

**DEVELOPMENT AND UTILIZATION OF CNT NANO-
LUBRICATION FOR HIGHER MACHINING
PERFORMANCE IN HIGH-SPEED HEAVY-DUTY CNC
MACHINING**

BY

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[To my beloved family |

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All praise be to Allah, the Most Compassionate, and the Most Merciful, for his ever-enduring blessings on me. May his peace be upon our prophet Muhammad, and his family.

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LIST OF ABBREVIATIONS

CNT:	Carbon Nano Tube
CNC:	Computerized Numerical Control
HSM:	High-Speed Machining
HSC:	High-Speed Cutting
MRR:	Material Removal Rate
MLQ:	Minimum Quantity Lubricant
SEM:	Scanning Electron Microscopy
EDX:	Energy Dispersive X-ray

ABSTRACT

Full Name : [Khadher Salem Ali Alnakhebi]
Thesis Title : [Development and Utilization of CNT Nano-Lubrication for Higher Machining Performance in High-Speed Heavy-Duty CNC Machining]
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A novel carbon nanotube (CNT) nano-lubrication system was developed for high-speed heavy-duty CNC milling processes to enhance production rates and product quality. Functionalized COOH-CNT nanoparticles with an average size of 5-50 nm were added to lubrication oil to prepare CNT nano-lubricant. A minimum quantity lubrication (MQL) system with double nozzles was utilized to deliver the CNT nano-lubricant to the tool-chip contact area. The effects of the CNT nano-lubricant on machining performance, specifically cutting force, were investigated under different MQL-controlled parameters, including nanoparticle concentrations, output oil rate, and air flow rate. The Taguchi optimization method, coupled with signal-to-noise (S/N) analysis, was employed to determine the optimal combination of CNT nano-lubricant factors for minimizing cutting force. The results indicated that a 0.3% concentration of CNT nano-lubricant yielded superior cutting force measurements. Additionally, the wear of the cutting tool was reduced when using CNT nano-lubricant compared to traditional oil lubricant. SEM and EDX images were conducted to compare oil lubricant with and without CNT. The machined surface with CNT nano-lubricant contained some extra Carbon particles in very small amounts. The CNT nano-oil provides better surface quality than the oil case. |

ملخص الرسالة

الاسم الكامل: خضر سالم الناجي

عنوان الرسالة: تطوير واستخدام الزيت المخلوط بحبيبات النانو كربون الأنبوبية لزيادة أداء القطع في أجهزة القطع الآلية ذات السرعة العالية والحمل الثقيل

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: يناير، 2023

تم تطوير نظام للتشحيم بحبيبات النانو باستخدام حبيبات نانو كربون الأنبوبية (CNT) لعملية القطع (Milling Process) باستخدام أجهزة القطع الآلية (CNC) عالية السرعة المعدة للاستخدامات الثقيلة من أجل الحصول على معدل إنتاج وجودة أعلى. حيث قمنا بإضافة جسيمات الكربون الوظيفية (COOH-CNT) التي يبلغ متوسط حجمها 5-50 نانومتر إلى زيت التشحيم لتحضير زيت النانو. تم استخدام جهاز تزييت يعمل بنظام التشحيم ذو الحد الأدنى (Minimum Quantity Lubricant MQL) الذي يملك فوهتين لتوصيل الزيت إلى منطقة الاتصال بين أداة القطع وقطعة الشغل أثناء عملية القطع. وقد تم دراسة تأثير زيت التشحيم بحبيبات الكربون الأنبوبية على أداء القطع عن طريق قياس القوة الناتجة من أداة القطع أثناء عملية القطع تحت تأثير معايير مختلفة يتم التحكم فيها بواسطة جهاز التزييت. هذه المعايير هي تركيزات الجسيمات النانوية في زيت التشحيم، ومعدل ضخ الزيت، ومعدل تدفق الهواء. تم إجراء طريقة اختيار أفضلية التجارب باستخدام طريقة (Taguchi) التي تستخدم تحليل مقدار الإشارة إلى الضوضاء (S / N) لتحديد أفضل مزيج من عوامل التشحيم النانوية لتقليل قوة القطع. أظهرت النتائج أن زيت التشحيم الذي يحتوي على تركيز حبيبات الكربون الأنبوبية بمقدار 0.3% يعطي نتائج أفضل في تقليل قوة القطع. أيضًا، كان معدل تآكل أداة القطع أقل في حالة الزيت الذي يحتوي على حبيبات النانو كربون الأنبوبية مقارنة بالزيت الذي لا يحتوي على هذه الحبيبات. تم التقاط صور بالمجهر الإلكتروني (SEM) لمقارنة السطح المقطوع بوجود الزيت المخلوط مع حبيبات الكربون والزيت الذي لا يحتوي على حبيبات الكربون الأنبوبية. السطح المقطوع أثناء التشحيم بزيت النانو كربون احتوى على نسبة أكبر من جزيئات الكربون متواجدة على سطحه، ولكن بكمية صغيرة جدًا. ساعد الزيت بحبيبات النانو كربون على إظهار جودة أعلى للسطح المقطوع مقارنة بالزيت العادي.

