of these factors may reasonably contribute to higher tool flank wear in lower speed. As for CPO effect in high speed, the overall results of CPO when compare to commercial condition it produced relatively similar effect in terms of flank wear growth.

4.2.2 Chip Formation

The chip samples were collected and examined for all experiment conditions. The following **Figure 32** and **33** shows the results of the chip obtained throughout the experiments.

[8] Caused by attrition and micro chipping at the sharp cutting edges

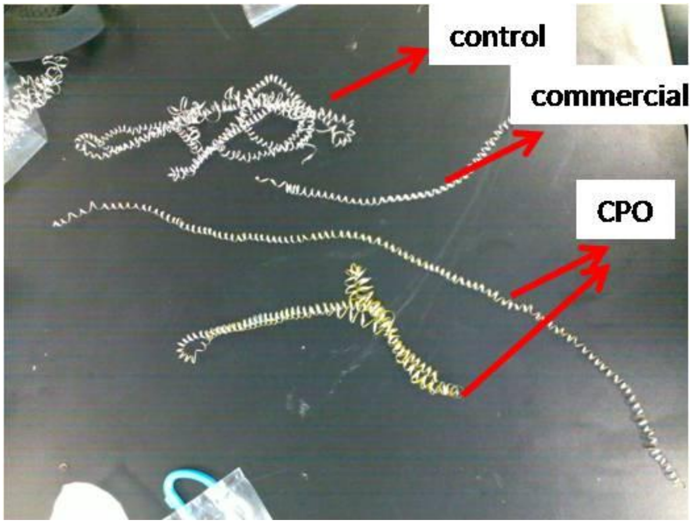


Figure 32: Chip samples collected from all conditions

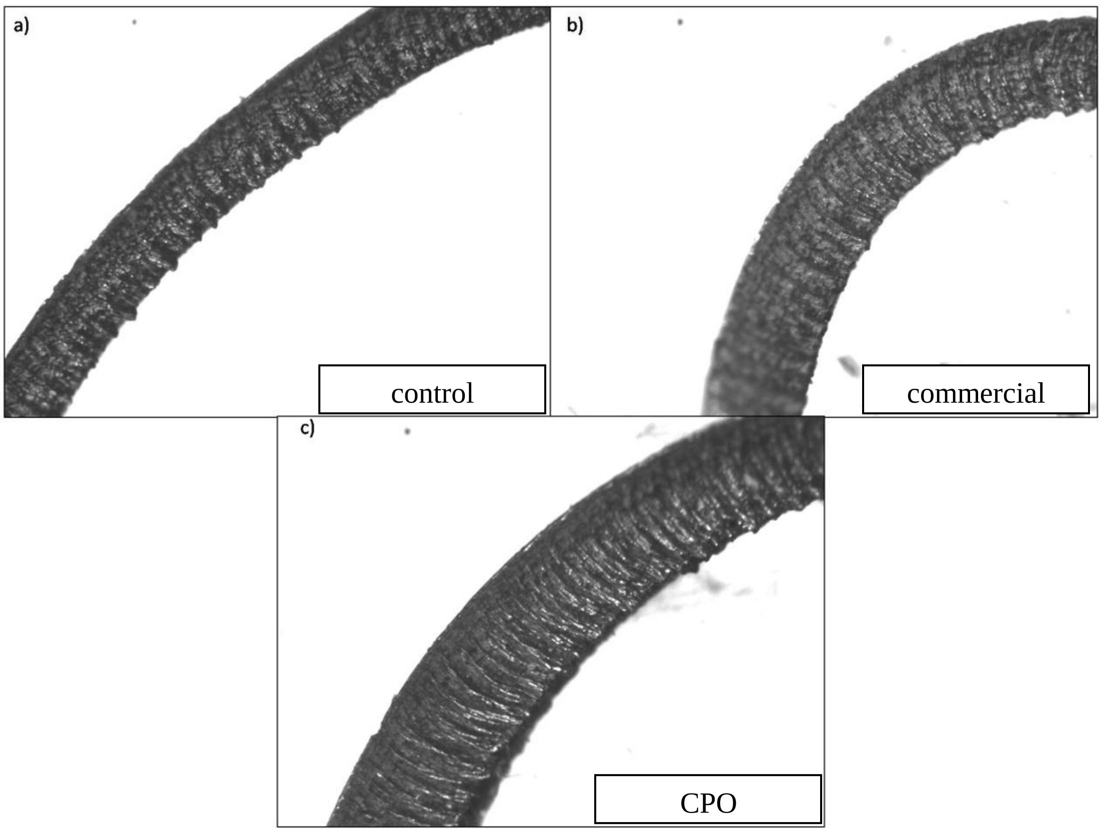


Figure 33: Images of chip samples examined under 3D Non-contact measuring machine with 2x magnification, (a) Control, (b) Commercial and (c) CPO for 100m/min of cutting speed, 0.067 mm/rev of feed and 0.5mm of depth of cut

Based on **Figure 32** and **33**, it envisages the chip formation resulted during the experiments for all conditions. The first observation was the continuity of the chip form. For all three conditions, the chip formed was a long, continuous chip, having different size of tubular/helical and curly shape. The size of the helical chip was reduced from the chip sample of control condition, followed by CPO condition and commercial condition being the smallest. It can be seen also from **Figure 33,** the radius of curvature of each chip being examined is different, having control condition the largest, followed by CPO condition then commercial. This may possibly be contributed by the instantaneous cooling effect and heat removal by *Solkut* cutting fluid during the machining process that curls up the chip becoming smaller.

The second observation of the chip being examined was the formation of serrated chip. Based on **Figure 33,** all three conditions produced a serrated type of chip and formation adiabatic shear band[9] can also be seen. This may considerably cause by the properties of AISI 304 stainless steel that has shear localization (adiabatic shear band) due to relatively low thermal conductivity. Thus, the heat produced is retained in the zone where it is created and shear deformation is localized, producing the shear bands.

The following **Figure 34** shows a sharp point saw-tooth shape of chip samples found in a control condition. Saw-tooth or segmented chips formation is noticeably common in higher cutting speed and the origin of the saw-tooth chips presently derived from two theories; the first to appear assumed they are of thermal origin which related to the adiabatic shear bands and the second assumes they arise due to periodic development of cracks in the original surface of the workpiece.

