# PERFORMANCE EVALUATION OF WHITE COCONUT OIL BASED METAL WORKING FLUID


Krishan Chanaka Wickramasinghe

(179265C)


Degree of Master of Engineering


Department of Mechanical Engineering

University of Moratuwa
Sri Lanka


September 2020

# PERFORMANCE EVALUATION OF WHITE COCONUT OIL BASED METAL WORKING FLUID

Krishan Chanaka Wickramasinghe

(179265C)

Thesis submitted in partial fulfillment of the requirements for the

Master of Engineering in Manufacturing Systems Engineering

Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

September 2020

## DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis/dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date:

The above candidate has carried out research for the master's thesis under my supervision.

Name of the supervisors: Dr. G.I.P Perera
Dr. Himan KG Punchihewa
Mr.S.W.M.A.I Senavirathne

Signature of the supervisor: Date:

Name of the supervisor: Dr. G.I.P Perera

Signature of the supervisor: Date:

Name of the supervisor: Dr. Himan KG Punchihewa

Signature of the co-supervisor: Date:

Name of the co-supervisor: Mr.S.W.M.A.I Senavirathne

**DEDICATION**

To the most courageous two persons who guided me to great achievements: my beloved father *Sri Lal Daneial Wickramasinghe* and mother *Pearl Wickramasinghe*

# ACKNOWLEDGEMENT

As a graduate student of the Faculty of Engineering, University of Moratuwa, I have to complete a research project for the partial fulfillment of the requirements for the MEng. in Manufacturing Systems Engineering. For that, I selected the topic "Performance Evaluation of White Coconut oil-based Metal Working Fluid". I am highly indebted to University of Moratuwa for the opportunity. Exclusively I would like to express my gratitude towards Dr. G.I.P Perera, Dr. Himan KG Punchihewa and Mr.S.W.M.A.I Senavirathne for their guidance and constant supervision as well as for providing necessary information regarding the project and for their support in completing the research project. Their kind co-operation and encouragement inspired me in completion of this project. Further, I acknowledge Mr. R.K.P.S Ranaweera for his valuable comments on my research. I would like to express my special gratitude and thanks to University of Ruhuna for giving me such information, time and engineering workshop facilities. My thanks and appreciation go to my colleagues in developing the project and people who have willingly helped me out with their abilities.

# ABSTRACT

Metal Working Fluids (MWFs) play a significant role in metal machining operations and vastly used in aerospace, automotive and marine industries to produce high tech components. The main purpose of using MWF during cutting operation is to facilitate a layer of lubricant between work tool interfaces to abate friction and heat. In the present context, industries practice to use mineral-based MWFs as of its good functional performance. However, health and environmental legislations have bounded the usage due to its carcinogenic behavior and adverse effects to the environment. Therefore, the requirement of ecological and user-friendly cutting fluid has raised substantially in manufacturing industries. Researchers have taken much effort to find an alternative for mineral oils and concluded the importance of vegetable oils as a substitute to use for the MWF. However, neat vegetable oil express poor cooling capability during machining due to its low oxidation stability. The authors have formulated a white coconut oil-based water soluble MWF to overcome the poor cooling ability by using water and permitted food grade surfactants. The main intention of the research is to assess the industrial applicability of the formulated fluid in term of functional performance while ensuring health and safety of the operators and environmental impact. The surface quality, chip curl radius, chip formation of 0.2% C and AISI 304 steels while using formulated novel white coconut oil based MWF, mineral oil based MWF in flood cooling and dry machining configurations have investigated for the conventional turning operation. The machining parameters were selected according to the recommended specifications of the work materials and tool manufacturers. Coated carbide indexable inserts have been used for the turning operation and surface quality of each set of cutting parameters were measured. Further, tool wear was investigated using scanning electron microscope (SEM). Work tool interface temperature was simulated using the DEFORM platform. The invented novel white coconut oil based MWF expressed better values for almost all the set of machining parameters when compared to the other cooling configurations and proven its industrial applicability for the sustainable machining. The performance of the formulated white coconut oil based MWF can be enhanced by adding nanoparticles and it is worthwhile to conduct the machining operations for hard to cut materials for further confirmation of the industrial applicability.

**Keywords:** Metalworking Fluid, Surface Quality, Turning, Tool Wear, Vegetable oil

**TABLE OF CONTENTS**

**LIST OF FIGURES**

**LIST OF TABLES**

## LIST OF ABBREVIATIONS

| **Abbreviation** | **Description** |
|---|---|
| AISI | American Iron and Steel Institute |
| BOD | Biological Oxygen Demand |
| BUE | Built Up Edge |
| COD | Chemical Oxygen Demand |
| CM | Chip Morphology |
| CNC | Computer Numerical Control |
| CR | Curl Radius |
| DoC | Depth of Cut |
| HLB | Hydrophilic Lithophilic Balance |
| IARC | International Agency for Research on Cancer |
| MSDS | Materials Safety Data Sheet |
| MR | Mean Roughness |
| MWF | Metal Working Fluid |
| SD | Standard Deviation |

# CHAPTER 01: INTRODUCTION

Machining is one of the most prominent and frequently conducted manufacturing procedures in industries, and it involves various materials and methodologies. The concept of sustainability in manufacturing has used to identify and evaluate the effects of machining applications and materials across a wide range of socio-economic and environmental aspects. In an assessment of sustainability, the precise effects of industrial processing methods and work materials on human health and ecological systems and their operational costs must be determined. Sustainable machining resources that ensure safe modes of formulation, usage, and disposal throughout the life cycle with reasonable operational costs exhibits a greater sustainability level. The dimensional accuracy of the required component is one of the most important factors among the output parameters in machining [1,2]. However, the lack of cooling and lubrication capability of the MWF to eliminate induce heat at work-tool interface, results the errors in dimensions with consume of higher energy for the operation and concludes with a poor surface quality of the component. For an example, Fig. 1-1 express that the dry machining induces 376 °C work tool interface temperature for AISI 304 steel with cutting parameters of 100 m/min speed and 0.2 mm depth of cut (DoC) in conventional orthogonal turning [3,4]. In this context, the importance of using well functioned MWF has identified in term of facilitating the cooling and lubrication between work tool interface for a longer tool life while preventing the cutting tool and workpiece from overheating [5].

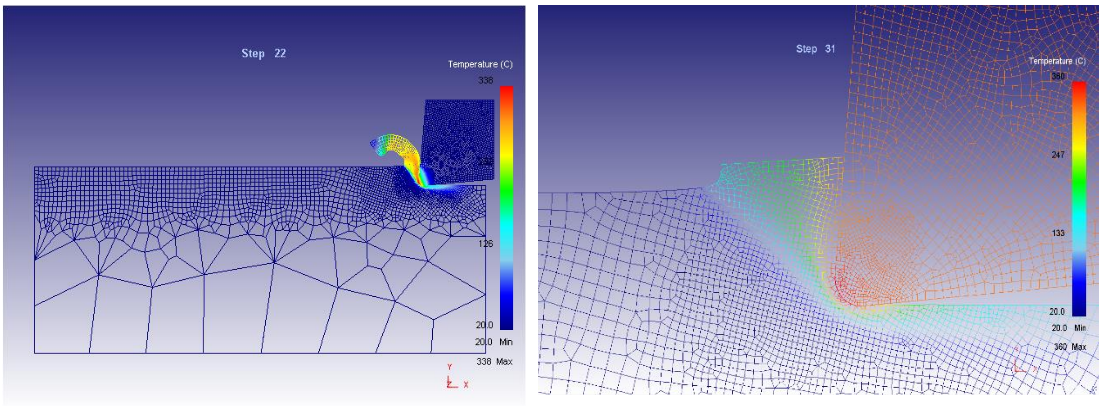



**Figure 1-1**: **Temperature distribution of work tool interface in dry cutting**

Almost all of the available MWFs are based on petroleum by-products (mineral oils), and it produces mist and oil smoke during machining operations, creating an uncomfortable and unsafe environment for the workers. Further, environmental regulatory bodies are keen on the discharge of mineral oil based MWF effluents from the industries to the environment and, already the environmental pollution has been controlled by introducing regulations to mitigate the effect to the natural resources [6,7]. In present context, industries are struggling to find an alternative to toxic and harmful mineral oil based MWF to ensure health and safety of the operators and ecological systems. Higher amount of assets need to allocate for the filtration of mineral based MWF effluents in order to adhere to the established health and environmental regulations at the disposal phase [8]. Hence, the economic and technical feasibility of the machining processes that use MWFs should also be considered, in order to ensure a reasonable profit margin in the production.

Therefore, it is highly important to introduce a sustainable green MWF for the industries to ensure the protection of operators from hazardous mineral based MWF and to ensure environmental protection at the disposal phase of the effluent with lower or no filtration cost. The saturated fatty acids of vegetable oil facilitate a better layer of lubricant at the work-tool interface compared to mineral oils. Lawal et. al. [4] revealed that the structure of the triglycerides in vegetable oils provide qualities that are desirable in lubricants. Friction at the work-tool interface is reduced by vegetable oils' long polar fatty-acid chains, which form a higher-strength lubricant film between metallic surfaces. However, vegetable oils have low oxidation stability, low hydrolytic stability, and poor heat bearing capacity due to their chemical structure. There is no literature available regarding the green MWF which has eliminated poor properties in vegetable oil and the details of empirical investigations on conventional turning while using cutting parameters recommended by the work materials manufacturers. Wickramasinghe et. al. [9] has prepared an emulsion using white coconut oil as the base oil and permitted food grade surfactants (to eliminate poor properties of the white coconut oil) which helps to improve the rate of cooling (due to higher content of water) and lubrication (higher content of free fatty acids in the white coconut oil) at the work-tool interface, during shear mechanism.

With having the motivation to present a sustainable solution for the industries in term of eliminating higher cost for the filtration and ensuring health and safety of the operators and ecological resources at the MWF usage, the stated research has carried out to assess the industrial applicability of the formulated white coconut oil based MWF in metal machining process. The white coconut oil based MWF effluent can be directly send to the natural resources after removal of the tiny metal chips in the fluid (i.e, primary filtration) due to the higher bio-based ingredients included in the fluid. The higher concentration of water in the developed MWF leads to absorb the induce heat at the cutting zone effectively due to its higher specific heat capacity. Thus, the formulated MWF is rich in cooling and lubrication properties while ensuring the health and safety of the operators and ecological resources.

Conventional turning operation was conducted with use of Lathe machine (Model CM6241X1000, spindle speed range of 45–1800 rev/min) for 0.2% C and AISI 304 steel while subjected to recommended cutting parameters by the tool and work material manufacturers. The cooling and lubrication performances of the developed MWF were empirically investigated with flood cooling technique and compared to commercially available mineral oil based MWF. Dry machining was carried out as the reference experiment. Surface quality, chip curl radius, chip formation and tool wear were investigated for each set of machining configurations for both developed MWF and mineral based MWF. The experimental procedures were conducted by following ISO 4288 for surface quality measurement with 0.8 mm cut-off length and 4 mm measurement length with total transvers length of 5.6 mm and tool wear evaluation and ISO 3685 for the chip form classification. Plotting and statistical methods were used to analysis the results and made the conclusions. Tool wear experiment was only conducted for the commercially available mineral oil based MWF. Further, orthogonal work tool temperature simulation study was carried out by using DEFORM commercial software. The tool edge temperature was investigated with the developed orthogonal 2D model and studied the residual stress subjected on the cutting process during shear mechanism. 3D model was not considered due to the higher computational time and complexity of the model.

## 1.1 Research Aims and Objectives

The foremost aim of the intended research is to introduce a high-performance health and environmental friendly cutting fluid to manufacturing industries. Specifically, the developed green MWF could able to address the health and environmental related issues (i.e: research gap) integrated in the most frequently consuming mineral oil based MWFs in current machining process. The pillars of socioeconomic and environment have been set as the research objectives to achieve and ensure process sustainability at each three phases of MWF formulation, usage and disposal. Additionally, achieving high performance machining has been set as a sub objective to obtain the promising machining responses (i.e: surface quality, chip formation, chip morphology, tool wear) to proven industrial applicability while using developed green MWF.

## 1.2 Thesis Overview

The thesis consists of five chapters. Chapter 1 describes the background study and research motivation along with the aims and objectives. Further, research methodology is stated in brief. Chapter 2 describes the referred literature related to the problem identification and significant of the research for the modern manufacturing industries. Further, details of the recently concluded research literature were discussed in order to find the research gap in the field of MWF in metal machining industries. Chapter 3, 4 and 5 express the detail description of methodology, results/discussion and conclusion respectively. The contents of the chapters are summarized in detail as below.

### Chapter 2: Literature Review

This chapter deliberates the background information and literature related to MWFs in metal machining. At the beginning of the chapter, the purpose of using MWF in cutting operation has discussed. Along with that, the current application methods and categories have described.

Apart from that the health, environmental effect and issues have comprehensively analyzed with examples. The importance of vegetable oil as the alternative to the mineral oil has emphasized with the details of significant tribological properties. The requirements in formulation process of water-based emulsion have discussed.

The potential opportunities and solutions to address the issues and problems related to current usage of mineral oil based MWF in metal machining have described under titles of minimum quantity lubrication (MQL) and Nano MWFs. Finally, the summery of the literature review has conversed.

### Chapter 3: Methodology

This chapter describes the detail procedures and apparatus used for the empirical investigation on surface quality, chip curl radius and chip formation. The tool wear investigation details were also included. Further, process modeling steps for the work tool temperature simulation were explained.

The methodology which was considered for each and every investigation were based on the scientific approach along with the recognized standards. The used apparatus for the experiments were calibrated before the investigations and confirmed the accuracy of the values.

### Chapter 4: Results and Discussion

The empirically obtained results related to the surface quality, chip curl radius and chip form were scientifically discussed based on the literature and ISO standards. Statistical approach was used to investigate the mean and standard deviation for the recorded values for the surface quality. Tables, charts and diagrams were used to compare and discuss the results related to the white coconut oil based MWF and mineral oil based MWF. Collected chips were categories according to the ISO standard for the assessment of the performance of developed MWF for the recommended cutting parameters by the tool and work materials manufacturers. Scanning electron microscope (SEM) images were used to discuss the crater and flank wear on the tool while using mineral oil based MWF.

### Chapter 5: Conclusion

The final chapter summarizes the contributions of the thesis, the conclusion, a brief discussion, and future directions for the betterment of the industries in field of MWF.

# CHAPTER 02: LITERATURE REVIEW

Cutting fluids have been used over the past of 200 years for various metal machining operations. The main purposes of using cutting fluids are to facilitate a fluid layer between work tool interface to abate high friction areas as shown in Fig. 2-1 and providing better cooling effect for heat reduction between work tool interface while acting as a flushing medium to facilitate a favorable condition for metal machining operation [10]. These functions are helped to reduce tool wear, lower the energy consumption for cutting process and produce required specified quality of the final part with required dimensional accuracy [11].

Cutting fluids can be considered in term of water-soluble liquids, straight cutting oils and gases [12]. Out of these categories water-soluble liquids are mainly used for machining applications in wide range of materials due to higher cooling capabilities [13]. Most of the cutting fluids are petroleum based mineral fluids hence, express considerable environmental and occupational health effects throughout the operating life cycle. Therefore, alternative solutions are highly expected in the modern manufacturing industries. Researches for the suitability of using vegetable oil based MWFs in metal machining applications have been conducted in recent years and many of them are now on evaluating the applicability of the varies types of available vegetable oils for metal machining applications [14].

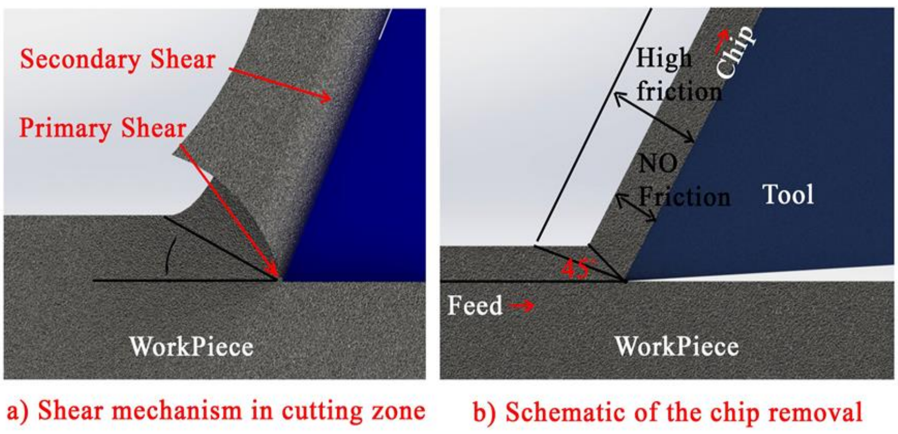



**Figure 2-1: The shear mechanism and chip removal in cutting region** [15]

Further, it has been found that water-soluble fluids can also be developed by using vegetable oils such as coconut oil, sunflower and soybean [16]. Most of the manufacturing industries intended to use machining operations to produce metal parts by a controlled material removal process. Not only for the metal machining but also it can be used in machining of nonferrous material such like wood, composites, plastic and ceramic.

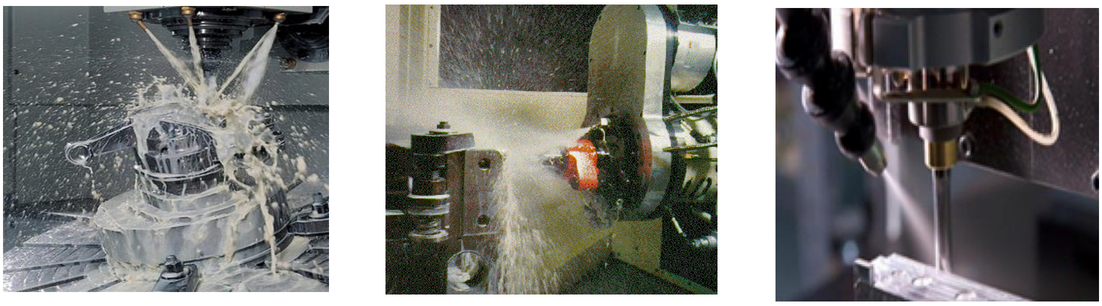
Computer numerical control (CNC) technique is extensively used in modern manufacturing industries for the high precision productions, where the computers and supportive accessories are used to control the movement and operation of work piece and cutting tool [17]. MWFs are used for the process optimization of cutting operations such as turning, profiling, boring, threading, grinding, drilling and milling. The fluid is used to flush the metal chips from the interfaces of work piece and tools while acting as cooling medium and abate friction between work piece and cutting tool by inducing a lubricating layer. Most of the machining operations are conducting with use of oil-in-water emulsions which commonly known as water soluble MWFs [18]. The growth of microorganisms increases with the addition of water to the oil and build a favorable environment for the microorganisms to live. Microbial development results in bio deterioration of cutting fluids due to break down of its components such as emulsifiers, additives and oils and finally results for the poor performance of the cutting fluids [19].

## 2.1 Methods of Metal Working Fluids Application

The Metal Working Fluids can apply into the work tool interface during metal machining as flood, jet and mist approaches [6]. A sliding surface should form between tool and work piece from a cutting fluid for an efficient machining [20]. The application should be continuous and pointed directly to the cutting zone for a better machining to obtain higher dimensional accuracy of the machined parts. The lubrication and cooling function cannot perform unless the fluid is carefully directed to the cutting zone. In manual approach, the MWF is applied to the cutting zone with use of an oil container. This approach is cheapest and easiest with comparing to the other approaches [3].