CHAPTER 1

INTRODUCTION

In the manufacturing industry, high-speed CNC machining processes (CNC milling and turning processes) have been widely practiced. Under these processes, many types of Saudi products can be produced especially in the automotive industry such as shafts and bearings. There are various types of high-speed and heavy-duty machine tools used for advanced applications such as aerospace, automotive, and energy sectors that require high torque and are equipped with high control capabilities. Among these high-speed machine tools, CNC milling is the most common process in machining process which has high productivity, better quality of products, and an overall better manufacturing economy. In addition, the versatility of CNC milling machines for generating complex shapes in a variety of materials as well as the introduction of high-speed machining technologies and advanced development in machine tool design has made them essential for industry in recent decades.

However, the generated heat during the machining process is the main factor causing tool failure and incremental cost. To overcome this issue, more effective lubrication systems should be used. The current lubrication system is less effective due to the failure of its penetration into the tool-workpiece interface region. Therefore, nano-lubrication has been introduced as an alternative solution introduced by many researchers with various application methods. To achieve optimum nano-lubrication performance, it is vital to

conduct a detailed analysis with the correct nano-lubrication parameters set during the machining process. Many types of nano-solid particles are available in the market that is suitable to be used for this purpose such as Graphite, Carbon Nano Tube (CNT), MoS₂ and SiO₂ to be used with proper sonification method to disperse the particle homogeneously in mineral oil with proper concentration. In this research, a carbon nanotube base lubrication system will be developed for higher quality and productivity in CNC machining (CNC milling machining). Machining performance would be investigated by considering the high production rate and product quality. Appropriate implementation of the CNT nano-lubrication system would reduce the friction coefficient between the contacted area between the cutting tool and workpiece and thus reduce the heat generated. This is due to the rolling action of many nano-solid particles between the tool-workpiece interface. Hence, thrust force and cutting temperature would considerably reduce. As for the consequences, the quality of the milling operation has been improved, which prolonged the tool's life.

This thesis is divided into different chapters which are summarized as follows:

- **Chapter 1** is the introductory chapter in which background about the topic is illustrated to provide the fundamental information needed to understand this thesis.
- **Chapter 2** presents a literature review that gives an overview of current knowledge of the related subjects including existing gaps in the current research topics ending with the motivation and objective of the thesis work.

- **Chapter 3** is the main section which describes the experimental setup and design of the experiment.
- **Chapter 4** is the main section which shows experimental results, and discussion.
- **Chapter 5** is the conclusion section which summarizes the thesis and ended up with recommendations for future work.

In this chapter, the reader is provided with the necessary knowledge and background information to get familiar with the different subjects discussed in this thesis. The sections in this chapter might not have a strong sequence or connection with each other but they, together, are related to the planned work presented to provide sufficient fundamental information about the selected subject.