Nevertheless, the effect of CPO in chip formation is insignificant as the ductile chip generally stays continuous and did not change appreciably for all the experiments. Discontinuous chips are however, considerably desirable for a better comfort of machining and ease of chip disposal.

[9] A plastic deformation at high rate in processes such as metal forming

Figure 34: Saw tooth shape of chip produced in high cutting speed with 2x magnification (condition: dry, cutting speed: 100m/min, feed: 0.067mm/rev, depth of cut: 0.5mm)

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on the overall progress, all the experiments to test CPO effect on tool wear and chip formation have been completed and the results have been obtained and analyzed. The conclusions that have been made upon completion of the project are:

5.1.1 CPO effect on tool wear

The results shows that CPO contributed positively to the reduction of the tool flank wear, establishing its credibility to be on the same par with the performance of commercial cutting fluid and at some cases, outperform the commercial's performance.

5.1.2 CPO effect on chip formation

As the case of chip formation however, CPO did not contributed significantly on the major changes in chip formation. This may due to the fact that chip formation usually varies with varying feed. Nevertheless, this proves that CPO does not give a bad impact on the chip formation during machining as it shows similar trend to other conditions.

At this stage, palm oil has revealed its potential in reducing the tool flank wear, and considerably improving the tool life and protecting the tool. However, the results are still inadequate to support the claim of palm oil can be a better cutting fluid. But having equipped with better lubricity properties as well as biodegradability characteristics, CPO is promising enough to encourage future undertakings and to be developed into cutting fluid and lubricants, replacing the commercial cutting fluid and thus, reducing pollution and helping the earth towards green environment.

5.2 Recommendation

Based on the results that have been obtained upon completion of this project, there are several recommendations that can be highlighted to assist future work for expansion.