The application area of the cutting fluid is limited compared to the flood, jet and mist cooling approaches as illustrated in Fig. 2- 2 [13]. The performance of the cutting fluid is lower due to the intermittent approach and access of the MWF to the work tool interface is limited in this method.

Flood cooling approach is widely using industrial application to apply MWF to the interfaces of work and tool. A large volume of continuous flow is delivered to the cutting region with use of a nozzle, hose or pipe [21]. In flood cooling approach, the MWF is stored in a tank, filtered and supply to the discharge port. The flow rate, number of nozzles or pipes and direction of flow are critical parameters in obtaining better machining performance [17]. In this method, the reach of MWF to the interfaces in complex machining is not in satisfactory level. The MWF is atomized and blown to the interfaces in mist approach. This method is more effective in complex machining due to the possibilities of delivering cutting fluids into the difficult to access places in the complex component [13]. However, the inhalation of generated mist from the mineral oil based MWF causes serious health issues and the need of proper ventilation is important in mist approach during machining.



(a) (b) (c)

**Figure 2-2: (a) Flood Cooling (b) Jet Cooling (c) Mist Cooling** [22]

## 2.2 Categories of the Metal Working Fluids

### 2.2.1 Straight Oils

The straight oils are commonly used for the metal cutting applications in term of neat oils without adding water or any other additives/ingredients which comprised basically the petroleum or vegetable oils [23].

The surface finish is in higher level with comparing to other types of cutting fluid applications while prevents rusting as well [24]. The mineral oils used in cutting fluids are generally neutral oils, light solvents or sometimes heavy bright [15]. Further, the wetting actions and lubricity can be increased in mineral oil with adding animal or vegetable oils in controlled proportions [25].

### 2.2.2 Soluble Oils

With the introduction of carbide cutting tools and high-speed machining into the metal machining industries, water-diluted cutting fluid requirement was induced. The neat mineral oil facilitates a better lubrication layer but the cooling capability is not in satisfactory level [9]. The fluids prevent the thermal distortion which resulted from the induced residual heat and abate cutting tool abrasive wear at the higher temperatures which address the short comes of the direct use of straight oils [26]. The well-refined petroleum oils are mixed with ingredients of higher viscosity liquids which are insoluble in independent manner in water [27]. Fig. 2-3 express the categories of water soluble MWFs.

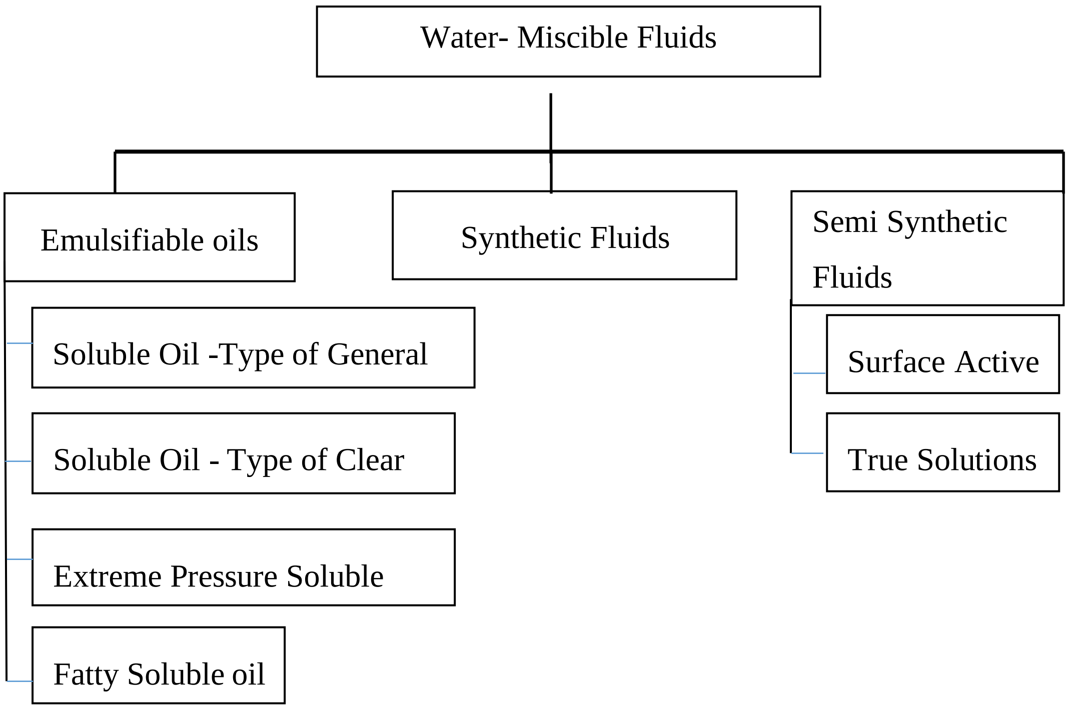



**Figure 2-3: Categories of the Water-Soluble Metal Working Fluids** [4]

### 2.2.3 Synthetic Metal Working Fluids

The synthetic cutting fluids can formulate with inorganic or organic solvents and mixed in water. Synthetic MWFs act as the lubricant and coolant which express the usage of eliminating smoke during machining, provide detergent action and reduce oxidation [28]. Rust protection and removal of induced heat is in higher level but poor in lubrication capability [19]. The semi synthetic MWF act as a significant place in term of addressing the poor lubrication property of the synthetic MWF. It contains more additives and surfactants to facilitate a better lubrication layer between work tool interfaces. The researchers are currently working on the evaluation of performance while using synthetic and semi synthetic vegetable based MWFs in metal machining operations. Further, synthetics can complement with biocides in term of reducing the intended microorganisms growth [7]. Table 2-1 and Table 2-2 are expressed the advantages and disadvantages of each category of MWFs.

**Table 2-1: Advantages comparison of cutting fluids** [6,14]

| Straight oils | Soluble oils | Semi-synthetics | Synthetics |
|---|---|---|---|
| Excellent rust control. | Good cooling. | Good cooling. | Excellent cooling. |
| Excellent lubricity. | Good lubricity. | Good microbial control. | Excellent microbial control. |
| | | Good rust control. | Reduced misting and foaming problems. |

**Table 2-2: Disadvantages comparison of cutting fluids** [6,14]

| Straight oils | Soluble oils | Semi-synthetics | Synthetics |
|---|---|---|---|
| Low cooling. | Rust control Problems. | Foam easily. | Poor lubricity. |
| Create a mist or smoke. | Evaporation Losses. | Easily contaminated by another machine fluids. | Easily contaminated by other machine fluids. |
| Limited to low speed. | Bacterial growth. | Stability is affected by water hardness. | |

## 2.3 The Environmental Impact of Metal Working Fluids

More than 30% industries in European countries and 25% of United States are used to dispose MWF effluents to the environment without proper treatment by neglecting the established environmental rules and regulations [29].

Large volume of cutting fluids released to the environment as effluents from industries in developed countries which negatively affect for the living beings and impact heavily for the sustainability of the entire world [21]. The physical and chemical properties of MWFs will change during the operational life cycle and it will directly influence for the selection process of the disposable method. Biodegradability, disposable methods and toxicity of cutting fluids are acting as the prominent factors for the environmental protection according to the stated regulations [34,35].

## 2.4 Disposal of Metal Working Fluids

After intended lifetime of the MWFs (about 3-4 months of usage), it is required to dispose the effluent to the environment with a proper treatment process. The available most frequently disposable methods can be categorized as: chemical, physical-mechanical, electrochemical and biological [32]. In chemical splitting technique, an electrolyte is added to neutralize the emulsifier where the emulsion breaks down while aquatic and oil phases are settled in a tank [33]. The electrochemical method is used the destabilization technique of stern ionic layer surrounding of the oil droplets in the emulsion [34]. The electrostatic filed is continuously generated from the immersed electrodes in the emulsion. The collection of the oil droplets is occurred around the electrodes in larger number [35]. The most common method which shown the better results of cutting fluid disposal is ultrafiltration thermal splitting where the evaporation and incineration are used to separate the oil and water in the emulsion [31].

## 2.5 Biodegradability of Metal Working Fluids

Biodegradability is an important phenomenon for the environmental suitability. It represents the removal process of oil from water and soil segments in the environment [36]. Acceptable level of biological oxygen demand (BOD) and chemical oxygen demand (COD), where the two laboratory experiments measure the biodegradability of the discharge effluent of environmental authorities in each country.

Variety of standard testing procedures are available to evaluate the biodegradability of the organic substances [37]. Following are the accepted methods for the biodegradation.

- Primary Biodegradation – Specific properties of the substance are impacted by the process of biological reactions to change the chemical structure [18].
- Ultimate Biodegradation – The microorganisms utilize the compound of the substance and release $H_2O$, $CO_2$, mineral salts and new microbial cellular constituents (biomass) [37].
- Readily Biodegradable – Chemicals use to break the properties of the substances and should operate the process in aquatic environments under aerobic conditions [37].

## 2.6 Adverse Effect of the Mineral oil based MWF

Minerals oils which are used in metal machining process were recorded as carcinogenic in 1987 according to the reports of International Agency for Research on Cancer (IARC) [38]. Further, the experiment on toxicity was concluded with some fluid additives and surfactants cause cancer in laboratory animals [39]. For example; the nitrosamines, liver carcinogen causes with ingredients of nitrates which use as the corrosion inhibitor and amines including agents of nitro sating for the antioxidant in the MWFs as shown in Fig. 2-4 [38]. The use of nitrites containing alkanol amines for the cutting fluid formulation was fully banned with a regulation by U.S. Environmental Protection Agency in 1984 [38].

Metal Working Fluid is a complex mixture of many ingredients which some of the substances are highly suspected for co-carcinogens and tumor promoters although epidemiological literature, it has been considered as a sole material [40].

In the research experiments, toxicologically suspects groups have been found in the aerospace manufacturing industries in U.S who were exposed to the cutting fluids during metal machining with include ingredients of the fluid of polycyclic aromatic hydrocarbons, N-nitroso compounds (including nitrosamines), and abrasives [41].

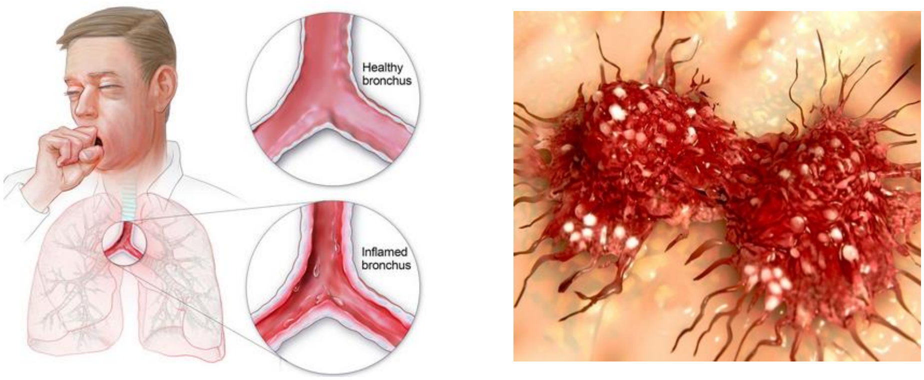



**Figure 2-4: Raspatory diseases and Cancer symptoms** [38]

According to the literature following one or mixture of contaminants and additives in cutting fluid was identified as the initiators and promotors for the cancer [29].

- Compounds including sulfur
- Nitrosamines
- Polyaromatic hydrocarbons (PAHs)
- Long-chain aliphatic
- Formaldehyde-releasing biocide

Skin cancer was recorded with use of acid refined minerals oils in laboratory experiments for the animals and humans as shown in Fig. 2-5. PAH amount can be reduced by refining the crude oil, but acid refined mineral oils still include such amount of PAH which directly causes for the skin cancer [41]. The common health influence from the exposure of cutting fluid during metal machining is skin irritation. Allergic and skin disorders are caused from the contact of fluid during machining [40].

The skin irritation is continuous type of irritant contact dermatitis as shown in Fig. 2-5. Still the exact phenomena for the mechanism cause for the skin irritation is under investigation [38].

Following components have suspected as the reason for the skin irritation [38].

- Antifoams
- Biocides
- Amines
- Preservatives
- Organic acids
- Emulsifiers
- System Cleaners
- Corrosion inhibitors

Almost all the mineral based cutting fluids behaver in the range of alkaline with 9.5 to 11 pH value [40]. Higher acidic value of the MWF directly effect for the skin irritation and other skin related diseases.

During metal machining, the induce heat should be effectively removed in order to obtain higher dimensional accuracy and in generally, elemental sulfur is adding to the straight cutting oils to enhance extreme pressure and capability to absorb heat [40]. Still the researchers could not clearly conclude the influence of independent or dependent effect of sulfur towards the laryngeal cancer and skin cancer [43,45].

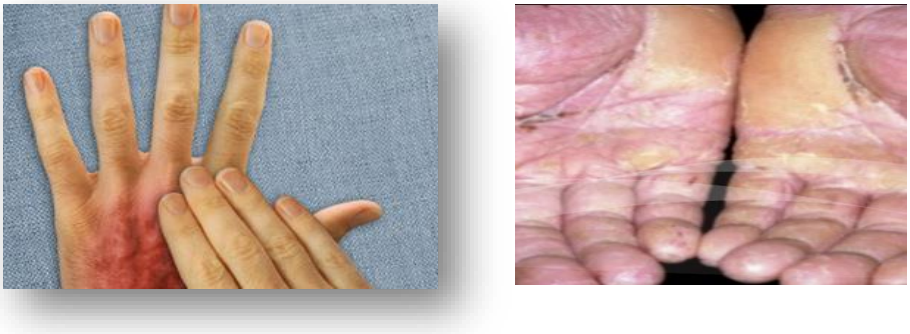


**Figure 2-5: Skin irritations during Metal Working Fluids usage** [38]

The exposure to the cutting fluid through unintentional inhale of the mist was drastically increased with the introduction of high speed machining [40]. The development of the technology should safeguard the occupational health and safety. Although, the potential effect is existing in the exposure of cutting fluid mist for the digestive and respiratory systems diseases and cancers.

According to the literature, following one or more Biocides are included in the cutting fluid [38].

- Formaldehyde
- Isohalines
- Phenols
- Morpholines
- Biostatic agents such as alkanol amine-borate
- Formaldehyde releasers
- Ethylenediamine

It has been found that dissolved ions of Cobalt, Chromium and Nickle in cutting fluid is caused for the skin sensitizers [40]. Most of the irritant reactions such as allergic eczematous eruptions happen in use of neat oils with association of furunculosis, folliculitis and oil acne [40]. Further, skin cancers, keratoses of the skin, epitheliomas and hyperpigmentation cause with contact of neat oil during machining [29]. The oil acne, epitheliomas and keratoses were not recorded during the use of water-soluble cutting fluids. Vesicular palmar and finger eczemas are rarely noted in soluble-oil dermatitis [29]. In its early stages, soluble oil dermatitis often represents as a fine follicular erythema, which may progress on to a patchy or even discoid popular eczema over the back of the hands and the forearms [40].

Many workers in the manufacturing industries with skin irritation due to the exposure of cutting fluids are also present dyshidrotic eczema dieses [29]. A field research for a ball-bearing manufacturing company in Singapore over a 6-month period among 24 newly recruited machinist’s occupational dermatitis increased from 38% at week 3 to 77% at week 6.

It then decreased to 50% at week 9 and thereafter remained constant at about 50% throughout the remaining study period. The skin irritation due to the exposure of cutting fluid was clinically diagnosed. Most of the machinists had mild dermatitis according to the clinical results [38]. The most frequently reported cancer was stomach cancer with associate with pancreatic cancer in workers of metal machining industries [40]. Large number of investigations are conducting to identify the causes for the digestive cancers for the machinists while using MWFs for the machining process

## 2.7 Role of Emulsions in Metal Working Fluids

An emulsion, which is a dispersion of oil in water (generally oil to water ratio of 5%: 95%) is made and pumped in to the cutting zone [42]. Commercially, oil and additive mixtures are purchased by the end user and mixed with prescribed quantity water whenever required [17].

The dimension of the desired final out put can be maintained in higher accurate level with control of work and tool interface temperature while using water soluble MWF (emulsion). Further, the generated heat can absorb effectively by the emulsion where the higher heat absorption component of water included in large percentage comparing to the neat oil during the metal machining operation [17].

Most of the additives used in the formulation process of water soluble MWFs are in the rage of acidic. Highly available ricinoleic acids such like oligomers, trimmer and dimmer have been used with appropriate reaction conditions to prepare MWFs. Following are some of the available literature which indicates the important esters for the cutting fluid preparation process [40,49,50].

1. Phosphonic acid and phosphoric esters have good properties for cutting fluids.
2. It is suspected that derivates of dimmer, trimmer and tetramer of higher fatty acid are good.
3. The presence of alkanolamines is essential for water based cutting fluids.
4. The amide group and boric ester increases antimicrobial activities.
5. Some sulfur compounds enhance initial seizure load.

6. Presence of bulky alkyl group in higher fatty acid molecule is essential for anti-rust and load carrying capacity.
7. Long fatty chain is good for initial seizure load.

Table 2-3 express the comparison in term of advantages and disadvantages between the formulated MWF emulsions, neat oils and neat oils with additives.

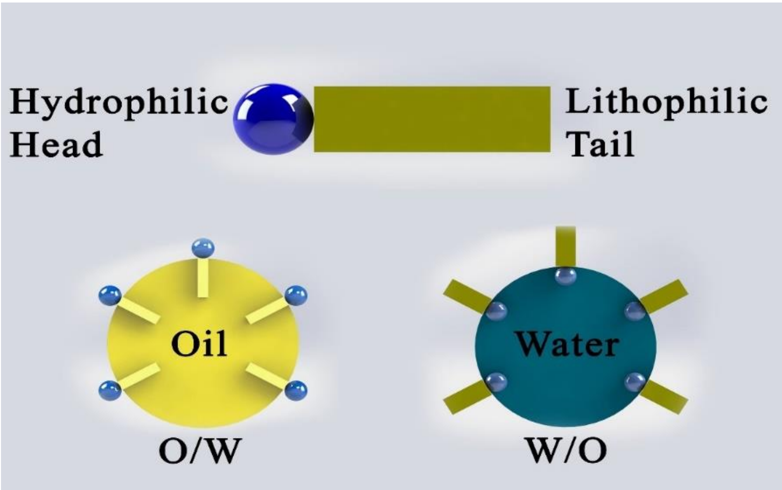
**Table 2-3: Advantages and disadvantages of MWF emulsions and neat oils** [13,14]

| MWF Type | Advantages | Disadvantages |
|---|---|---|
| Water-based emulsions | Highly available.<br>Highest heat carrying capacity. | Low viscosity.<br>Corrodes the metal very quickly.<br>Environmental issues and healthy issues. |
| Straight mineral oils | Lubrication and rust prevention.<br>Chemically stable.<br>Low cost. | Only used for the light duty application.<br>Health issues.<br>Environmental issues at the disposal. |
| Mineral oils with additives (Neat oils) | Largest variety of cutting fluids available.<br>Produce desirable characteristics for different machining situations.<br>Can improve the load carrying capacity.<br>Used for more difficult to machine situation. | Anti-welding layer is continuously broken by the severe rubbing action between chip and the tool.<br>Healthy and environmental issues.<br>Difficulties in the case of disposal of the used fluids. |

### 2.7.1 Importance of Hydrophilic and Lithophilic (HLB) value

An emulsifier has an amphi hydrophilic group at one end, head, and lithophilic chain at the other end, tail for the formulation of the emulsion as shown in Fig. 2-6 [37]. By the definition, the hydrophilic group has a strong affinity for water and lithophilic group for oil [6]. The hydrophilic and lithophilic properties of emulsifiers are identified by, hydrophilic and lithophilic balance (HLB).