1.1 Overview of Machining Operation

Machining operation is a manufacturing process that uses a sharp cutting tool to gradually remove the excess materials from a work material as chips to achieve a desirable part shape. The common machining operation includes turning, milling, and drilling operations. Machining or conventional machining is part of a family of shaping operations called material removal processes which also include abrasive processes and nontraditional machining processes. In abrasive processes, hard abrasive particles are used to remove the material like in the grinding process. In nontraditional machining, various energy forms are used to remove the material instead of sharp cutting tools. Figure 1.1 illustrates the family tree of material removal processes [1].

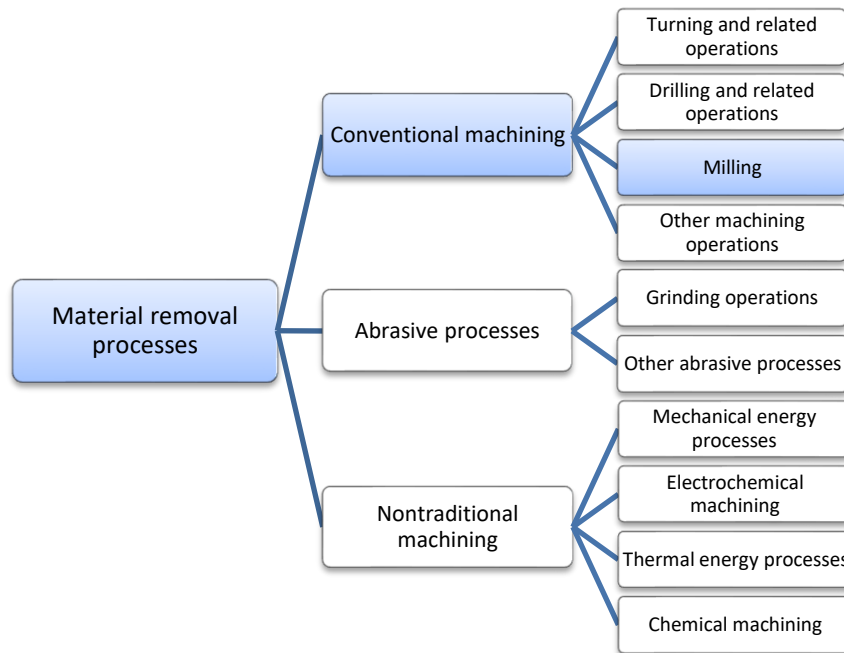


Figure 1.1 Hierarchical structure of material removal processes.

Machining operation is considered one of the important and widely used manufacturing processes because of several reasons:

- **Using a variety of materials as workpieces:** We can apply machining operations to many different work materials such as solid metals, plastic, and most ceramics.
- **Creating different part geometries and complex features:** Machining operations can produce any regular shapes and different complex irregular geometries using different cutting tool shapes, tool paths, and combined machining operations.
- **Producing precise geometries.** Machining processes can produce parts with very accurate dimensions and achieve tolerances of ± 0.025 mm (0.001 in) [1].
- **Making parts with a good surface finish.** Machining can produce parts with a surface roughness of fewer than 0.4 microns (0.016 μ -in) for traditional machining and better surface finishes with abrasive processes [1].

Although all the above-mentioned advantages, machining operations are associated with certain disadvantages such as:

- **Wastage of removed material:** Material waste occurs naturally during machining when chips are formed even when we recycle these chips, they still are considered as waste in unit operation.
- **Time-consuming during the operation:** Machining processes usually consume longer time to produce a part than other shaping processes such as forging and casting.

In machining, the main action includes shear deformation of the workpiece which creates chips. When the chips are removed, a new surface is revealed. To perform machining a relative motion between cutting tool and workpiece is needed. There are three main parameters to be considered during machining which are responsible for the relative motion: cutting speed, feed rate, and depth of cut. The cutting speed which is the primary motion is the workpiece rotation in turning and the tool rotation in drilling and milling. Feed rate is the lateral movement of cutting tools per revolution. The depth of cut is a measure of the distance that the cutting tool penetrates the workpiece.