5.2.1 Improving the properties of CPO

As there are some drawbacks when using CPO in its crude state, it is recommended to improve the properties of CPO by some means:

- Genetic engineering of palm to reduce saturates and increase monosaturates – this will help improving the oxidative stability and low pour points of CPO, which contributes to better lubricity properties

- Adding additives to CPO in boosting its performance such as antioxidants, detergents, rust and corrosion inhabitants and others. Mineral oil too, cannot meet most lubrication performance needs without additives. Thus, the use of additives in formulated lubricant systems will undoubtedly needed.

5.2.2 Implementing Minimum Quantity Lubrication (MQL)

The recommendation on implementing MQL is mainly driven by most of the literature review from all over researchers' revealing the performance of vegetable oil in MQL. Not only it drives towards reducing the cost of cutting fluid management, but also contributes on sustainable development of vegetable oil, specifically CPO in this context.

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APPENDICES

APPENDIX 3-1: Recommendation for turning operation

TABLE 23.4

General Recommendations for Turning Operations

Workpiece material	Cutting tool	General-purpose starting conditions: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min	Range for roughing and finishing: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min
Low-C and free machining steels	Uncoated carbide	1.5–6.3	0.35	90	0.5–7.6	0.15–1.1	60–135
	Ceramic-coated carbide	•	•	245–275	•	•	120–425
	Triple-coated carbide	•	•	185–200	•	•	90–245
	TiN-coated carbide	•	•	105–150	•	•	60–230
	Al_2O_3 ceramic	•	0.25	395–440	•	•	365–550
	Cermet	•	0.30	215–290	•	•	105–455
Medium and high-C steels	Uncoated carbide	1.2–4.0	0.30	75	2.5–7.6	0.15–0.75	45–120
	Ceramic-coated carbide	•	•	185–230	•	•	120–410
	Triple-coated carbide	•	•	120–150	•	•	75–215
	TiN-coated carbide	•	•	90–200	•	•	45–215
	Al_2O_3 ceramic	•	0.25	335	•	•	245–455
	Cermet	•	0.25	170–245	•	•	105–305
Cast iron, gray	Uncoated carbide	1.25–6.3	0.32	90 (300)	0.4–12.7	0.1–0.75	75–185
	Ceramic-coated carbide	•	•	200	•	•	120–365
	TiN-coated carbide	•	•	90–135	•	•	60–215
	Al_2O_3 ceramic	•	0.25	455–490	•	•	365–855
	SiN ceramic	•	0.32	730	•	•	200–990

(Continued)