HLB value indicates the composition of two categories of the lithophilic group and a hydrophilic group within an emulsifier. Ranging from 1 to 20, this scale indicates the attraction either to oil or water [45]. High HLB values are assigned to more hydrophilic (more water soluble) emulsifiers suitable for oil in water emulsions and low HLB values to more lithophilic (more oil soluble) ones suitable for water in oil emulsions [16]. Although, different applications require different HLB values.




**(a)** **(b)**

**Figure 2-6: (a) oil - water and (b) water - oil emulsion** [46]

### 2.7.2 Categories of Emulsion

- Oil - water emulsions
- Multiple emulsions
- Water - oil emulsions
- Micro emulsions

### 2.7.3 The Role of Emulsifier in Emulsion

While the shaking process is done for the water and oil mixture, a scattering of oil droplets in phase of water is formed. When the sharking process stops the oil and the water phases trend to separate immediately. The separation can be eliminated with addition of emulsifier to the system which results for the steady dispersion of the droplets by making a stable emulsion. Oil-attractive hydrophobic tail and a water attracting hydrophilic head plays a significant role for the formulation of stable emulsion [37]. Most of the times formulation process of MWF emulsion has considered base oil of mineral oils. The reasonable price and good technical properties made the sense for the selection of mineral oil for the development process of MWF emulsions [12].The demand has been generated for a health and ecofriendly cutting fluid emulsion to address the short comes of the mineral based cutting fluid emulsions. Biodegradable vegetable oils have been addressed most of the short comes/issues and still the developments are carrying out for the invention of suitable cutting fluid as the alternative to the mineral oil-based emulsions [9].

Table 2-4 express the emulsifiers (additives) which can use for the formulation of emulsion and to enhance the performance. The selection of the MWF for a machining operation requires a number of parameter selections such as work piece material, cutting operation, cutting tool material, and other ancillary factors. When considering the literature, vegetable base oils have used for various type of machining applications. The applications can be mentioned as drilling, reaming, tapping and turning [6,41,53]. As according to literature, following materials have been frequently used for the qualitative and quantitative investigations of the machining performance while using vegetable oil based MWFs. Recently, hard to cut materials plays a prominent place in automotive, aerospace and ship building industries. Most of the researches are currently investigating the performance of vegetable based MWF in both categories of synthetic and semi synthetic in machining of hard to cut materials. Ex : Titanium Alloys, AISI 316L, AISI 304 austenitic stainless steel, AISI 4340 steel, AISI 1040 steel, AISI 9310 alloy steel, AISI 420 steel, Mild steel, 100 Cr Alloy (hardened bearing steel), AISI 316L austenitic stainless steel, [6,14,54,55].

## 2.8 Additives used in Metal Working Fluid Formulation

**Table 2-4: Compilation of additives used in MWFs** [14,56]

| Additive type | Substances | Mode of action, function |
|---|---|---|
| Anti-aging additive, oxidation inhibitor | Aromatic amines, Organic sulphide, zinc dialkyldithiophosphate | Prevention of oxidation of base oil at high temperatures and stabilization. |
| Anti-wear additive, | Acid and nonionic Phosphoric acid ester, zinc dialkyldithio-phosphate. | Reduces abrasive wear of rubbing surfaces by physisorption. |
| Biocides | Phenol derivatives, formaldehyde releasers, isothiazolinones | Prevention of excessive microbial growth. |
| Detergent, dispersant | Sulfonate, phenolate, salicylate | Prevents build-up of varnishes on surfaces, and agglomeration of particles to form solid deposits, promotes their suspension. |
| Emulsifier | Anionic: sulfonates, potassium-soap, alkanolamine-soap; Nonionic: fatty alcohol | Emulsion formation and stabilization. |
| Extreme pressure additive | Chlorineparaffine, sulphurous ester, phosphoric acid ester, polysulphide, PS | Protection against wear by formation of adsorption or reaction layers, prevent micro fusing of metallic surfaces. |
| Foam inhibitor | Silicone polymers, tributyl phosphate | Destabilize foam in oil. |
| Friction modifier | Glycerol mono oleate, whale oil, natural fats, oils, synthetic ester | Lowers friction and wear, improve adhesion of lubricating film. |
| Metal-deactivators | Heterocycles, di-amine, triaryl phosphite | Adsorptive film formation. |

## 2.9 Vegetable Oils

Mineral oils for the formulation of water soluble MWF can be replaced with the alternation of vegetable oils to address the health and environmental concerns [50]. Vegetable oils are non-toxics and readily biodegradable in the waste treatment systems. Cutting fluid has selected based on the machining operation, material type, tool material and machining condition in traditional approach. But the current selection process is mainly focus on the requirements of the health and environmental safety characteristics. Table 2-5 is shown the properties comparison of varies types of vegetable oils with mineral oil. The lubrication property is higher in vegetable base water soluble fluids than the mineral oils. Separation of tramp oils and absorption are not in difficult with vegetable oil-based cutting fluids. In general, it is difficult to emulsify the vegetable oils and the emulsions trend to separate expressing poor stability [42]. Further, the advantages and disadvantages of vegetable oil based MWFs are shown in Table 2-6. Mineral oils trend to destabilized with the heat induced oxidation and generate oily mists and residues [3]. Health and eco-friendly properties of the vegetable oils such like readily biodegradable, less toxics and renewable express the higher suitability as the sustainable substitute to the mineral based oils for the formulation of water soluble MWFs [58].

Some historical records expressed that the vegetable oil and animal oils have taken for the variety lubrication purpose in early civilization [51]. But the evidences regarding the usage as lubricant for the metal machining (crafts work) is not available in literature. In some certain situations and periods, the lubricating oil was used for the wire drawing process to comfort the drawing process [52]. The readily available oils such like animal oils (tallow, lard and whale) and vegetable oils such like seed oil, castor oil and palm were used for the process where the better lubrication needed [16]. Most of the scientists believe that the first invention from the humankind was likely to be the lubrication oils which was applicable in varies process and applications in ancient time period [51]. Tallow and vegetable oils have used for lubricating rough surfaces in 17$^{th}$ and in 19$^{th}$ century, further, it was used to investigate the Reynolds' theory of fluid film lubrication [44].

**Table 2-5: Comparison of the properties of vegetable oils and mineral oil** [60,61]

| **Performance** | **Canola oil (vegetable oil)** | **TMPTO (polyol ester)** | **Sat/Complex (synthetic ester)** | **PAG (petroleum synthesized)** | **Mineral oil (petroleum)** |
|---|---|---|---|---|---|
| Biodegradability | Excellent | Very good | Very good | Good | Poor |
| Toxicity | Low | Low | Low | Low | High |
| Oxidative stability | Poor | Moderate | Very good | Good | Very good |
| Lubrication | Excellent | Very good | Very good | Very good | Good |
| Low temperature | Poor | Good | Good | Good | Good |
| Viscosity index | Very good | Very good | Very good | Very good | Moderate |
| Hydrolytic stability | Poor | Moderate | Good | Good | Very good |
| Viscosity index | Very good | Very good | Very good | Very good | Moderate |
| Thermal stability | Moderate | Good | Very good | Good | Good |
| Seal compatibility | Moderate | Moderate | Moderate | Good | Very good |
| Relative cost* | 2 | 2 | 6-8 | 4 | 1 |

*Cost with respect to the mineral oil (1)

Subsequently, vegetable-based oils have a good potential to use as the alternative to the mineral oil based industrial lubricants. Most of the researches are ongoing to develop and investigate the influence of bio based MWFs for the metal machining around the world. The requirement of biodegradable lubricants is in higher level due to the introduction and growth of the regulations for environmental protection. US market is expecting bio based MWFs annual growth rate of 7-10% which is 2% of the total lubrication market in next five years [54].

**Table 2-6: Advantages and Disadvantages of Vegetable Base MWF** [48,57]

| Advantages | Disadvantages |
|---|---|
| Non-toxic. | Oxidative instability. |
| Biodegradability. | Poor temperature properties. |
| Resource renewable. | Perceived poor hydrolytic stability. |
| Good lubricity. | |
| High viscosity index. | |
| Affordable application cost. | |

## 2.10 Minimum Quantity Lubrication (MQL)

Minimum quantity lubrication (MQL) or micro lubrication or near dry lubrication, is a lubrication technique of applying fine mist of oil instead a flood of MWF [55]. Through the exploration of researches, it was found that typical flow rate of MWF in MQL is 10-500 ml/hr which is nearly four times reduction of usage volume than the flood approach [56]. In MQL system, the cutting fluid should supply at high speed and high pressure to the cutting region as shown in Fig. 2-7, where the high pressure is supplied through a compressor unit. Therefore, at first the MWF is mixed with compressed atmospheric air. The mixing of MWF and compressed air can be achieved externally via inside the mixing chamber or internally via inside the nozzle or tool spindle. According to the type of feed or delivery, the MQL system can be categorized into two groups which a nozzle is used for the external distribution and the internal distribution is done through the cutting tool [57].

Both internal feed and external feed systems have number of advantages and disadvantages. For an example external feed system needs low investment cost but it has limitations in some machining operations like drilling, taping and reaming. In internal feed system, it gives optimal lubrication at the cutting point but it requires high investment cost [54]. The conventional cooling techniques had shown inefficient performances due to disability of reach the real cutting area with increase in feed rate and cutting velocity [42].

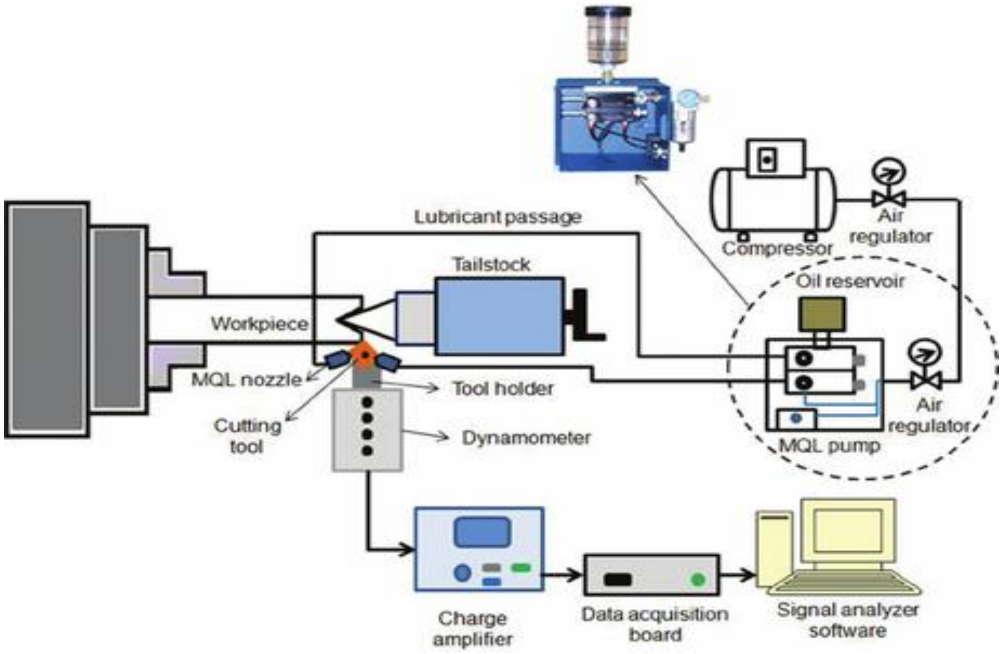



**Figure 2-7: Schematic representation of MQL application** [56]

It was revealed through experiments that the MQL technique is more convenient for not only low but also high cutting speeds and feed rates. In MQL, the heat transfer from the machining zone to the MWF is occurred in efficient manner due to increase of surface contact area of MWF through the evaporation by tiny droplets and forced convection by compressed air [58]. The MQL is a credible technique of cooling/lubrication within industrial applications, because it minimizes the usage of quantity of MWF, machine cleaning cycle time, overall cost of machining, demand of infrastructure facilities, environmental pollution, ecological and human health issues [56].

At the same time, it has improved machining performances like feed force, cutting force, tool wear, chip thickness ratio, surface roughness and cutting temperature. This cooling technique is sometimes called micro lubrication or dry lubrication [55].

The main advantages of MQL are reduction of the fluid volume, cost saving (material), reduction of environmental impact (with use of minimum volume), improvement on overall performance of operation and increment of surface quality. MQL application has identified as one of the most suitable methods for the green manufacturing in the aspect of sustainable manufacturing. With the experimental records in literature expressed that using vegetable oil as MWF via MQL approach provides more benefits mainly by improving the surface finish, reducing the cutting temperature, increasing dimensional accuracy and reducing cutting forces in term of reducing the friction between work tool interfaces.

## 2.11 Nano Metal Working Fluids

Nanofluids can be obtained from the dispersion of nanoparticles in a base liquid such like water, oil or ethylene glycol [59]. The tribological properties, heat transfer capacity can improve with the concentration of the suspended nanoparticles in the cutting fluid [60]. The nanofluids express good lubrication properties for wide range of temperatures and make significant advantages for the new technology inventions in MWFs to perform better in reliability. According to the literature, the better wear and friction properties were shown for the water with oxide graphene nanosheets other than water with oxide multiwall nanotubes [15].

Variety of nanoparticles have taken for the experiments to identify and investigate the effect of lubrication property in nanofluids during metal machining. Most of the researches, in the field of nanofluids have discussed the better machining performance with use of the Silicon Dioxide ($SiO_2$) nanoparticles which consumes the benefit of higher availability in the market, cheap and hard with comparing to the other available nanoparticles. Further, $SiO_2$ express good mechanical properties such like hardness of 1000 kgf/mm$^2$ (Vickers Scale) and availability of the particles with range of 5 nm up to 100 nm sizes.

As shown in Fig. 2-8, the $SiO_2$ nanoparticles in the mineral oil express the combination effect of sliding and rolling at work-tool interfaces. This mechanism reduces the thrust force and other forces which results for the reduction of friction coefficient and help for the increment of machining performance significantly [15]. The additives which expressed in Table 2-4 can also be used to enhance the chemical and mechanical properties in nanofluids. Recently, number of research investigations have conducted to investigate the performance of nanofluids with the combination of MQL technique to address the conventional problems. Still the researches for the vegetable oil-based nanofluids in MQL have not conducted which will definitely a breakthrough in addressing the same conventional issues and problems.

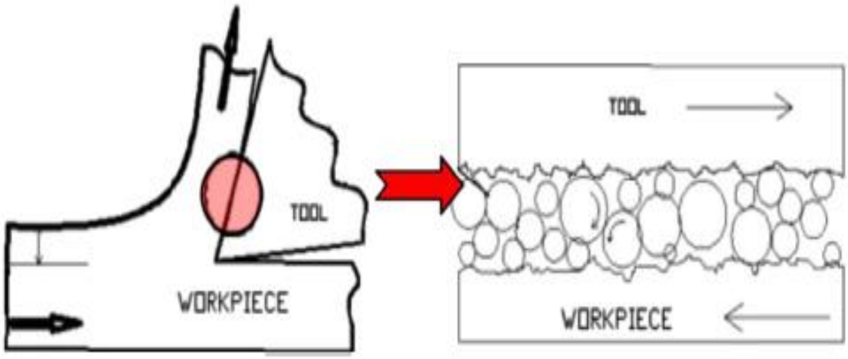



**Figure 2-8: Rolling elements in the tool chip interface** [15]

The productivity of the machining operation can be increased through lower usage of nanofluid which gives the better machining performance and saving the environment with comparing to the conventional cutting fluids [59]. Most of the MWFs research experiments have shown that the dispersed nanoparticles in fluids can simply penetrate into the rubbing surfaces of work-tool interfaces. Hence, the electrohydrodynamic lubrication property induced and enhances the lubrication capability of the fluid [15]. The researchers reported the experimental results of single-thrust bearing tester that the nanofluid prevents the contact between two metal pieces and improves the lubrication performance, reducing the frictional coefficient and extreme pressure with comparing to the pure liquid [59]. Further, the results discussed that the thermal conductivity is increased with the increment the concentration of nanoparticles in the MWF [15].

## 2.12 Summary of Literature Review

It is essential use a fluid to lubricate and cool between contact surfaces (work and tool interfaces) to obtain a higher dimensional accuracy on machined components during machining. More than 200 years ago water was used as a cooling medium due to its higher availability and thermal capacity (higher specific heat capacity). Poor lubrication and corrosion of parts were identified as the main two problems of the water coolant. The petroleum based cutting fluids have played a substantial role in addressing the drawbacks of water coolant. But the use of neat mineral oil has constrained to the lower cutting speed due to its poor cooling capability and higher cost. Although, the mineral oils have expressed good lubrication properties for the machining operations. Later on, the mineral oils were added with suitable additives to the water which generally called as the soluble oils to address the poor cooling effect. But the mineral oils in MWF pose significant health and environmental problems.

Wide scale of researches is conducting to identify the effect of occupational health effect from water soluble MWFs. As according to the conducted surveys, the workers who exposure to the MWFs have shown significant symptoms of cancers in many origins and diseases in respiration. Therefore, the need of health and environmentally friendly cutting fluid has been raised in manufacturing industries. The dry machining can identify as the best solution where the cutting fluid is completely removed from the machining process. It can address the drawbacks and issues related to the health and environment by ensuring workers safety and clean atmosphere, but it has many application constraints. Further, research experiments were conducted to investigate a near dry machining process to address the aforementioned problem and ended up with the technique of MQL where the usage of MWF is significantly minimum with comparing to the flood cooling approach. MQL technique will address the health, environmental and economic requirement with having a better machining performance compared to other cooling methods. MQL method expressed a longer tool life on difficult-to-machine materials which are generally use in aerospace, ship building and automobile industries.

Further, the researchers have investigated the suitability of vegetable oils as an alternative to the mineral oils. Vegetable oils have excellent tribological properties and readily biodegradable with comparing to the mineral oils. It has been found that the unsaturated fatty acid of the vegetable oil facilitates an effective layer of lubricant between work tool interface than the mineral oils. Water has been identified as the good coolant. Vegetable oil was mixed with water and suitable additives to formulate an emulsion. Currently, researches are conducting to investigate the performance and enhancing the properties in vegetable oil-based emulsions.

The use of nanoparticle additives for the MWF formulation has led better results in machining operations. The outstanding properties can be integrated to the base oil of vegetable in emulsion to obtain effective performance while making as an alternative to the mineral oil base MWF in term of addressing the health and environmental drawbacks. Further, MQL technique and bubbling can be used on vegetable oil-based emulsions to obtain excellent performance during machining operations. It is important to study the cooling and lubrication performance of the sustainable MWF for the difficult to cut materials through MQL or bubbling effect approaches for the process optimization in machining operation. The application of a such process make a significant positive impact for the socio economic and environmental sustainability, hence, it helps to perform the machining operation in an effective and efficient manner.