1.1.1 Machining System

A machining system constitutes of three main components which are cutting tool, workpiece, and machine tool.

- **Cutting Tool**

A cutting tool is a tool used to remove material during machining operations. It can have single or multiple sharp edges which are made of harder material than work material so it

can cut chips from the workpiece efficiently. The cutting edge consists of two main surfaces: rake face and flank. The rake face is the surface that leads the flow of the newly formed chip oriented at a certain angle called the rake angle. The flank creates a space between the tool surface and the newly formed surface of the work material that is directed at an angle called a relief angle. The flank surface protects the newly work surface from abrasion. Cutting tools are classified into two types according to the complexity of the tool geometry. The first type is a single-point tool where only one cutting edge is used to remove the material like in a turning operation. The alternative type is the multiple-cutting edge tool, wherein more than one edge is employed to remove material from the workpiece. This tool type is commonly encountered in drilling and milling operations. Figure 1.2 shows different cutting tools with different cutting edges [1].

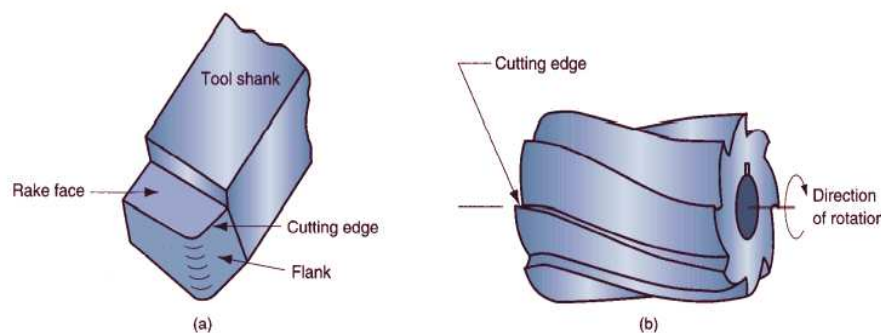


Figure 1.2 (a) A single point tool, (b) Multiple-cutting edge tool.

- **Workpiece**

Workpiece is the part to be machined. Work parts are generally classified into two types rotational and non-rotational. The rotational workpiece has a cylindrical or disc-like shape whereas the non-rotational workpiece has a block-like or plate-like shape.

Workpieces can be made of a wide variety of materials in such a way that these materials can be machined where very hard materials are difficult to machine. Workpiece material can include all solid metals, plastic, plastic composite, and some types of ceramics.

- **Machine Tool**

A Machine tool is any power-driven machine used to perform machining operations. Machine tools are responsible for holding the workpiece, providing a good position for the cutting tool relative to the workpiece, and providing the required power to control cutting parameters and perform machining operations. Conventional machine tools are operated by humans where human involvement is necessary in most of the steps during the operation. Modern machine tools include more automation in their processes, which is called computer numerical control (CNC).

1.1.2 High-Speed Machining

The utilization of faster and higher cutting speeds has been a consistent trend throughout the history of metal machining. Due to the possibility of increased part quality, decreased cost, shorter cycles time, and quicker manufacturing rates, there has been increasing interest in this sector in recent years. High-speed machining (HSM) or in another name called high-speed cutting (HSC) uses cutting speeds considerably higher than those used in conventional machining in which we can achieve high metal removal rates (MRR), usually referred to as milling operations performed at high feed and spindle speeds. The cutting speed ranges in HSM depend on different factors such as workpiece material, tool material, machine tool, and cutting parameters. Different cutting speed values for conventional and HSM for different work materials with different cutting tools are

presented in Table 1.1. According to data collected from [2]. Another illustration by Schulz [3] showed different cutting speed ranges for different work materials where a transition speed range is introduced between conventional and HSM ranges, see Figure 1.3.

Table 1.1 Comparison of cutting speeds between conventional and HSM [2].