TABLE 23.4 *(Continued)*

General Recommendations for Turning Operations

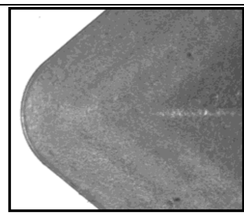
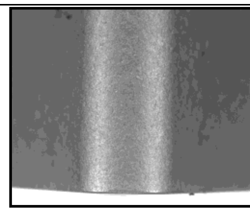
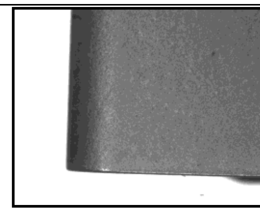
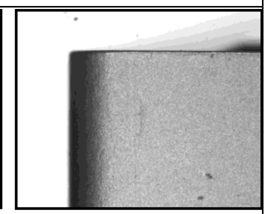
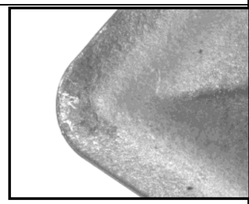
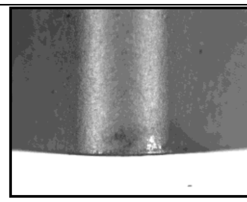
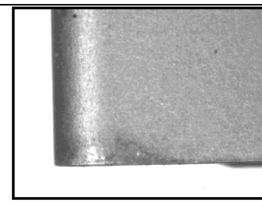
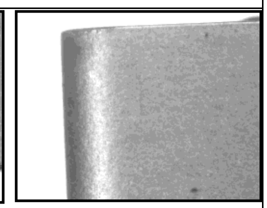
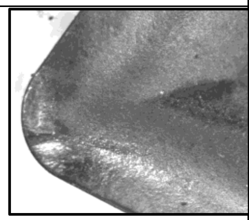
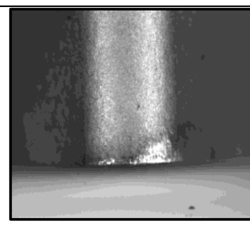
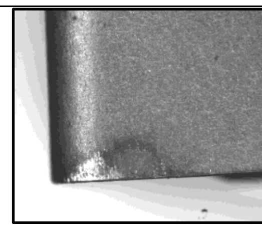
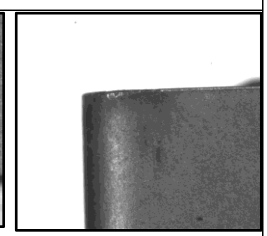
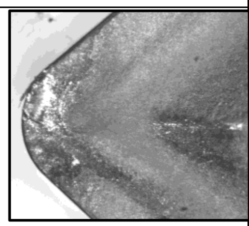
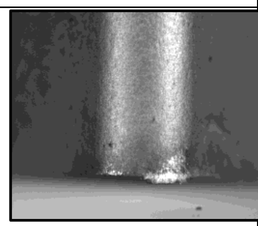
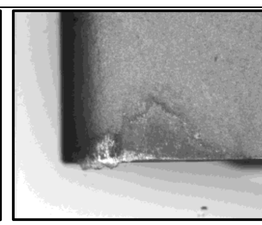
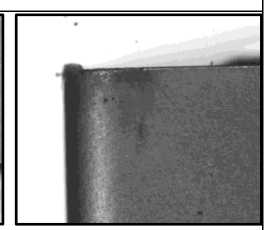
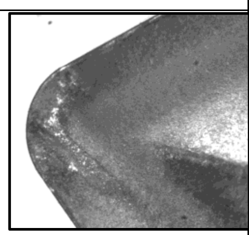
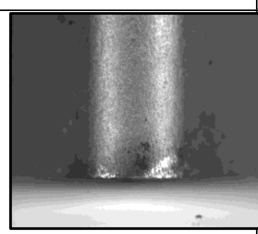
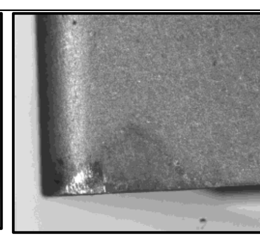
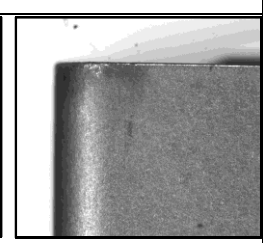
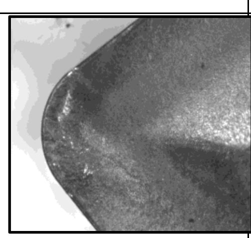
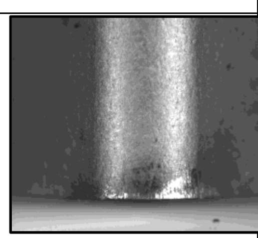
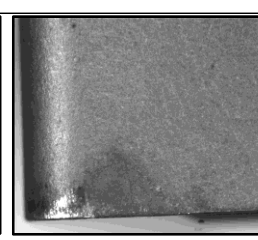
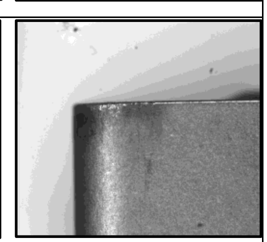
Workpiece material	Cutting tool	General-purpose starting conditions: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min	Range for roughing and finishing: Depth of cut, mm	Feed, mm/rev	Cutting speed, m/min
Stainless steel, austenitic	Triple-coated carbide	1.5–4.4	0.35	150	0.5–12.7	0.08–0.75	75–230
	TiN-coated carbide	•	•	85–160	•	•	55–200
	Cermet	•	0.30	185–215	•	•	105–290
High-temperature alloys, nickel based	Uncoated carbide	2.5	0.15	25–45	0.25–6.3	0.1–0.3	15–30
	Ceramic-coated carbide	•	•	45	•	•	20–60
	TiN-coated carbide	•	•	30–55	•	•	20–85
	Al_2O_3 ceramic	•	•	260	•	•	185–395
	SiN ceramic	•	•	215	•	•	90–215
	Polycrystalline cBN	•	•	150	•	•	120–185
Titanium alloys	Uncoated carbide	1.0–3.8	0.15	35–60	0.25–6.3	0.1–0.4	10–75
	TiN-coated carbide	•	•	30–60	•	•	10–100
Aluminum alloys							
Free machining	Uncoated carbide	1.5–5.0	0.45	490	0.25–8.8	0.08–0.62	200–670
	TiN-coated carbide	•	•	550	•	•	60–915
	Cermet	•	•	490	•	•	215–795
	Polycrystalline diamond	•	•	760	•	•	305–3050
High silicon	Polycrystalline diamond	•	•	530	•	•	365–915