# CHAPTER 03: METHODOLOGY

## 3.1 Experimental Investigation of Surface Quality

The surface quality was investigated on 0.2% C and AISI 304 steels during different cooling media in turning with controlled cutting parameters. Linear speed, feed rate and DoC were selected as the machining parameters. Lubricating media were selected as commercially available MWF, developed white coconut oil based MWF and measured the surface quality of the work materials for the selected machining parameters. Dry machining operation was conducted as the reference operation. The novel vegetable oil based MWF was prepared with nontoxic and ecofriendly food grade surfactants with white coconut oil as the base oil. This mixture was slowly added to a weighted percentage of water while rousing using a magnetic stirrer. The stability of the novel white coconut oil emulsion sample was visually inspected throughout 6 months and confirmed the firmness by observing none of the separate layers in the sample. Fig. 3-1 shows the prepared setup to measure surface roughness on the selected machined material. Following Table 3-1 and Table 3-2 express the chemical composition of the selected two work materials. Table 3-3 and Table 3-4 express the physical properties of the selected two work materials.

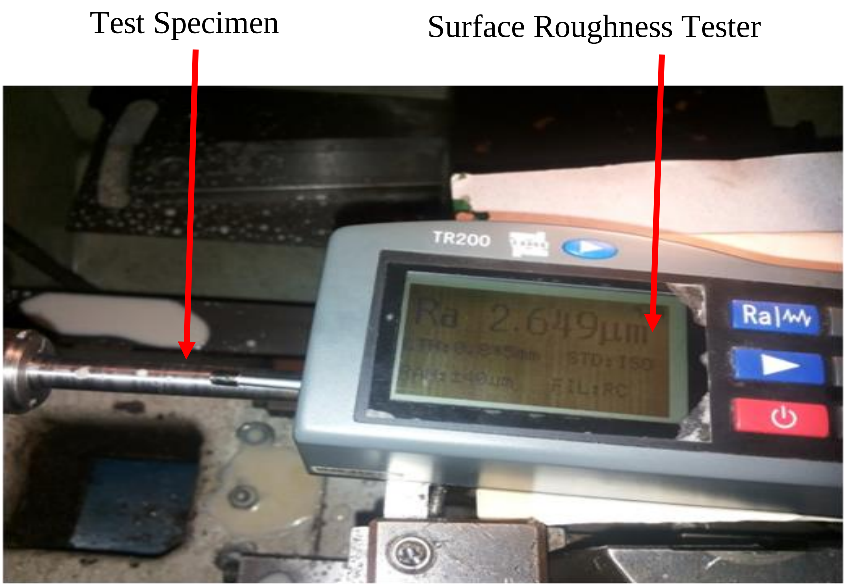



**Figure 3-1: Measuring Surface Roughness of the Work Material**

**Table 3-1: Chemical composition of 0.2% C steel (Weight %)**

| | C | Si | Mn | P | S | Cr | Mo | Ni | Al |
|---|---|---|---|---|---|---|---|---|---|
| **Min** | - | 0.05 | - | - | - | - | - | - | - |
| **Max** | 0.2 | 0.35 | 1.0 | 0.060 | 0.060 | - | - | - | - |
| **Results** | 0.2 | 0.24 | 0.8 | 0.042 | 0.025 | - | - | - | - |

**Table 3-2 Chemical composition of AISI 304 steel (Weight %)**

| | C | Si | Mn | P | S | Cr | Mo | Ni | Al |
|---|---|---|---|---|---|---|---|---|---|
| **Min** | - | - | - | - | - | 18.00 | - | 8.00 | - |
| **Max** | 0.08 | 1.00 | 2.00 | 0.045 | 0.030 | 20.00 | - | 10.5 | 11.00 |
| **Results** | 0.026 | 0.42 | 1.60 | 0.037 | 0.019 | 18.25 | - | 8.00 | 8.02 |

**Table 3-3: Physical Properties of 0.2% C steel**

| Proof Stress ($N/mm^2$) 0.2% | Tensile Strength ($N/mm^2$) | Elongation (%) | Reduction of Area (%) | Hardness (BHN) |
|---|---|---|---|---|
| 371 | 498 | 36 | 64 | 111 |

**Table 3-4: Physical Properties of AISI 304 C steel**

| Proof Stress ($N/mm^2$) 0.2% | Tensile Strength ($N/mm^2$) | Elongation (%) | Reduction of Area (%) | Hardness (BHN) |
|---|---|---|---|---|
| 580 | 752 | 43 | 63 | 235 |

The influence of the sustainable cooling medium can be discussed according to the observed results for the surface quality for the selected materials with arrangements of the recommended machining setup (Table 3-5 and Table 3-6).

The range of the machining parameters have mentioned by the materials and tool manufacturers as 98-150 m/min cutting speed, 0.2 mm/rev feed rate, 0.5-1.0 mm DoC for 0.2% C and AISI 304 steels in order to obtain optimal surface quality of the machining operations. The respective experiments were conducted at 64 and 102 m/min cutting speed, 0.18 mm/rev feed rate, 0.5 mm and 1.0 mm DoC to satisfy the recommended requirements.

Lathe machine (Model CM6241X1000) with spindle speed limits of 45–1800 rev/min was used for the experiments. The work materials were selected as 0.2% C and AISI 304 steels. Contribution of the selected parameters on the workpiece surface quality was separately investigated in turning with coated carbide insert of CNMG 433-M/Grade T 9325 (Fig. 3-2). Selected MWFs were subjected to the work tool interface with 8 liters/min flow rate. Qualitest TR 200 portable tester was used to measure the surface roughness of machined materials for each set of selected machining configurations (Fig. 3-1). Equipment calibration was done according to the recommended procedure by the manufacturer before the investigations. ISO 4288 procedure was followed for carrying out the surface roughness measurements with 0.8 mm cut-off length and 4 mm measurement length with total transvers length of 5.6 mm.

Five different locations of each machined surface were measured. The largest and smallest values were omitted and mean value of the remaining three values were tabulated for analysis (Table 4-1 to Table 4-6).

**Table 3-5: Recommended cutting parameters for the tool**

| Designation | Grade | Tool Nose Radius (mm) | Feed Rate (mm/rev) | | Depth of Cut (mm) | |
|---|---|---|---|---|---|---|
| | | | Min | Max | Min | Max |
| CNMG 433-M | T 9325 | 1.2 | 0.18 | 0.78 | 1.2 | 6.00 |

Following Table 3-5 express about the recommended cutting parameters by British steel Association for turning operation [61].

**Table 3-6: Recommended cutting parameters for the materials**

| Material | Condition and/or hardness (HB) | Roughing (R) or Finishing (F) | Speed sm/min* | | |
|---|---|---|---|---|---|
| | | | HSS | Brazed carbide | Disposable carbide |
| Wrought martensitic | | R | 45 | 150 | 170 |
| Free machining grades | Ann 160 | F | 52 | 170 | 190 |
| | | R | 33 | 120 | 145 |
| Lower C/lower Cr grades | Ann 175 | F | 40 | 145 | 175 |
| | | R | 20 | 80 | 100 |
| Lower C/lower Cr grades | Q&T 300 | F | 25 | 98 | 120 |
| | | R | 20 | 95 | 105 |
| Higher C/higher Cr grades | Ann 240 | F | 24 | 105 | 120 |
| | | R | 15 | 67 | 80 |
| Higher C/higher Cr grades | Q&T 320 | F | 21 | 80 | 92 |
| Wrought Ferritic | | R | 45 | 150 | 165 |
| Free machining grades | Ann 160 | F | 50 | 165 | 185 |
| | | R | 33 | 137 | 155 |
| 12-17% Cr grades | Ann 160 | F | 40 | 155 | 180 |
| Wrought Austenitic | | R | 31 | 125 | 140 |
| Free machining grades | Ann 160 | F | 36 | 140 | 155 |
| | | R | 23 | 85 | 95 |
| Other grades (304,316,321 etc) | Ann 160 | F | 28 | 97 | 112 |
| Wrought Duplex | | R | 24 | 53 | 55 |
| | Ann 230 | F | 30 | 60 | 70 |
| Cast Plain Cr | | R | 21 | 83 | 100 |
| | N&T 210 | F | 27 | 105 | 130 |
| Cast Austenitic | | R | 15 | 68 | 83 |
| | | F | 20 | 83 | 100 |

Roughing depth of cut 3.8 mm    Feed 0.38 mm per rev
Finishing depth of cut 0.5-1.0 mm    Feed 0.20 mm per rev

sm/min = Surface meters per minute   C= Carbon   Cr= Chromium

Ann= Annealed
Q&T= Quenched & Tempered
N&T= Normalized & Tempered

*Speeds for coated carbides are approximately 30% higher than those for disposable carbide

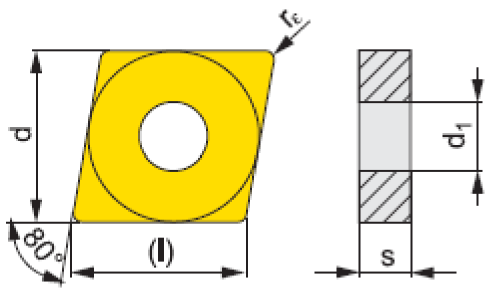



**Figure 3-2: Selected cutting tool geometry** [62]

## 3.2 Experimental Investigation of Chip Curl Radius and Chip Form

The curl radius for the observed chips during the machining operation were measured by using digital Vernier calliper and values were plotted for the analysis. 0.2 % C and AISI 304 steels were used for the conventional turning operation as the work materials. The Vernier calliper was calibrated before the measurements and ensured none of the zero errors. The cutting parameters and tool were selected as same in the as Table 3-5 and Table 3-6 which were recommended by the materials and tool manufacturers. Seah et al. [51] published curl radius measuring approach and equation were used as expressed in Fig. 3-3, Fig. 3-4 and Equation 3-1 for the experiments.

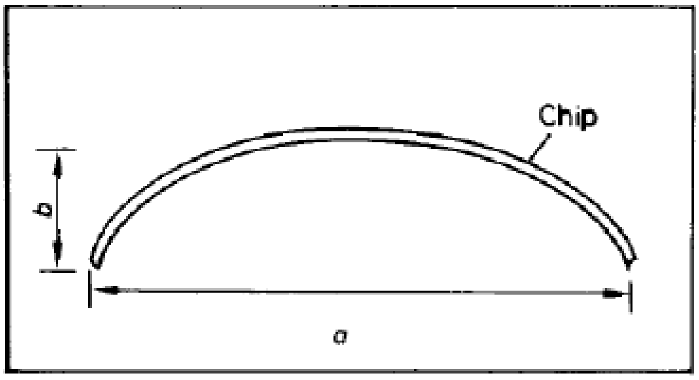



**Figure 3-3: Parameters for the chip curl radius** [51]

$$\text{Chip Curl Radius} = \frac{\left(\frac{a^2}{4}+b^2\right)}{2b} \qquad (3\text{-}1)$$

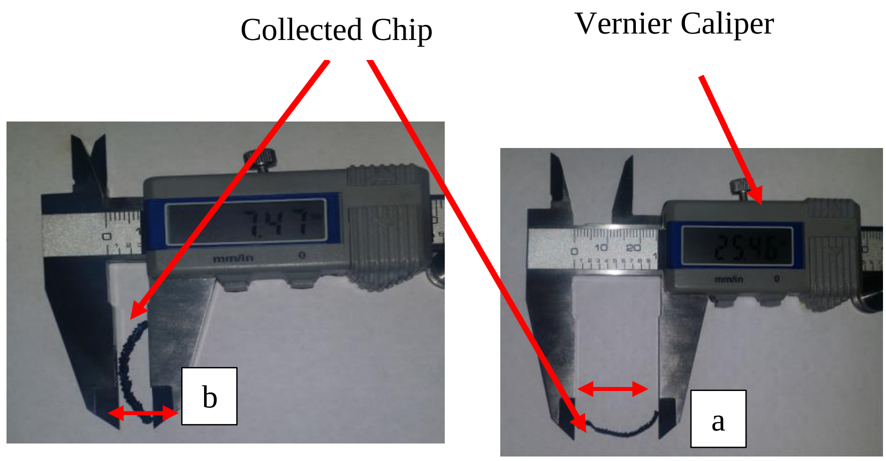



**Figure 3-4: Measuring chip curl radius parameters**

## 3.3 Work Tool Interface Temperature Simulation

The work tool interface temperature was simulated using thermo-mechanically coupled finite element model in DEFORM 11.1.1 platform for AISI 304 machining with uncoated carbide cutting tool. The machining parameters were selected as 100 m/min cutting speed and 0.2 mm DoC. The 2D simulation was carried out assuming orthogonal cutting model of dry machining because of computing time and complexity in 3D model. Fig. 3-5 express the initial simulation model of the workpiece and cutting tool in 20 °C reference temperature. The workpiece was defined as elastic-plastic body and tool defined as a rigid body.

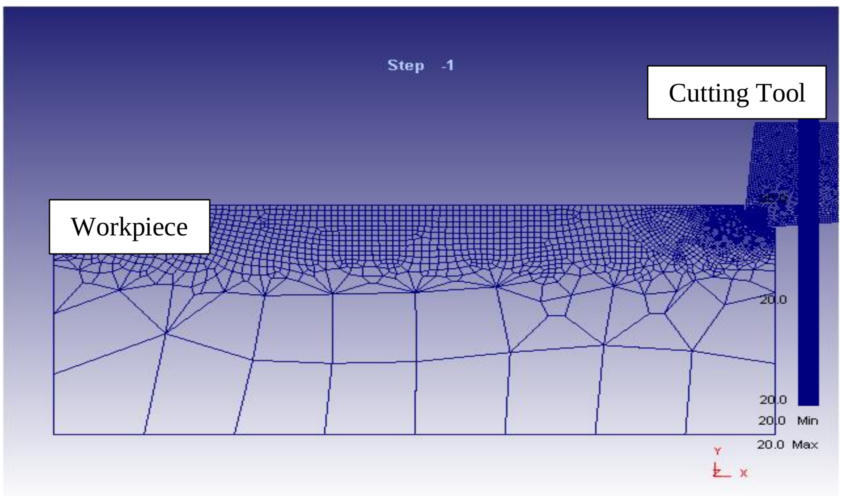



**Figure 3-5: Initial configuration for the simulation**

The strain rate and temperature combined effect was used for the material to identify the flow stresses. The DEFORM pre-processor platform was used to build the simulation model. Constant shear frictional model and tool/chip perfect interactions were assumed. The cutting tool was retracted from the workpiece after reaching the desired stroke and allowed to cool down to room temperature [63].The meshing for the workpiece was done using meshing window tool with sizes of 0.1 mm near cutting edge, 0.3 mm for cutting zone, 0.5 mm for surface and 1.0 mm for remaining part of the work piece. The tool meshing was done with the same mesh sizes which were taken for the workpiece. Tool tip, flank face and other heat dissipation areas were critically considered for the meshing of tool. The average strain rate for the workpiece material was set to 145160 1/s. The boundary conditions were applied for both tool and workpiece with heat transfer coefficient of 100000 kW/m$^2$K. The initial thermal simulation was carried out considering unsteady condition of the machining where the cutting tool moves with 100 m/min while workpiece is in stationary.

After that the work tool maximum temperature step was identified and proceeded the steady state thermal simulation where the workpiece moves with 100 m/min while tool in stationary. Again, the work tool interface maximum temperature was identified at the steady state simulation and carried out the unsteady thermal simulation where the initial simulation configuration was considered. Fig. 3-6, Fig. 3-7 and Fig. 3-8 express the unsteady thermal simulation step of 2,11 and 22.

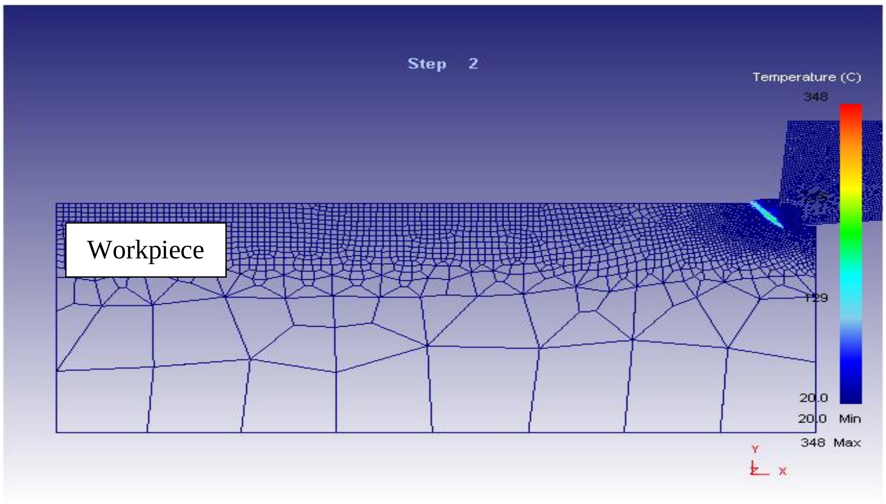



**Figure 3-6: Work tool interface temperature at initial cutting**

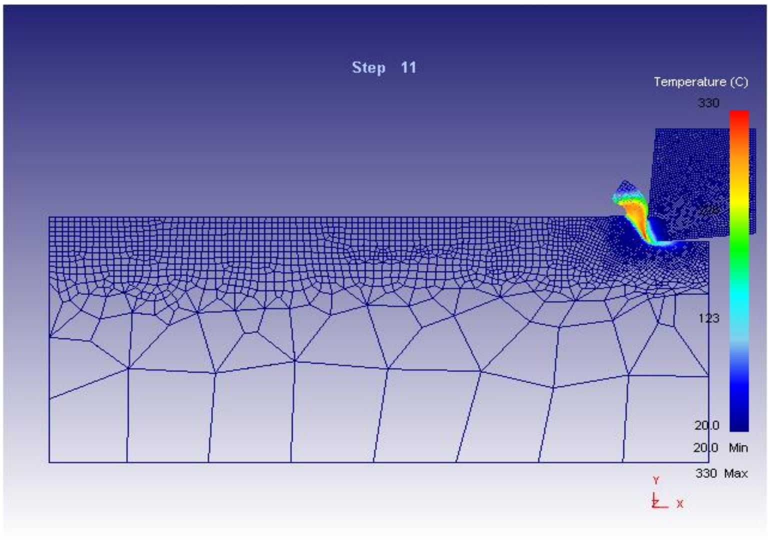



**Figure 3-7: Work tool interface temperature at simulation step of 11**

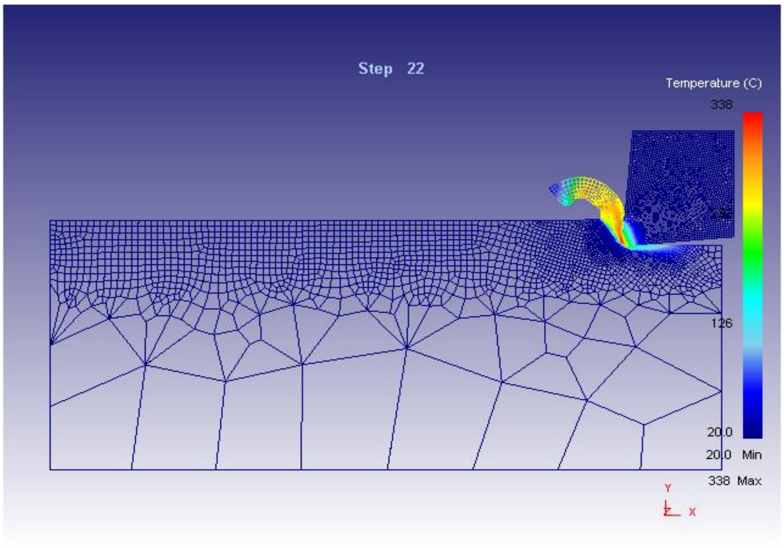



**Figure 3-8: Unsteady thermal simulation step of 22**

The Newton-Raphson iteration method and skyline solver were used with convergence error limit of 0.001 and force error of 0.01 for all configurations. The geometry error in tangential direction was taken 0.0001% and normal direction of 0.01% [64,65].