	Solid Tools (end mills, drills): WC, coated WC, PCD, ceramic		Indexable Tools (shell mills, face mills): WC, ceramic, sialon, CBN, PCD	
Work Material	Conventional cutting speed (m/min)	High cutting speed (m/min)	Conventional cutting speed (m/min)	High cutting speed (m/min)
Aluminum	>350 (WC, PCD)	>3050 (WC, PCD)	>610	>3660 (WC, PCD)
cast iron soft	150	360	360	1220 (sialon, ceramic)
cast iron ductile	110	240	240	910 (ceramic)
Steel, free machining	110	366	366	610
Steel, alloy	80	240	210	360
Titanium	38	61	46	91

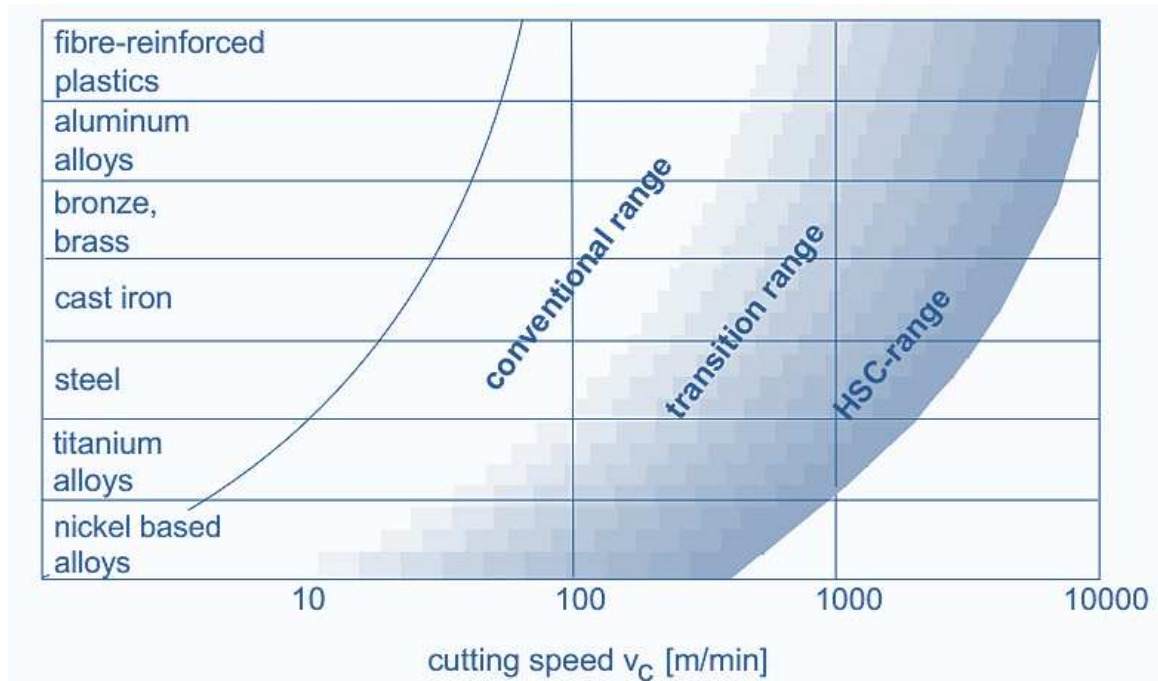


Figure 1.3 Different cutting speed ranges for different materials [3].

HSM has many advantages that overcome conventional machining. It has higher productivity with higher MRR which reduces the machining time. Also, the cutting forces in HSM are much lower than those of conventional machining which reduced the damage on the machined surfaces producing more accurate and precise parts. Also, HSM produces parts with excellent surface finish compared to conventional machining. Because of the abovementioned advantages, HSM is commonly used in different industries such as the aircraft industry, automotive industry, medical industry, and die and mold industry [4].

One thing is to be mentioned that HSM is considered an eco-friendly process that usually does not need the cutting fluid and operates at dry cutting. However, depending on the conditions of the machining operations, it might need mist lubricant where a small amount of cutting fluid is used. Thus, HSM can be utilized to process materials that are

difficult to machine, possess a high chemical affinity, and are highly reactive to cutting fluid.