(Continued)

APPENDIX 3-2: AISI 304 Stainless steel material properties

Properties	Value	Comment
Physical properties		
density	8.00 g/cc	Converted from Rockwell B hardness
Mechanical properties		
Hardness, Brinell	123	Converted from Rockwell B hardness
Hardness, Knoop	138	
Hardness, Rockwell B	70	Converted from Rockwell B hardness
Hardness, Vickers	129	
Tensile strength, ultimate	505MPa	
Tensile strength, yield	215MPa	At 0.2% offset
Elongation at break	70%	In 50mm
Modulus of elasticity	193-200GPa	
Poissons ratio	0.290	
Charpy impact	325 J	
Shear modulus	86.0 GPa	
Electrical properties		
Electrical resistivity	0.0000720 ohm-cm	
Magnetic permeability	1.008	At RT
Thermal properties		
CTE, linear	17.3µm/m-ºC	
Specific heat capacity	0.500 J/g-ºC	
Thermal conductivity	16.2 W/m-K	
Melting point	1400-1455ºC	

APPENDIX 4-1: Image results from control condition with 50m/min cutting speed (2x magnification)

Time, min	Wear on tool			
	Top	Front	Right	Left
0				
5				
10				
15				
20				
25				

APPENDIX 4-2: Image results from commercial condition with 50m/min cutting speed (2x magnification)