Process convection heat coefficient was set to 0.00025 kW/m$^2$K and friction coefficient between the contact surfaces (tool and workpiece) were set to 1.0 in order to facilitate the simulation in dry machining condition. The simulation process duration time was taken as 5 sec with 5 mm machining length. The simulations were done as considering the work materials plastic behavior in unsteady state and steady state and elastic-plastic behavior for final thermal unsteady configurations respectively. Element and node simultaneous simulation were done for the two unsteady configurations while only element simulation was carried out for the steady state configuration. USUI tool wear model (Equation 3-2) was used for compensation of the tool depreciation during the machining for all simulation configurations. Empirically calibrated coefficients were taken as a = 1 × e $^{-5}$ and b= 1000.

$$\mathbf{W} = \int \boldsymbol{apVe^{\frac{-b}{T}}dt} \tag{3-2}$$

Where p is interface pressure, W is tool wear, T is interface temperature and V is sliding velocity.

# CHAPTER 04: RESULTS AND DISCUSSION

## 4.1 Surface Quality Investigation

According to Fig. 4-1 and Table 4-3, the dry machining has indicated substantial difference with comparing to the other cooling media. 1.0% reduction for 64 m/min speed and 4.6% reduction for the 102 m/min have observed for the surface roughness use of developed MWF for 0.2% C steel with 0.5 mm DoC while maintaining the feed rate at 0.18 mm/rev (Fig. 4-1, Table 4-1 and Table 4-2).

**Table 4-1: MSR values for 0.2% C steel at developed MWF**

| Speed (m/min) | Spindle Speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness-Ra (µm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | Mean | SD |
| 64 | 585 | 0.18 | 0.50 | 0.94 | 0.91 | 0.91 | 0.920 | 0.014 |
| | | | 1.00 | 0.98 | 0.95 | 0.94 | 0.957 | 0.017 |
| 102 | 900 | 0.18 | 0.50 | 0.86 | 0.88 | 0.86 | 0.867 | 0.009 |
| | | | 1.00 | 0.88 | 0.87 | 0.90 | 0.883 | 0.012 |

**Table 4-2: MSR values for 0.2% C steel at commercial MWF**

| Speed (m/min) | Spindle Speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness-Ra (µm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | Mean | SD |
| 64 | 585 | 0.18 | 0.50 | 0.95 | 0.94 | 0.91 | 0.933 | 0.026 |
| | | | 1.00 | 0.99 | 0.95 | 0.98 | 0.973 | 0.026 |
| 102 | 900 | 0.18 | 0.50 | 0.91 | 0.92 | 0.90 | 0.910 | 0.014 |
| | | | 1.00 | 0.90 | 0.97 | 0.98 | 0.950 | 0.046 |

**Table 4-3: MSR values for 0.2% C steel at dry machining**

| Speed (m/min) | Spindle Speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness-Ra (µm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | Mean | SD |
| 64 | 585 | 0.18 | 0.50 | 0.52 | 0.52 | 0.52 | 0.522 | 0.003 |
| | | | 1.00 | 0.61 | 0.62 | 0.61 | 0.619 | 0.001 |
| 102 | 900 | 0.18 | 0.50 | 0.35 | 0.39 | 0.34 | 0.360 | 0.022 |
| | | | 1.00 | 0.36 | 0.37 | 0.37 | 0.372 | 0.003 |

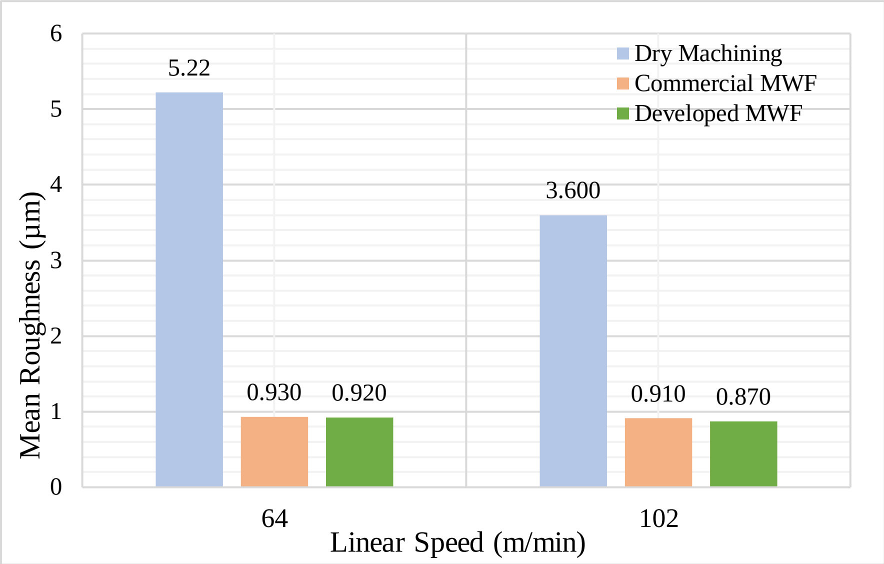



**Figure 4-1: Surface roughness- Ra variation for 0.2% C steel at 0.5 mm depth of cut**

Fig. 4-2 expressed the observed results for 1 mm DoC in 0.18 mm/rev feed rate for 64 m/min and 102 m/min cutting speeds. 1.0% and 8.0% reduction have been reported respectively for the surface roughness values with use of developed MWF. The developed MWF expressed a better surface quality for all set of configurations with comparing to the mineral oil based MWF for 0.2% C steel.

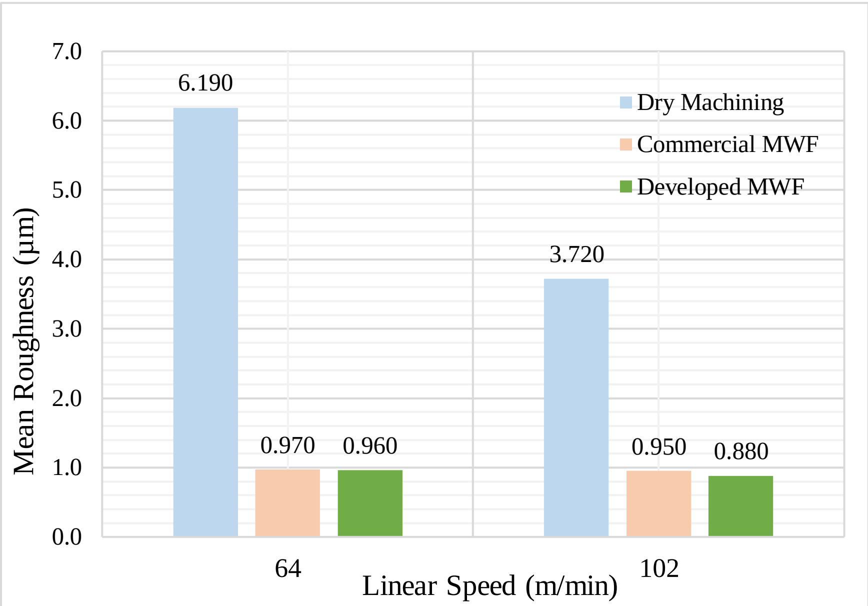



**Figure 4-2: Surface roughness- Ra variation for 0.2% C steel at 1 mm depth of cut**

The fatty acid content of the developed MWF facilitates better lubrication layer between work tool interfaces. As a result of that the dynamic friction coefficient for contacting surfaces was reduced. Hence, less wear was resulted and the cutting tool was enabled a smooth cutting operation.

The surface roughness values for the dry machining was also reduced with the increment of the cutting speed while keeping the feed rate and DoC constant for the 0.2% C steel.

$$\frac{\sin \emptyset}{\cos(\emptyset - \propto)} = \frac{Vc}{V} \qquad (4\text{-}1)$$

Where, Ø is Shear angle, α is Rake angle, V is Cutting velocity and Vc chip velocity.

According to the Equation 4-1, when increasing the cutting velocity, the shear angle reduces. The reduction of the shear angle result for the smooth cutting operation while shearing the work material at the cutting point with low power consumption. During lower cutting speeds, where BUE may be continually building up and breaking down with the fractured particles carried away on the underside of the chip. As a result of that the highly strained particles would rub along the newly formed work surface and would affect in a rough surface [51].

Table 4-4, Table 4-5 and Table 4-6 express the observed surface roughness values for AISI 304 steel. The recorded values indicated a large difference between each of the cooling media.

**Table 4-4: MSR values for AISI 304 steel at developed MWF**

| Speed (m/min) | Spindle Speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness-Ra (µm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | Mean | SD |
| 64 | 585 | 0.18 | 0.50 | 0.95 | 0.93 | 0.94 | 0.940 | 0.008 |
| | | | 1.00 | 1.11 | 1.12 | 1.14 | 1.123 | 0.012 |
| 102 | 900 | 0.18 | 0.50 | 0.76 | 0.74 | 0.74 | 0.747 | 0.009 |
| | | | 1.00 | 0.87 | 0.89 | 0.86 | 0.873 | 0.012 |

**Table 4-5: MSR values for AISI 304 steel at commercial MWF**

| Speed (m/min) | Spindle Speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness-Ra (μm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | Mean | SD |
| 64 | 585 | 0.18 | 0.50 | 1.21 | 1.22 | 1.23 | 1.223 | 0.008 |
| | | | 1.00 | 0.95 | 0.94 | 0.92 | 0.939 | 0.016 |
| 102 | 900 | 0.18 | 0.50 | 0.75 | 0.76 | 0.76 | 0.760 | 0.002 |
| | | | 1.00 | 0.89 | 0.89 | 0.89 | 0.893 | 0.004 |

**Table 4-6: MSR values for AISI 304 steel at dry machining**

| Speed (m/min) | Spindle Speed (rpm) | Feed Rate (mm/rev) | Depth of Cut (mm) | Surface Roughness-Ra (μm) | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 1 | 2 | 3 | Mean | SD |
| 64 | 585 | 0.18 | 0.50 | 2.64 | 2.56 | 2.68 | 7.901 | 0.063 |
| | | | 1.00 | 2.75 | 2.78 | 2.58 | 8.123 | 0.107 |
| 102 | 900 | 0.18 | 0.50 | 1.87 | 1.83 | 1.88 | 5.594 | 0.024 |
| | | | 1.00 | 2.14 | 2.16 | 2.12 | 6.424 | 0.020 |

Dry machining was expressed the largest surface roughness values for both depth of cuts. The lowest surface roughness values were obtained for the developed MWF. It was declared a significant percentage reduction of the surface roughness values while using the developed MWF at two depth of cuts with the same parameter configurations than mineral oil based commercial MWF.The dry machining for AISI 304 was indicated the largest values for the two depth of cuts compared to 0.2% C steel (Fig. 4-3 and Fig. 4-4). Both material conditions are different mainly in term of hardness (0.2 % C is 111 HB and AISI 304 is 235 HB) and directly it caused for the increment of the surface roughness values for dry machining. The surface roughness values for the commercial MWF was also increased with the increment of the hardness values of the materials. But the developed MWF expressed surface roughness value reduction with the increment of the hardness.

According to Equation 4-2, the work tool interface temperature is increased with the increment of the cutting speed and the condition of the work material. The cutting tool trend to wear, if the MWF is unable to abate the induce heat at the work tool interface. As a result of that the surface quality of the work material reduced.

Developed MWF was expressed lowest surface roughness values for both materials in all set of parameters and expressed the effective capability of heat removal with the increment of the hardness values of the materials.

$$T = KV^{m} \quad (4\text{-}2)$$

Where, T is tool chip interface temperature, V is Cutting speed, K and *m* are parameters depending on cutting conditions and work materials.

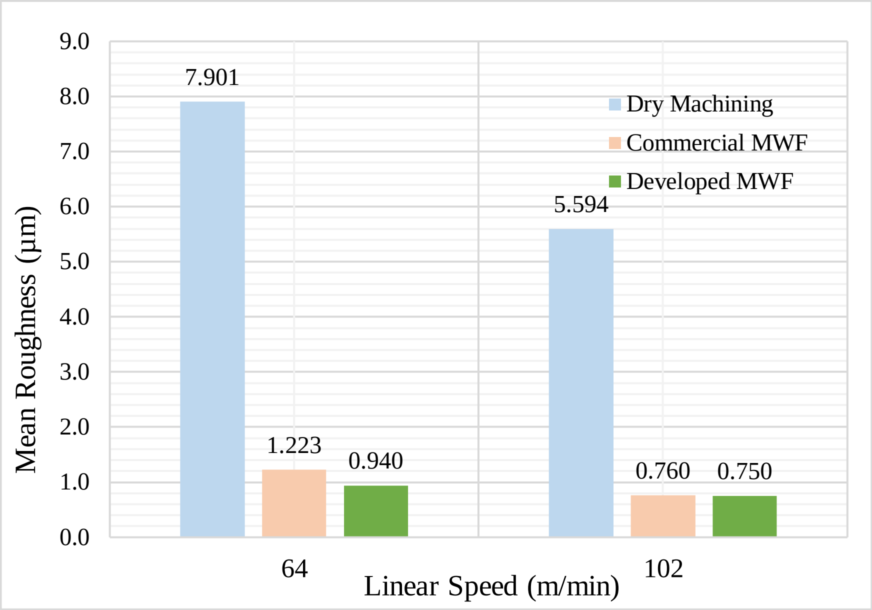



**Figure 4-3: Surface roughness- Ra variation for AISI 304 steel at 0.5mm depth of cut**

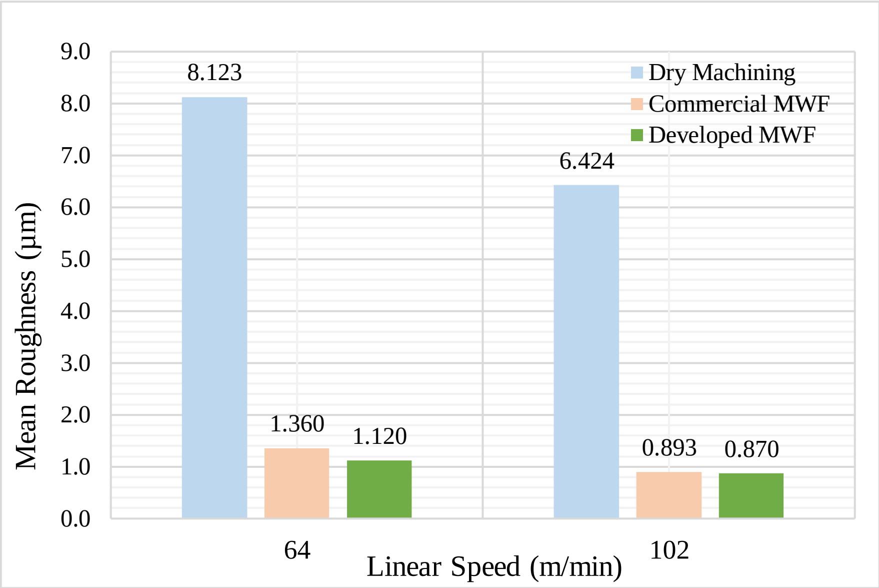



**Figure 4-4: Surface roughness- Ra variation for AISI 304 steel at 1 mm depth of cut**

## 4.2 Chip Curl Radius and Chip Form Investigation

The collected chips were categorized according to the cutting configuration and measured the parameters a and b (Fig. 3-3 and Fig. 3-4) to calculate chip curl radius (Equation 3-1) [51]. The calculated chip curl radius values were plotted for the analysis to identify the relationship between cutting configuration and cooling condition. Each of the three conditional values for the chip curl radius of dry, commercial MWF and developed MWF were expressed in the same graph for different cutting speeds and depth of cuts. Fig. 4-5 express the chip curl radius values for 0.2% C steel in 0.5 mm DoC with different cooling conditions while increasing the cutting speed. The performance of formulated novel coconut oil based MWF was investigated with comparing to commercially available MWF. It can be observed that the chip curl radius has a proportional relationship with linear cutting speed. The largest values for the chip curl radius were obtained while using developed MWF and lowest values were conquered for the dry machining in almost all the conditions.

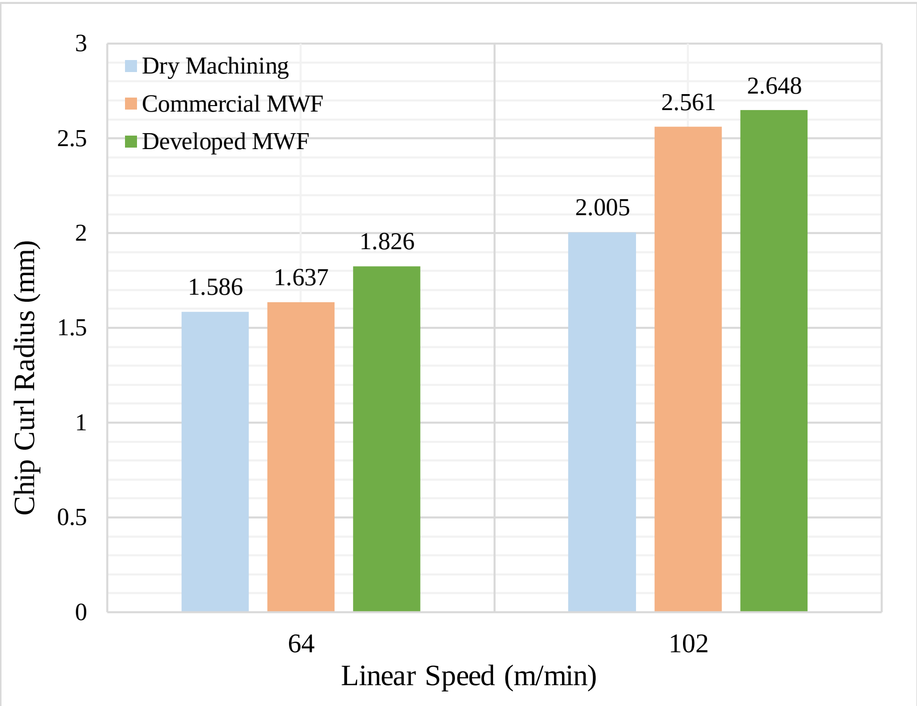



**Figure 4-5: Chip curl radius variation for 0.2% C steel at 0.5 mm depth of cut**

3.2% and 11.5% increment on chip curl radius were obtained at 64 m/min cutting speed, 0.18 rev/min feed rate and 0.5 mm DoC with 0.2% C steel for dry to commercial MWF and commercial MWF to developed MWF respectively. 27% and 3.4% increment for the chip curl radius were obtained at 102 m/min linear cutting speed, 0.18 rev/min feed rate and 0.5 mm DoC configuration with 0.2% C steel for dry to commercial MWF and commercial MWF to developed MWF respectively. With the increment of the DoC, the chip curl radius has expressed the value reduction except the dry machining value for 102 m/min in 1 mm DoC.

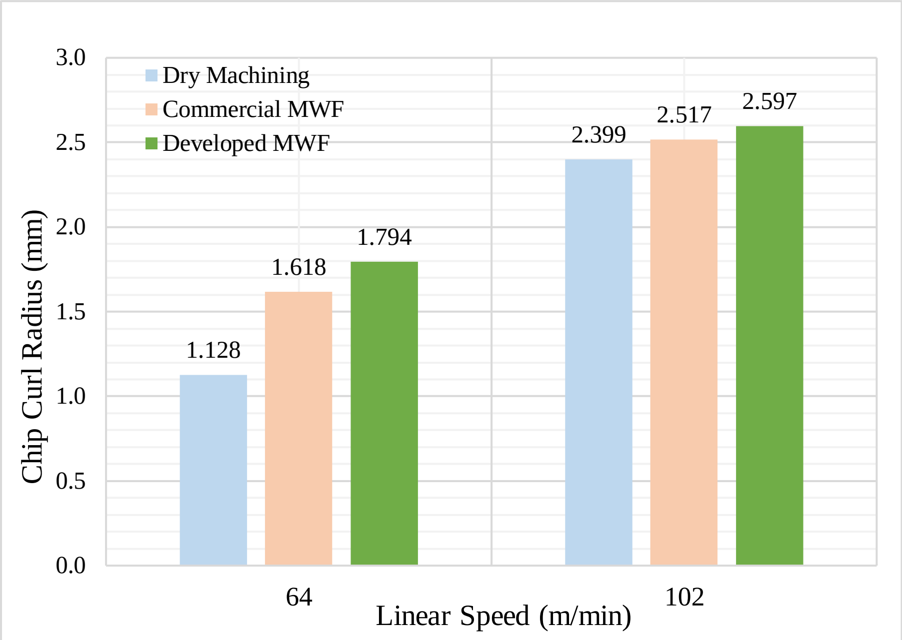



**Figure 4-6: Chip curl radius variation for 0.2% C steel at 1 mm depth of cut**

According to Fig. 4-6, the largest values were observed for the developed MWF and smallest for the dry machining for the selected cutting conditions. 43% and 10% increment in chip curl radius were obtained at 64 m/min linear cutting speed, 0.18 rev/min and 1 mm DoC with 0.2% C steel for dry to commercial MWF and commercial MWF to developed MWF. 5% and 3.2% increment for the chip curl radius were obtained at 102 m/min linear cutting speed, 0.18 rev/min feed rate and 1 mm DoC with 0.2% C steel for dry to commercial MWF and commercial MWF to developed MWF respectively.

Fig. 4-7 and Fig. 4-8 express the experimental results of the chip curl radius for AISI 304 in selected cutting configurations with different cooling conditions.

Almost all the values for the chip curl radius were increased with respect to the previous cutting condition except commercial MWF at 102 m/min in 0.5 mm DoC. 9% and 9.7% increment were obtained for the cutting configurations of 64 m/min linear cutting speed for 0.18 rev/min feed rate and 0.5 mm DoC. 3.8% decrement was obtained for the chip curl radius value with respect to dry cutting at 102 m/min linear cutting speed for 0.18 rev/min feed rate and 0.5 mm DoC. But, for the developed MWF the chip curl radius was expressed 25% and 20% increment compared to the commercial MWF and dry machining respectively at 102 m/min linear cutting speed for 0.18 rev/min feed rate and 0.5 mm DoC.

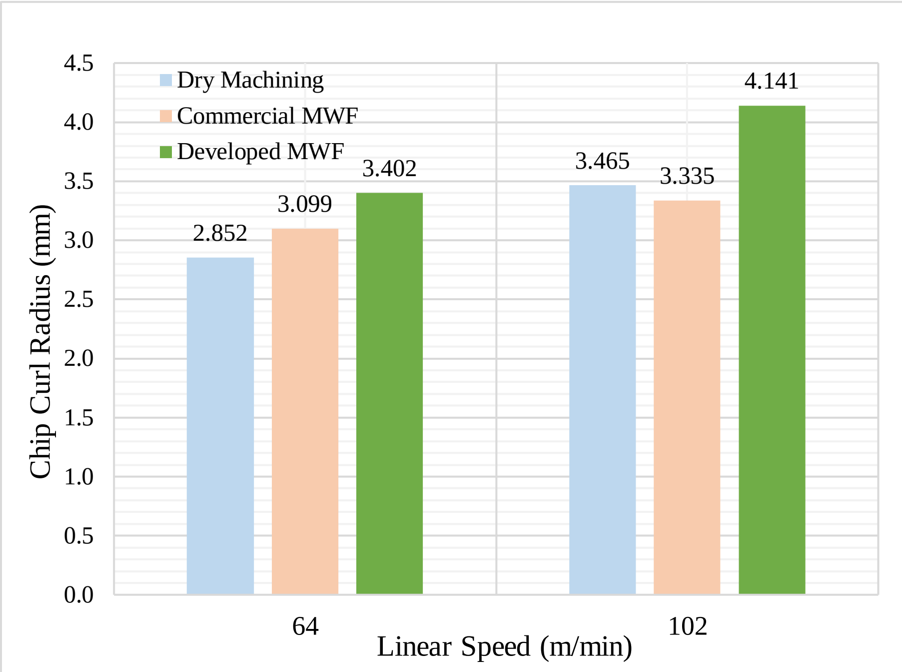



**Figure 4-7: Chip curl radius variation for AISI 304 steel at 0.5 mm depth of cut**

The increment of the chip curl radius is about 2% ,47% for commercial MWF and developed MWF respectively with comparing to the dry machining according to Fig. 4-6 at 64 m/min cutting speed. Further, it can be observed that 20%, 40% increment for commercial MWF and developed MWF with dry machining at 102 m/min cutting speed.

For the same cutting parameters for both 0.5 mm and 1 mm depth of cuts in 0.2% C and AISI 304, the increment of the chip curl radius is larger for the developed MWF with comparing to the commercial MWF and dry machining.

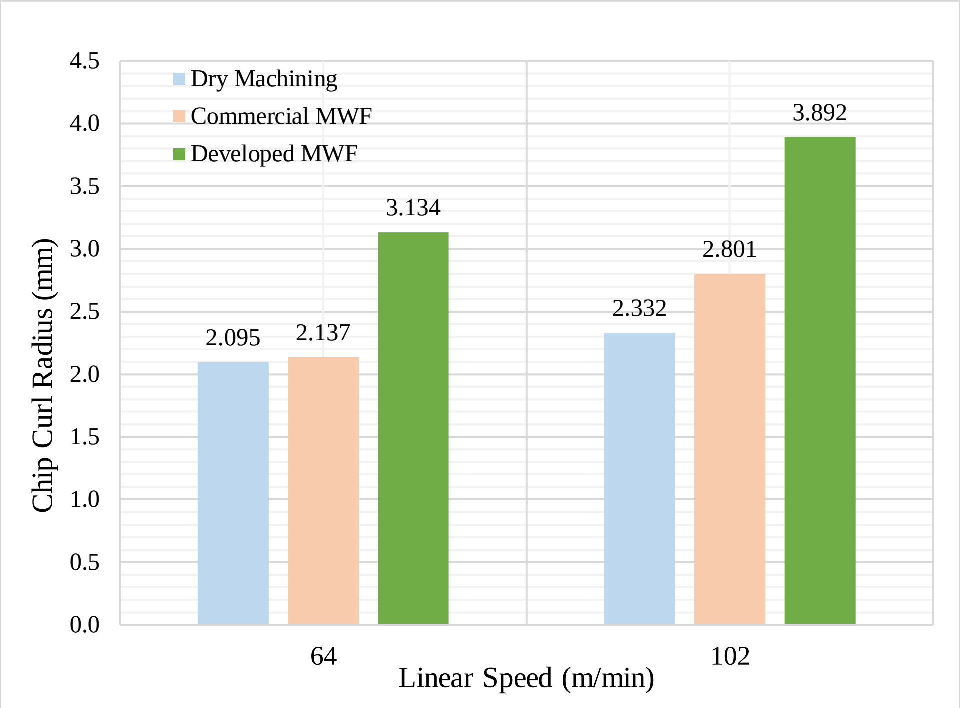



**Figure 4-8: Chip curl radius variation for AISI 304 steel at 1 mm depth of cut**

The increment percentage of the chip curl radius for the developed MWF expressed larger value for AISI 304 steel compared to the commercial MWF. During metal cutting operation, there is a retarded layer formed at the underside of the chip due to friction at the tool chip interfaces. According to the velocity profile described by Seah et al. [51], the near material to the work surface in the retarded layer has low or zero velocity and far from the surface has higher velocity. The material outside the retarded layer remain undeformed while underside of the chip been stretched. Hence, the difference of the velocities of the retarded layer, causes curling of the chip.

The work material is softened with the increment of the work tool interface temperature during higher cutting speed and reduces the frictional force. Thus, chip with larger radius curl are formed by gaining the higher speed of the retarded layer [58,69].

The lubrication effect of the MWF facilitate further to reduce the frictional force between work tool interfaces, lowering the degree of the retardment in the retarded layer which results the larger chip curl radius [58,69]. The chip breaks when the tensile strain larger to the actual fracture strain as according to the Nagayama's chip breaking criterion [67]. The fracture strain is propositional to the chip curl radius and chip thickness.

$$\varepsilon_B \propto \frac{t_c}{R_c} \tag{4-3}$$

Where, $t_c$ chip thickness, $\varepsilon_B$ tensile strain of the chip and $R_c$ chip curl radius.

Equation 4-3 express that the larger curl radius in the chip occurred due to the smaller strain. The energy consumption for the smaller strain is lower for the cutting mechanism due to the application of lower forces for breaking chip and make positive impact for the economical aspect of the operation. Apart from that, while increasing cutting speed with lower feed rate, trend to induce larger curl radius of the chip and results for the better surface quality of the machined material due to the lower frictional force. Developed MWF expressed better lubrication property with comparing to the commercial MWF. The obtained values for the chip curl radius for the developed MWF are higher for all configurations. According to Seah et al [51] and Nagayama's criterion [67], the developed MWF has facilitated more reduction in frictional force and tensile stain for the cutting mechanism. These observations are also agreed with the experimental investigations carried by Sun et al. [66].

The cutting-edge position, cutting condition, work material, tool material and tool geometry are prominent factors which influence for the chip characteristics during metal machining operation. The formation does not change unless one of the above-mentioned factors used to change at any given condition. The observation of the chip formation is important indicator to identify the changes in operational condition and machinability of the work material and also, unexpected edge failure can be observed. Therefore, it is essential to observe and report the chip characteristics in continues manner during the operation. Turning process is most likely to generate long and continuous chips during machining. The lack of availability guidelines in chip formation characteristics make difficult to evaluate the machining process.

Fig. 4-9 shows the schematic representation of standard chip characteristics based on ISO 3685 fundamental diagram to identify the chip formation in favourable and unfavourable condition during turning operation. Further, it specifies the nature of the chip characteristic as ribbon, tubular, spiral, washer and conical.

*Fav/Unf: Favourable and Unfavourable

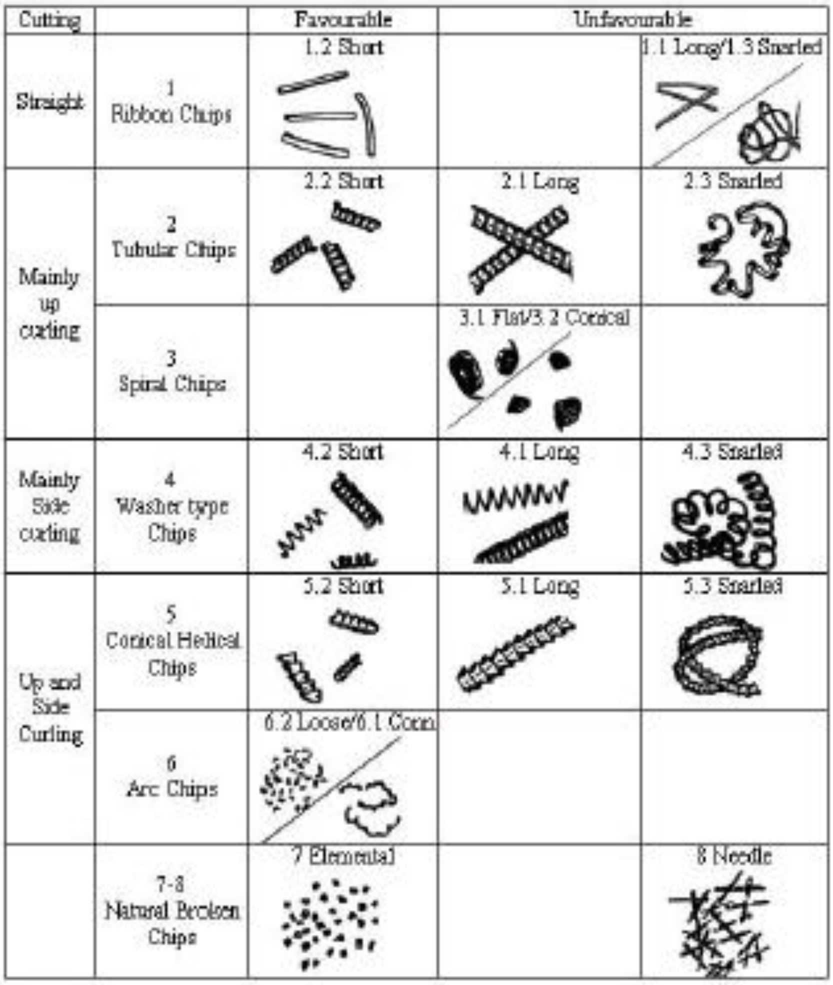



**Figure 4-9: ISO 3685 chip form classification standard** [68]

Table 4-7 and Table 4-8 express the empirical observations for 0.2% C and AISI 304 steels in recommended machining configuration. The forms of the chips were favourable for almost all the machining parameters in developed MWF and commercial MWF for 0.2% C steel unless 102 m/min cutting speed for 0.18 rev/min feed rate and 1 mm DoC for commercial MWF (Table 4-9 and Table 4-10).

The dry machining for 0.2% C and AISI 304 steels expressed unfavourable chip formation characteristic for all of the machining parameters. The chip forms expressed favourable condition for AISI 304 during the use of developed MWF unless 102 m/min cutting speed for 0.18 rev/min feed rate and 1 mm DoC. The commercial MWF expressed the capability of producing favourable chips only for the 0.5 mm DoC in 64 m/min and 102 m/min cutting speed for AISI 304 steel (Table 4-11 and Table 4-12). The dry machining was unaccepted for any of the configuration discussed above based on the results obtained for the chip form characteristics according to ISO 3685. The commercial MWF expressed good results for less harder work material for lower cutting speeds and depth of cuts. The developed MWF expressed better results for harder work material for lower cutting speeds and depth of cuts. It is essential to conduct the further experiments for developed MWF to make a conclusion for the machining status in harder materials with high speeds and higher depth of cuts.

**Table 4-7: Chip form classification details of 0.2%C steel**

| **Machining Parameters** | | | **Developed MWF** | | **Commercial MWF** | | **Dry Machining** | |
|---|---|---|---|---|---|---|---|---|
| **Speed (m/min)** | **Spindle Speed (rpm)** | **Depth of Cut (mm)** | **ISO Number** | ***Fav/ UnF** | **ISO Number** | ***Fav/ Unf** | **ISO Number** | ***Fav/ Unf** |
| 64 | 585 | 0.50 | 4.2 | Fav | 4.2 | Fav | 5.1 | Unf |
| | | 1.00 | 4.2 | Fav | 4.2 | Fav | 5.1 | Unf |
| 102 | 900 | 0.50 | 4.2 | Fav | 5.2 | Fav | 4.1 | Unf |
| | | 1.00 | 5.2 | Fav | 4.3 | Unf | 4.1 | Unf |

**Table 4-8: Chip form classification details of AISI 304 steel**

| **Machining Parameters** | | | **Developed MWF** | | **Commercial MWF** | | **Dry Machining** | |
|---|---|---|---|---|---|---|---|---|
| **Speed (m/min)** | **Spindle Speed (rpm)** | **Depth of Cut (mm)** | **ISO Number** | ***Fav/ UnF** | **ISO Number** | ***Fav/ UnF** | **ISO Number** | ***Fav/ UnF** |
| 64 | 585 | 0.50 | 4.2 | Fav | 4.2 | Fav | 4.3 | Unf |
| | | 1.00 | 4.2 | Fav | 4.3 | Unf | 4.1 | Unf |
| 102 | 900 | 0.50 | 4.2 | Fav | 4.2 | Fav | 4.1 | Unf |
| | | 1.00 | 4.1 | Unf | 4.3 | Unf | 4.3 | Unf |

**Table 4-9: Chip morphology of 0.2% C steel for dry machining and developed MWF**

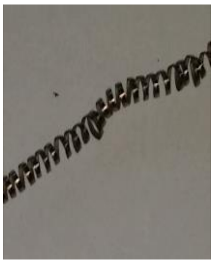
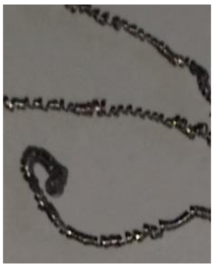
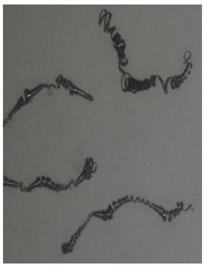
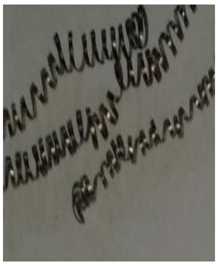
| | | | | | |
|---|---|---|---|---|---|
| Depth of Cut (mm) | 1.0 |  |  |  |  |
| | 0.5 |  |  |  |  |
| Condition | | Dry Machining | Developed MWF | Dry Machining | Developed MWF |
| Speed | | 64 m/min | | 102 m/min | |

**Table 4-10: Chip morphology of 0.2% C steel for commercial MWF and developed MWF**

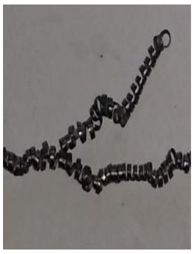
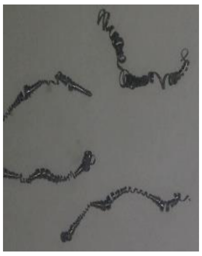
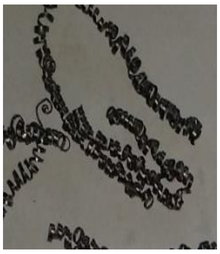
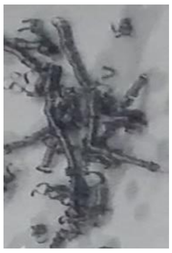
| | | | | | |
|---|---|---|---|---|---|
| Depth of Cut (mm) | 1.0 |  |  |  |  |
| | 0.5 |  |  |  |  |
| Condition | | Commercial MWF | Developed MWF | Commercial MWF | Developed MWF |
| Speed | | 64 m/min | | 102 m/min | |