Time, min	Wear on tool			
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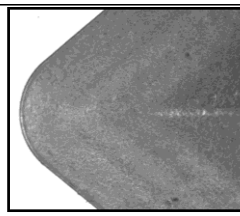
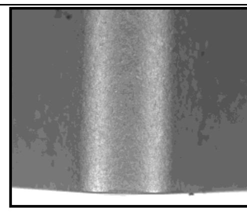
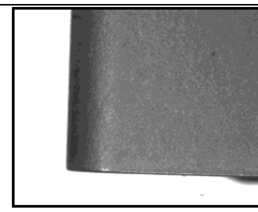
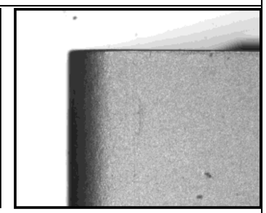
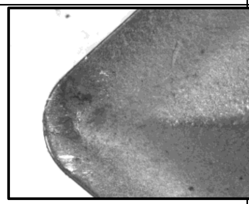
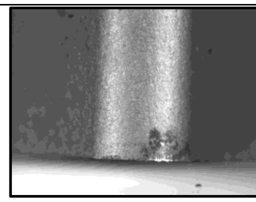
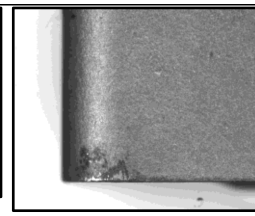
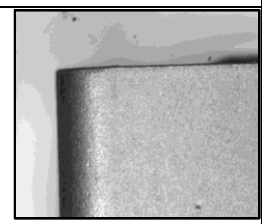
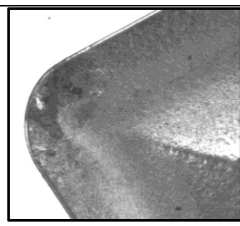
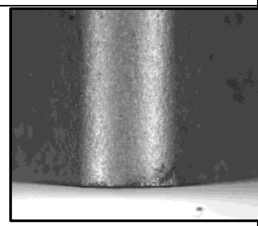
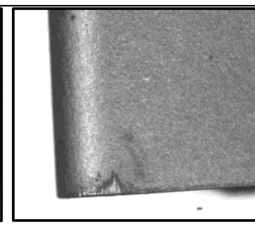
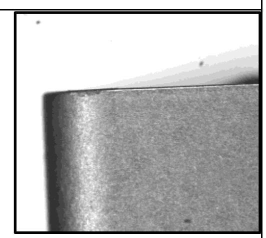
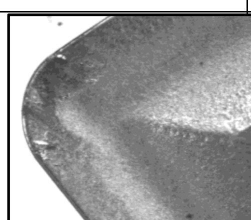
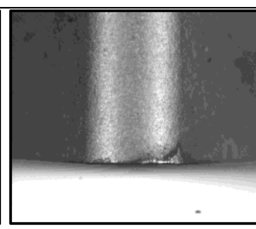
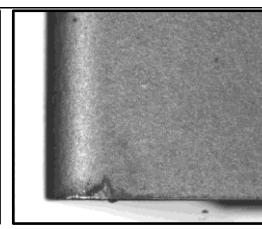
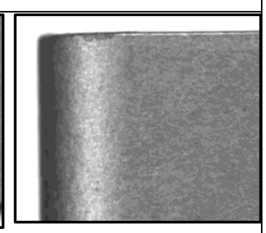
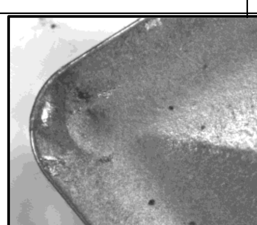
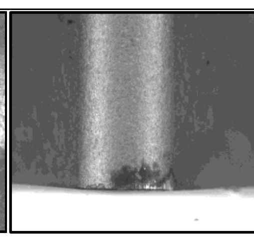
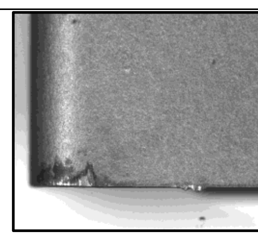
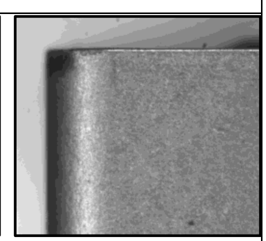
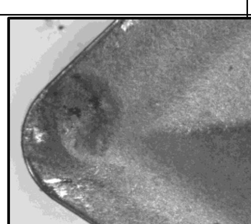
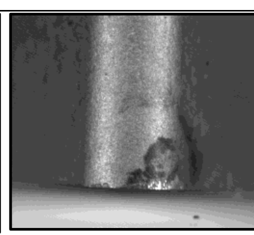
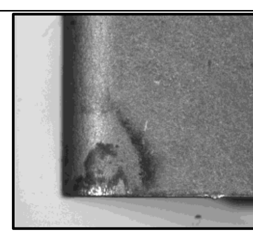
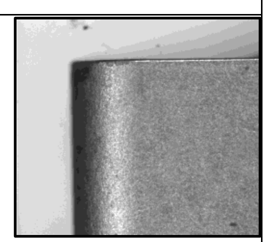