**Table 4-11: Chip morphology of AISI 304 steel for dry machining and developed MWF**

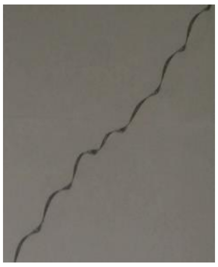
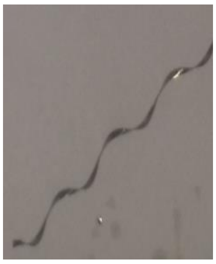
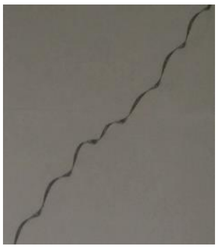
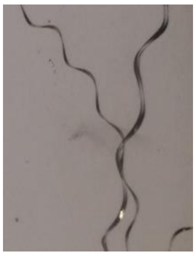
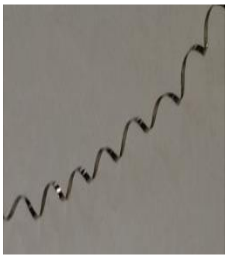
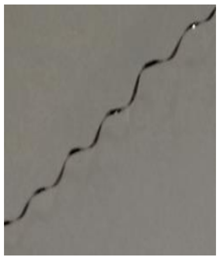
| | | | | | |
|---|---|---|---|---|---|
| Depth of Cut (mm) | 1.0 |  |  |  |  |
| | 0.5 |  |  |  |  |
| Condition | | Dry Machining | Developed MWF | Dry Machining | Developed MWF |
| Speed | | 64 m/min | | 102 m/min | |

**Table 4-12: Chip morphology of AISI 304 steel for commercial MWF and developed MWF**

| | | | | | |
|---|---|---|---|---|---|
| Depth of Cut (mm) | 1.0 |  |  |  |  |
| | 0.5 |  |  |  |  |
| Condition | | Commercial MWF | Developed MWF | Commercial MWF | Developed MWF |
| Speed | | 64 m/min | | 102 m/min | |

## 4.3 Tool Wear Investigation

The cutting-edge geometry is important for the high precision machining. If it is worn out, the required dimensional accuracy could not be obtained. The coated carbide insert (CNMG 433-M/Grade T 9325) geometry of initial and after machined were investigated using scanning electron microscope (SEM) at Industrial Technology Institute (ITI), Sri Lanka. The tool wear was evaluated during the use of commercial MWF for cutting parameters of 64 m/min cutting speed, 18 rev/min and 0.5 mm DoC in AISI 304 steel. The operation was conducted continuous 300 mm length machining for 30 minutes. Fig. 4-10 and Fig. 4-11 express the initial tool nose and flank face geometry respectively.

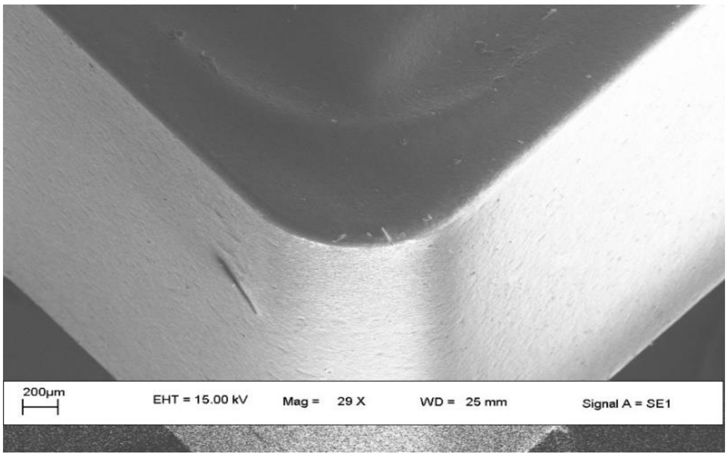



**Figure 4-10: Initial tool geometry of the nose in cutting tool**

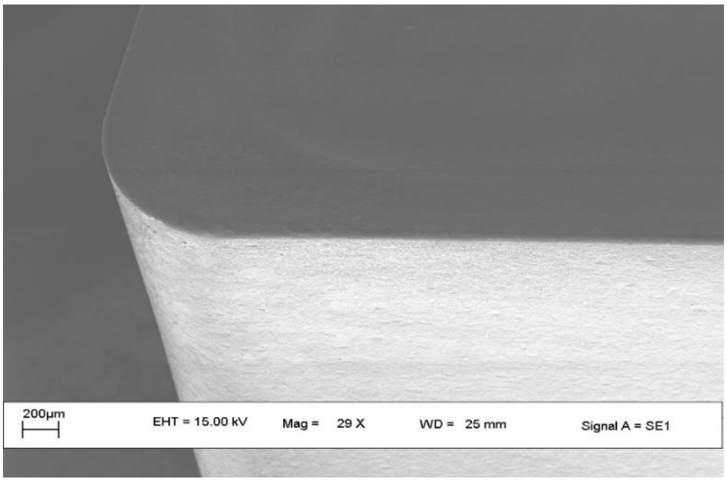



**Figure 4-11: Initial tool geometry of the flank face in cutting tool**

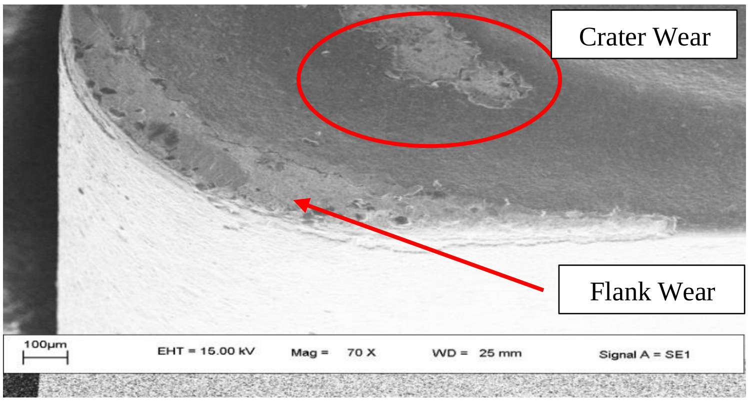



**Figure 4-12: Tool geometry of the cutting tool of commercial MWF**

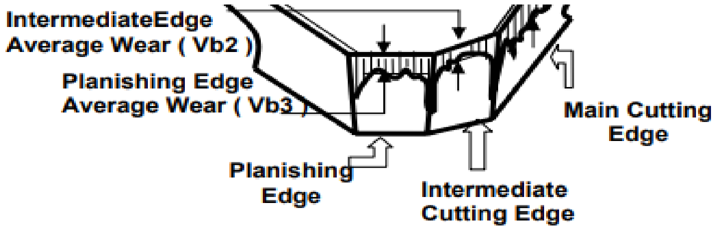



**Figure 4-13: Cutting edges in tool insert**

$$VT^n = C \tag{4-4}$$

Where T is the tool life, V is the cutting velocity (m/min), n and C depend on the condition of tool work configuration (cutting environment, type of material etc)

According to Taylors Tool Life equation (Equation 4-4), the life of the cutting tool mainly depends upon the cutting velocity. For the higher cutting velocities, the expected life of the tool is minimum than at the lower cutting speeds. Diffusion wear can be observed in the rubbing surfaces in Fig. 4-12 (main cutting edge as expressed in Fig. 4-13), the higher velocity caused for generating higher temperature in work tool interfaces. Such incident results the rake surface gradual diffusion into the flowing chips either in bulk or atom by atom. The rate of tool wear increases with the increment of the work tool interfaces temperature. It is essential to use a better MWF with higher cooling capability for the cutting operation to abate the generate heat and ensure the long tool life.

## 4.4 Simulation of Work Tool Interface Temperature

The thermal simulation was performed based on the shear frictional machining concept where the formation of chip was assumed to be only from shearing. The load along the cutting direction was evaluated with number of stokes at the initial unsteady thermal simulation and observed the convergence throughout the machining process. Fig. 4-14 express the load variation along the cutting direction with number of strokes.

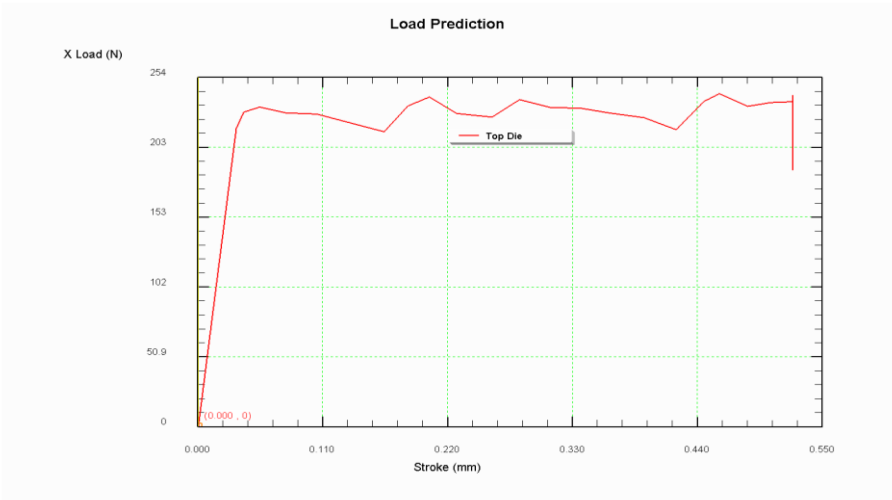



**Figure 4-14: Load prediction during initial unsteady thermal simulation**

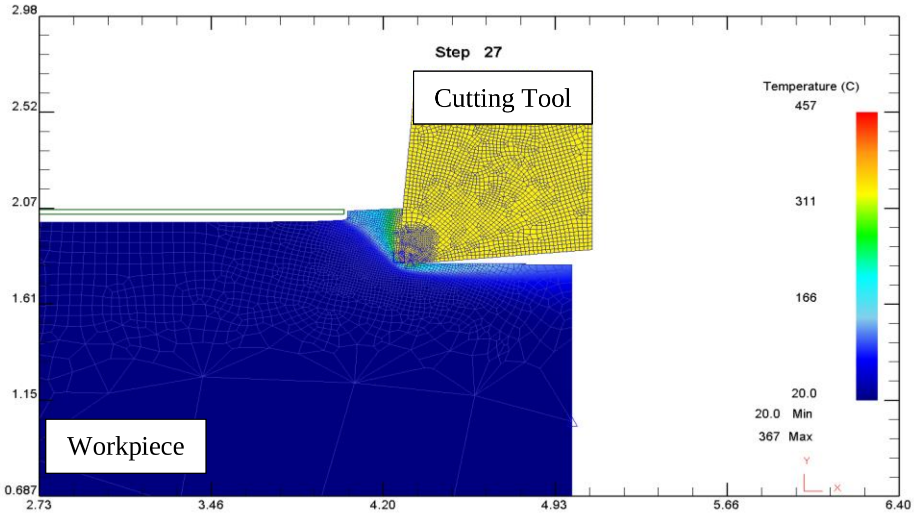



**Figure 4-15: Maximum work tool interface temperature**

As express in Fig. 4-15, 367 $^0$C maximum temperature was obtained in the initial unsteady thermal simulation (step 27). Therefore, the steady state thermal simulation was conducted at step 27. The step 28, thermal simulation was started with the same velocity of the tool substituting for the workpiece. At the steady state condition, the velocity of the cutting tool is zero relative to the workpiece. Fig. 4-16 deliberates the work tool interfaces heat transfer during the machining process. Step 31 express the lower temperature of 360 $^0$C which was lower than step 27.

Finally, the unsteady thermal simulation was conducted considering elastic plastic behavior of the work material where the relative velocity was zero to the motion of the tool. The highest temperature could identify at tool tip according to Fig. 4-16. Gradually the higher heat spread throughout the tool and workpiece. Chip carries more than 80% generated heat and rest transfer to the tool and workpiece [51]. The effective chip removal is essential for the proper cutting process. The surface of the material trend to soften due to the transfer heat and it facilitates the effective machining with lower cutting forces. The induce chips and heat will efficiently remove at the work tool interface with use of MWF. The use of MWF significantly helps to abate the generated heat at work tool interface and maintain the proper tool edge geometry (longer tool life) to ensure the dimensional accuracy.

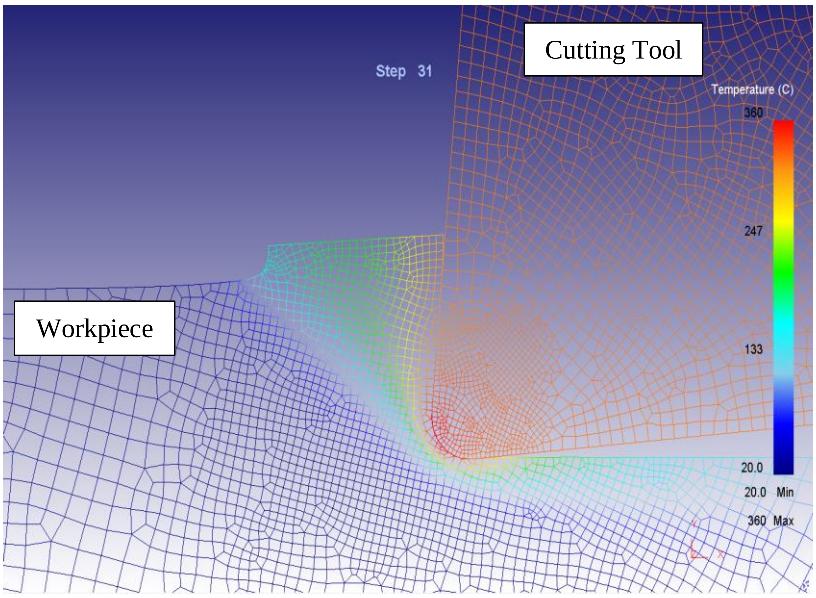



**Figure 4-16: Work tool interface temperature at steady state step 31**

The maximum principal stress has observed 797 MPa as indicated in Fig. 4-17. The subjected cutting force is higher in dry machining and it requires more than 250 MPa yield stress to make a fracture in the AISI 304 steel. The higher stress at the cutting zone cause diffusion wear on the tool and it accelerates with the increment of the temperature in high speed machining due to more interaction of flank face of the tool to the work surface. Therefore, it is worth to investigate the combine effect of the principal stress in high speed with flank wear and work tool interface temperature [63].

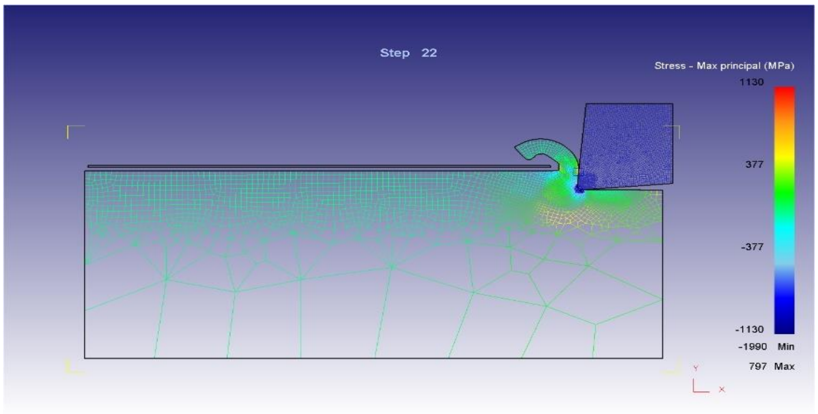



**Figure 4-17: Principal stress distribution during the machining process**

# CHAPTER 05: CONCLUSION

Metalworking Fluid (MWF) plays a prominent role in machining operations to provide a better lubrication layer for obtaining higher surface quality and dimensional accuracy of the machined components. Manufacturing industries are currently consuming mineral oil based MWFs in large volume for the machining process due to its superior cooling and lubrication performance. However, the higher toxic and harmful chemical components in the mineral oil based MWFs have reported adverse impact on health and environment features during usage and disposal phases. Hence, the research was conducted to introduce a high-performance bio based MWF for metal machining process to ensure industrial sustainability.

- Water-soluble white coconut oil based MWF was developed to introduce to the metal machining process for replacing toxic and hazardous mineral oil based MWFs. The novel green cutting fluid was formulated using food grade ingredients to eliminate harmful effect on the health and environmental features. The base oil (i.e: white coconut oil) and food grade surfactants are highly available in market with lower price compared to mineral oil based MWF. The formulation is required only a simple stirring process with minimum energy consumption. Hence, the introduced green cutting fluid has fulfilled the socioeconomic and environmental aspects of the sustainability and can recognize as a potential candidate for cooling and lubrication of the contact surfaces during machining operations.

- The higher free fatty acid content and better wettability properties (i.e: higher rheological and tribological characteristics) of the white coconut oil based MWF has caused 4.6% and 8% reduction on surface roughness values for 0.2% C steel compared to mineral oil based MWF at 102 m/min cutting speed, feed rate of 0.18 mm/rev for 0.5 mm and 1.0 mm depth of cuts respectively. Further, surface roughness value reduction of 30% and 22% were recorded for the AISI 304 steel at 64 m/min cutting speed, feed rate of 0.18 mm/rev for 0.5 mm and 1.0 mm depth of cuts respectively.

- Moreover, 47% and 40% increment of the chip curl radius values were obtained for the AISI 304 work material at 64 m/min and 102 m/min respectively at 0.18 mm/rev feed rate and 1.0 mm DoC. The higher chip curl radius values expressed lower energy consumption for the shear mechanism and indicated the economic benefit of using white coconut oil based MWF for metal machining operation. The collected chips were examined according to ISO 3685, chip form and classification standard to identify the condition of machining configurations. Favorable chip forms were noted for almost all the machining specifications on AISI 304 and 0.2% C steels under white coconut oil based MWF.

- Larger crater and flank wear were observed while using commercially available MWF for coated carbide cutting tool. The tool wear investigations were done only for the mineral oil based MWF due to the technical and financial difficulties to conduct SEM investigations in Sri Lanka. However, the white coconut oil based MWF has expressed lower flank, notch and crater wear for high speed steel tool (HSS) in a previous study and revealed its ability for the longer tool life for the selected cutting configuration.

- Moreover, work tool interface temperature, cutting forces and chip formation for AISI 304 steel were simulated using commercially available software. The higher cutting temperature and cutting forces in dry machining condition has expressed the necessity of better cooling and lubrication medium. Additionally, the empirical and simulation results for the machining responses can be compared in future studies. Though, the unavailability of the tool dynamometer and accessorises to measure work tool interface temperature in Sri Lanka will make a substantial impact to clarify the applicability of the developed green MWF.

As a summary, the introduced white coconut oil based MWF has expressed favorable machining responses while ensuring the process sustainability. The aforementioned research objectives and sub objectives have been achieved while adding a value to the environmental conscious high-performance machining for socioeconomic benefit in manufacturing industries.