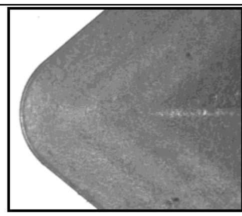
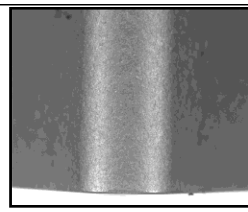
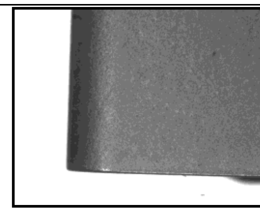
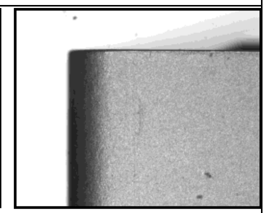
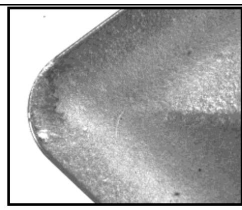
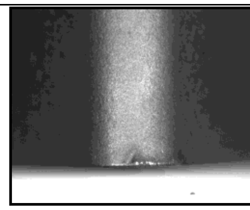
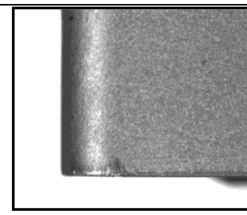
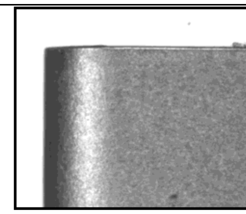
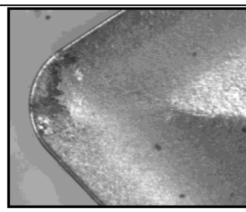
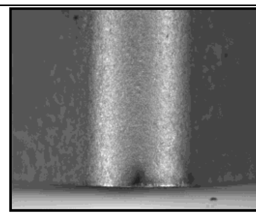
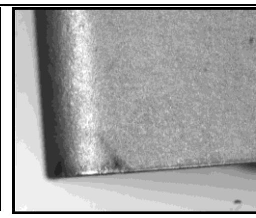
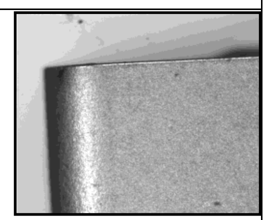
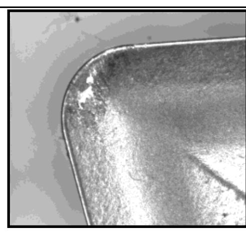
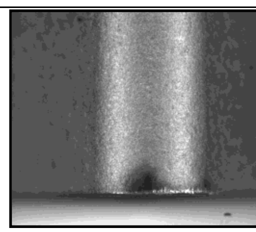
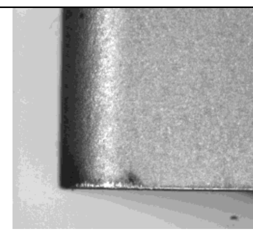
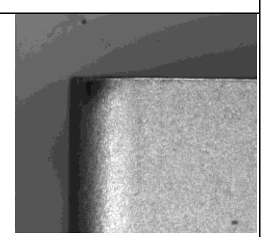
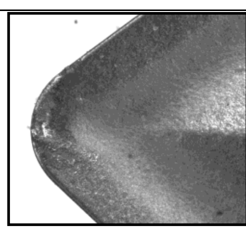
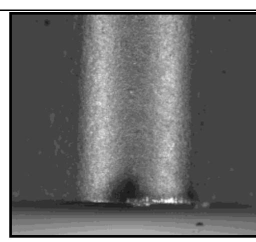
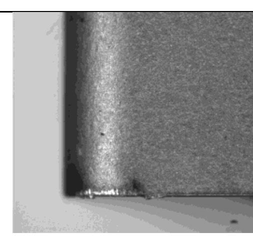
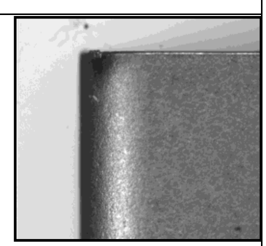
0				
5				
10				
15				
20				
25				

APPENDIX 4-3: Image results from CPO condition with 50m/min cutting speed (2x magnification)

Time, min	Wear on tool			
	Top	Front	Right	Left
0				
5				
10				
15				
20				
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