# PUBLICATIONS

1. K.C Wikramasinghe, G.I.P Perera, S.W.M.A.I Senavirathne, Himan K.G Punchihewa, Hiroyuki Sasahara, “Surface Quality Evaluation of 0.2% C and AISI 304 steels in Turning with Sustainable Lubricating Condition”, Journal of Mechanical Science and Technology (Springer) vol 33(12),1-7,2019.

2. K.C Wikramasinghe, G.I.P Perera, S.W.M.A.I Senavirathne, Himan K.G Punchihewa, Hiroyuki Sasahara, “Surface Quality Evaluation of 0.2% C and AISI 304 steels in Turning with Sustainable Lubricating Condition”, 8$^{th}$ International Conference on Manufacturing, Machine Design and Tribology, Kagoshima, Japan, April 24-27, 2019.

3. K.C Wikramasinghe, G.I.P Perera, S.W.M.A.I Senavirathne, Himan K.G Punchihewa, Hiroyuki Sasahara “Investigation of the Chip Curl Radius of 0.2% C and AISI 304 steel during Turning under Sustainable Lubricant”, 8$^{th}$ International Conference of Asian Society of Precision Engineering and Nanotechnology, Matsue, Japan, November 12-15, 2019.

## REFERENCES


[1] A. Rave and S. Joksch, “Monitoring metalworking fluids,” *Metalwork. Fluids Cut. Grind. Fundam. Recent Adv.*, no. March, pp. 317–337, 2012, doi: 10.1016/B978-0-85709-061-4.50007-4.

[2] A. Panda, J. Duplák, and K. Vasilko, “Analysis of Cutting Tools Durability Compared with Standard ISO 3685,” *Int. J. Comput. Theory Eng.*, vol. 4, no. 4, pp. 621–624, 2012, doi: 10.7763/IJCTE.2012.V4.544.

[3] G. Arora *et al.*, “Vegetable oil based cutting fluids – green and sustainable machining - II,” *J. Mater. Sci. Mech. Eng.*, vol. 2, no. 9, pp. 1–5, 2015.

[4] S. A. Lawal, I. A. Choudhury, and Y. Nukman, “Application of vegetable oil-based metalworking fluids in machining ferrous metals - A review,” *Int. J. Mach. Tools Manuf.*, vol. 52, no. 1, pp. 1–12, 2012, doi: 10.1016/j.ijmachtools.2011.09.003.

[5] A. Antić, P. B. Petrović, M. Zeljković, B. Kosec, and J. Hodolič, “The influence of tool wear on the chip-forming mechanism and tool vibrations,” *Mater. Tehnol.*, vol. 46, no. 3, pp. 279–285, 2012.

[6] E. Kuram, B. Ozcelik, E. Demirbas, E. Şik, and I. N. Tansel, “Evaluation of new vegetable-based cutting fluids on thrust force and surface roughness in drilling of AISI 304 using Taguchi method,” *Mater. Manuf. Process.*, vol. 26, no. 9, pp. 1136–1146, 2011, doi: 10.1080/10426914.2010.536933.

[7] S. J. Skerlos, K. F. Hayes, A. F. Clarens, and F. Zhao, “Current advances in sustainable Metalworking Fluids research,” *Int. J. Sustain. Manuf.*, vol. 1, no. 1/2, p. 180, 2008, doi: 10.1504/IJSM.2008.019233.

[8] H. Sasahara, T. Nitta, and K. Nishi, “Analysis of Tool Temperature in High-Speed Milling Temperature,” pp. 279–280, doi: 10.1007/s003380000118.

[9] K. C. C. Wickramasinghe, G. I. P. I. P. Perera, and H. M. C. M. M. C. M. Herath, “Formulation and performance evaluation of a novel coconut oil–based metalworking fluid,” *Mater. Manuf. Process.*, vol. 32, no. 9, pp. 1026–1033, Jul. 2017, doi: 10.1080/10426914.2016.1257858.

[10] H. R. Landis, K. F. Hayes, and S. J. Skerlos, “Experimental Comparison of Vegetable and Petroleum Base Oils in Metalworking Fluids Using Tapping Torque Test,” *Proc. JUSFA Japan-USA Symp. Flex. Autom.*, pp. 1–6, 2004.

[11] G. Kant and K. S. Sangwan, “Prediction and optimization of machining parameters for minimizing power consumption and surface roughness in machining,” *J. Clean. Prod.*, vol. 83, pp. 151–164, 2014, doi: 10.1016/j.jclepro.2014.07.073.

[12] E. M. Trent and P. K. Wright, *Metal Cutting*, 4th ed. United States of America: Butterworth–Heinemann, 2000.

[13] E. Kuram, B. Ozcelik, E. Demirbas, and E. Şık, “Effects of the Cutting Fluid Types and Cutting Parameters on Surface Roughness and Thrust Force,” *World*

*Congr. Eng.*, vol. II, pp. 1–4, 2010, doi: 10.1109/MNRAO.1994.346257.

[14] K. P. Sodavadia and A. H. Makwana, "Experimental Investigation on the Performance of Coconut oil Based Nano Fluid as Lubricants during Turning of AISI 304 Austenitic Stainless Steel," *Int. J. Adv. Mech. Eng.*, vol. 4, no. 1, pp. 55–60, 2014.

[15] M. Sayuti, A. A. D. Sarhan, and F. Salem, "Novel uses of SiO2 nano-lubrication system in hard turning process of hardened steel AISI4140 for less tool wear, surface roughness and oil consumption," *J. Clean. Prod.*, vol. 67, pp. 265–276, 2014, doi: 10.1016/j.jclepro.2013.12.052.

[16] R. Yunus, A. Fakhru'l-Razi, T. L. Ooi, S. E. Iyuke, and J. M. Perez, "Lubrication properties of trimethylolpropane esters based on palm oil and palm kernel oils," *Eur. J. Lipid Sci. Technol.*, vol. 106, no. 1, pp. 52–60, 2004, doi: 10.1002/ejlt.200300862.

[17] S. A. Lawal, "A review of application of vegetable oil-based cutting fluids in machining non-ferrous metals," *Indian J. Sci. Technol.*, vol. 6, no. 1, pp. 3951–3956, 2013, doi: 10.1016/j.ijmachtools.2011.09.003.

[18] M. P. Groover, *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*. 2010.

[19] V. P. Astakhov, "The assessment of cutting tool wear," *Int. J. Mach. Tools Manuf.*, vol. 44, no. 6, pp. 637–647, 2004, doi: 10.1016/j.ijmachtools.2003.11.006.

[20] S. A. Lawal, I. A. Choudhury, and Y. Nukman, "Developments in the formulation and application of vegetable oil-based metalworking fluids in turning process," *Int. J. Adv. Manuf. Technol.*, vol. 67, no. 5–8, pp. 1765–1776, 2013, doi: 10.1007/s00170-012-4607-0.

[21] S. A. Lawal, I. A. Choudhury, and Y. Nukman, "A critical assessment of lubrication techniques in machining processes: A case for minimum quantity lubrication using vegetable oil-based lubricant," *J. Clean. Prod.*, vol. 41, pp. 210–221, 2013, doi: 10.1016/j.jclepro.2012.10.016.

[22] E. Kuram, B. Ozcelik, and E. Demirbas, "Environmentally Friendly Machining: Vegetable Based Cutting Fluids," in *Green Manufacturing Processes and Systems, Materials Forming, Machining and Tribology*, Springer, Berlin, Heidelberg, 2013, pp. 23–47.

[23] B. E, M. Garbrecht, C. Heinzel, T. Koch, and J. Eckebrecht, "Current approaches in design and supply of metalworking fluids," *Tribol. Trans.*, vol. 52, no. 5, pp. 591–601, 2009, doi: 10.1080/10402000902825739.

[24] F. O. F. Application, "Tapping Torque Test for Cutting Fluid Evaluation," pp. 1–7, 1988.

[25] M. A. El Baradie, "Cutting fluids: Part I. Characterisation," *J. Mater. Process. Technol.*, vol. 56, no. 1–4, pp. 786–797, 1996, doi: 10.1016/0924-0136(95)01892-1.

[26] M. Kaladhar, K. V. Subbaiah, and C. S. Rao, "Determination of Optimum

Process Parameters during turning of AISI 304 Austenitic Stainless Steels using Taguchi method and ANOVA," *Int. J. Lean Think.*, vol. 3, no. 1, 2012.

[27] M. A. El Baradie, "Cutting fluids: Part II. Recycling and clean machining," *J. Mater. Process. Technol.*, vol. 56, no. 1–4, pp. 798–806, 1996, doi: 10.1016/0924-0136(95)01893-X.

[28] P. Adegbuyi, "Analysing the effect of cutting fluids on the mechanical properties of mild steel in a turning operation," *Am. J. Sci. Ind. Res.*, vol. 2, no. 1, pp. 1–10, 2011, doi: 10.5251/ajsir.2011.2.1.1.10.

[29] C. C. Wu and H. M. Liu, "Determinants of metals exposure to metalworking fluid among metalworkers in taiwan," *Arch. Environ. Occup. Heal.*, vol. 69, no. 3, pp. 131–138, 2014, doi: 10.1080/19338244.2012.750589.

[30] S. Mccoy, "The Development of An Engine Lubricant Containing Soyabean Oil," p. 80, 2007.

[31] K. Gerulová, O. Tatarka, T. Štefko, and T. Škulavík, "The Study Of Metalworking Fluids Biodegradability By Indirect Measurement Of Bacterial Inoculum Respiration," *Res. Pap. Fac. Mater. Sci. Technol. Slovak Univ. Technol.*, vol. 23, no. 36, pp. 65–75, 2015, doi: 10.1515/rput-2015-0008.

[32] A. Eisentraeger, M. Schmidt, H. Murrenhoff, W. Dott, and S. Hahn, "Biodegradability testing of synthetic ester lubricants - Effects of additives and usage," *Chemosphere*, vol. 48, no. 1, pp. 89–96, 2002, doi: 10.1016/S0045-6535(02)00084-X.

[33] A. Muszyński and M. Łebkowska, "Biodegradation of used metalworking fluids in wastewater treatment," *Polish J. Environ. Stud.*, vol. 14, no. 1, pp. 73–79, 2005.

[34] S. Z. Erhan, B. K. Sharma, and J. M. Perez, "Oxidation and low temperature stability of vegetable oil-based lubricants," *Ind. Crops Prod.*, vol. 24, no. 3, pp. 292–299, 2006, doi: 10.1016/j.indcrop.2006.06.008.

[35] Giraltoš P, Maga D, and Klekovkin V, "Ecological Aspects of Cutting Fluids & Minimization of the Ecological Impacts of Cutting Fluids," in *KOPES 2007*, 2007, [Online]. Available: http://www.cybletter.com/index.php?s=file_download&id=20.

[36] N. A. Negm, M. M. El-Sukkary, G. H. Sayed, M. G. Mohamed, and M. Bekhit, "Eco-Friendly Vegetable Oil-Based Metalworking Fluid (MWFs) from Modification of Glycolyzed Products of Polyurethane," *J. Surfactants Deterg.*, vol. 19, no. 3, pp. 455–466, 2016, doi: 10.1007/s11743-016-1806-y.

[37] P. S. Lathi and B. Mattiasson, "Green approach for the preparation of biodegradable lubricant base stock from epoxidized vegetable oil," *Appl. Catal. B Environ.*, vol. 69, no. 3–4, pp. 207–212, 2007, doi: 10.1016/j.apcatb.2006.06.016.

[38] K. Li, F. Aghazadeh, S. Hatipkarasulu, and T. G. Ray, "Health risks from exposure to metal-working fluids in machining and grinding operations," *Int. J. Occup. Saf. Ergon.*, vol. 9, no. 1, pp. 75–95, 2003, doi:

10.1080/10803548.2003.11076555.

[39] E. O. Bennett, “Water based cutting fluids and human health,” *Tribol. Int.*, vol. 16, no. 3, pp. 133–136, 1983, doi: 10.1016/0301-679X(83)90055-5.

[40] D. Park, P. A. Stewart, and J. B. Coble, “A comprehensive review of the literature on exposure to metalworking fluids,” *J. Occup. Environ. Hyg.*, vol. 6, no. 9, pp. 530–541, 2009, doi: 10.1080/15459620903065984.

[41] D. Park, P. A. Stewart, and J. B. Coble, “Determinants of exposure to metalworking fluid aerosols: A literature review and analysis of reported measurements,” *Ann. Occup. Hyg.*, vol. 53, no. 3, pp. 271–288, 2009, doi: 10.1093/annhyg/mep005.

[42] S. A. Lawal, I. A. Choudhury, I. O. Sadiq, and A. Oyewole, “Vegetable-oil based metalworking fluids research developments for machining processes: survey, applications and challenges,” *Manuf. Rev.*, vol. 1, no. January 2016, p. 22, 2014, doi: 10.1051/mfreview/2014021.

[43] A. S. Abdul Sani, E. A. Rahim, S. Sharif, and H. Sasahara, “The influence of modified vegetable oils on tool failure mode and wear mechanisms when turning AISI 1045,” *Tribol. Int.*, vol. 129, no. August, pp. 347–362, 2019, doi: 10.1016/j.triboint.2018.08.038.

[44] S. Watanabe, “Characteristic Properties of Water-Soluble Cutting Fluids Additives for Iron Materials,” *J. Oleo Sci.*, vol. 397, no. 8, pp. 385–397, 2007, doi: 10.1504/IJMPT.2007.014719.

[45] A. C. Rustan and C. A. Drevon, “Fatty Acids: Structures and Properties,” *Encycl. Life Sci.*, pp. 1–7, 2005, doi: 10.1038/npg.els.0003894.

[46] U. S. Choi, B. G. Ahn, O. K. Kwon, and Y. J. Chun, “Tribological behavior of some antiwear additives in vegetable oils,” *Tribol. Int.*, vol. 30, no. 9, pp. 677–683, 1997, doi: 10.1016/S0301-679X(97)00039-X.

[47] C. C. Tsao, “An experiment study of hard coating and cutting fluid effect in milling aluminum alloy,” *Int. J. Adv. Manuf. Technol.*, vol. 32, no. 9–10, pp. 885–891, 2007, doi: 10.1007/s00170-006-0417-6.

[48] M. A. Islam, M. J. Uddin, M. A. Alim, and N. R. Dhar, “An ExperimentalInvestigation ofVegetable Oil Based Cutting Fluid on Drilling Medium Carbon Steel by HSS Drill Bit,” *ICME2009, held Dhaka, Bangladesh, 26th – 28th Dec.*, vol. 2009, no. December, pp. 26–28, 2009.

[49] E. Brinksmeier, D. Meyer, A. G. Huesmann-Cordes, and C. Herrmann, “Metalworking fluids - Mechanisms and performance,” *CIRP Ann. - Manuf. Technol.*, vol. 64, no. 2, pp. 605–628, 2015, doi: 10.1016/j.cirp.2015.05.003.

[50] N. S. S. & R. . Vaibhav Koushik A.V, “Vegetable Oil-Based Metal Working Fluids-A Review,” *Int. J. Theor. Appl. Res. Mech. Eng. Signif.*, vol. 1, no. 1, pp. 95–101, 2012.

[51] K. H. W. Seah and X. Li, “Influence of Coolant on Cutting Tool Performance,” *Journal of Materials Science & Technology*, vol. 13. pp. 199–205, 1997.

[52] K. A. G. Gopala, G. Raj, A. S. Bhatnagar, P. Kumar, and P. Chandrashekar, "Coconut oil: chemistry, production and its applications - A Review," *Indian Coconut J.*, pp. 15–27, 2010, doi: 10.1111/j.1751-908X.2004.tb00761.x.

[53] Steven ODI-OWEI, "Tribological Properties of Some Vegetable Oils and Fats," *J. Soc. Tribol. Lubr. Eng.*, vol. 45, no. 11, pp. 685–690, 2011.

[54] E. Benedicto, D. Carou, and E. M. Rubio, "Technical, Economic and Environmental Review of the Lubrication/Cooling Systems Used in Machining Processes," *Procedia Eng.*, vol. 184, pp. 99–116, 2017, doi: 10.1016/j.proeng.2017.04.075.

[55] M. A. Hasib, A. Al-Faruk, and N. Ahmed, "Mist application of cutting fluid," *Int. J. Mech. Mech. Eng.*, vol. 10, no. 4, pp. 13–18, 2010.

[56] P. C. Raynor, S. W. Kim, and M. Bhattacharya, "Mist generation from metalworking fluids formulated using vegetable oils," *Ann. Occup. Hyg.*, vol. 49, no. 4, pp. 283–293, 2005, doi: 10.1093/annhyg/meh092.

[57] S. Pervaiz, "Investigation Cooling and Lubrication Strategies for Sustainable Machining of Titanium Alloys," KTH Royal Institute of Technology, 2015.

[58] M. M. A. Khan and N. R. Dhar, "Performance evaluation of minimum quantity lubrication by vegetable oil in terms of cutting force, cutting zone temperature, tool wear, job dimension and surface finish in turning AISI-1060 steel," *J. Zhejiang Univ. A*, vol. 7, no. 11, pp. 1790–1799, 2006, doi: 10.1631/jzus.2006.A1790.

[59] P. Taylor and Khandekar, "Nano-Cutting Fluid for Enhancement of Metal Cutting Performance," *Mater. Manuf. Process.*, vol. 27, no. 9, pp. 963–967, 2012, doi: 10.1080/10426914.2011.610078.

[60] M. Amrita, R. R. Srikant, and A. V. Sitaramaraju, "Evaluation of Cutting Fluid With Nanoinclusions," *J. Nanotechnol. Eng. Med.*, vol. 4, no. 3, p. 031007, 2014, doi: 10.1115/1.4026843.

[61] Speeds and feeds for turning stainless steels, British Stainless Steel Association, Sheffield, UK, 2015. https://www.bssa.org.uk/topics.php?article=193.

[62] General Tool Catalog PARAMET, Dormer Paramet, Barlborough, Chesterfield, UK 2017.

[63] E. Abboud, B. Shi, H. Attia, V. Thomson, and Y. Mebrahtu, "Finite element-based modeling of machining-induced residual stresses in Ti-6Al-4V under finish turning conditions," *Procedia CIRP*, vol. 8, pp. 63–68, 2013, doi: 10.1016/j.procir.2013.06.066.

[64] B. Shi and M. H. Attia, "Evaluation criteria of the constitutive law formulation for the metal-cutting process," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 224, no. 9, pp. 1313–1328, 2010, doi: 10.1243/09544054JEM1787.

[65] B. Shi, H. Attia, and N. Tounsi, "Identification of material constitutive laws for machining - Part II: Generation of the constitutive data and validation of the constitutive law," *J. Manuf. Sci. Eng. Trans. ASME*, vol. 132, no. 5, 2010, doi: 10.1115/1.4002455.

[66] R. A. Mahdavinejad and S. Saeedy, “Investigation of the influential parameters of machining of AISI 304 stainless steel,” *Sadhana - Acad. Proc. Eng. Sci.*, vol. 36, no. 6, pp. 963–970, 2011, doi: 10.1007/s12046-011-0055-z.

[67] K. Nakayama, “Machining of hard materials,” *Mach. Hard Mater.*, vol. 37, no. l, pp. 89–92, 1988, doi: 10.1007/978-1-84996-450-0.

[68] Tool-life testing with single-point turning tools, ISO 3685:1993, 1993.