1.2 Milling Operation

There are different machining operations in which they can provide different part geometry and surface texture. The classification of machining operation depends generally on the relative motion between the workpiece and cutting tool and the shape of the cutting tool. The most conventional types of machining operations are turning, drilling, and milling operations. In this section, we focus our attention on the milling operation only. In milling operation, multiple cutting-edge tools are rotated and fed into the workpiece material to produce a plane or straight surface. The cutting speed is provided by rotating the milling tool. The feed motion is perpendicular to the axis of the milling cutter. The tool in milling operation is named a mill cutter that has multiple cutting edges called teeth. The machine tool in milling is called a milling machine.

1.2.1 Type of Milling Operation

There are two types of milling operations which are horizontal milling and vertical milling.

- **Horizontal Milling**

In horizontal milling, also called peripheral milling or plain milling, the cutting tool axis is parallel to the surface being milled. The cutting operation is performed by the cutting edges on the outside periphery of the tool. Several types of horizontal milling are shown in Figure 1.4. (a) Slab milling, the milling cutter width is more than the workpiece width

from both sides. (b) In slot milling, the milling cutter width is less than the workpiece width from both sides which allows making a slot in the workpiece. (c) In side milling, the milling cutter width is less than the workpiece width from one side only, and cut the other side. (d) Straddle milling is the same as side milling, but it occurs on both sides of the workpiece. (e) Form milling is similar to slot milling but the slot takes the same profile of milling cutter teeth which has a special profile.

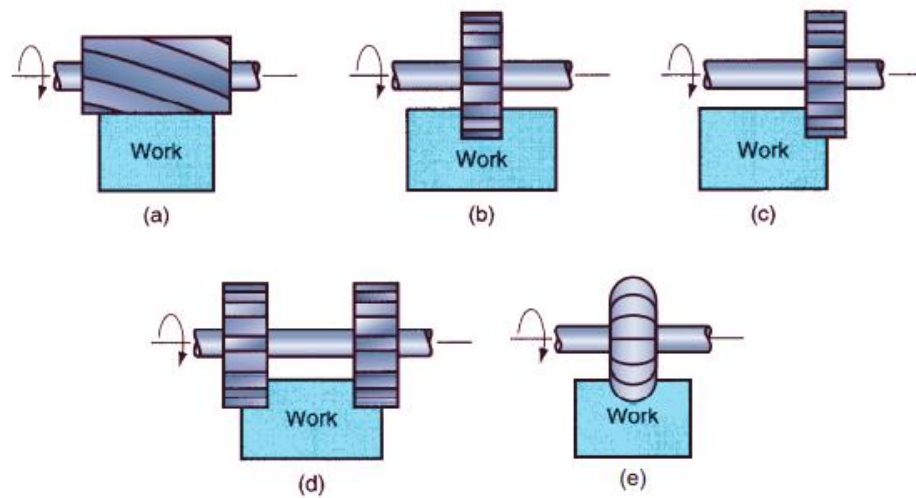


Figure 1.4 (a) Slab milling, (b) Slot milling, (c) Side milling, (d) Straddle milling, and (e) Form milling.

- **Vertical Milling**

In vertical milling, also called face, the cutting tool axis is perpendicular to the surface being milled and this operation is performed by the cutting edges on both the end and the outside periphery of the milling tool. Several types of vertical milling are shown in Figure 1.5. (a) Conventional face milling, the diameter of the milling cutter is larger than the workpiece width from both sides. (b) In partial face milling, the milling cutter cuts the workpiece from one side only. (c) In end milling, the diameter of the milling cutter is smaller than the workpiece width from both sides which cut a slot in the workpiece. (d)

Profile milling is a type of end milling used to cut the outside periphery of a flat part. (e)
 Pocket milling is a type of end milling used to cut shallow pockets inside a flat part. (f)
 Surface countering, a ball-nose cutter is fed across the workpiece along a curvilinear path to create a three-dimensional surface.

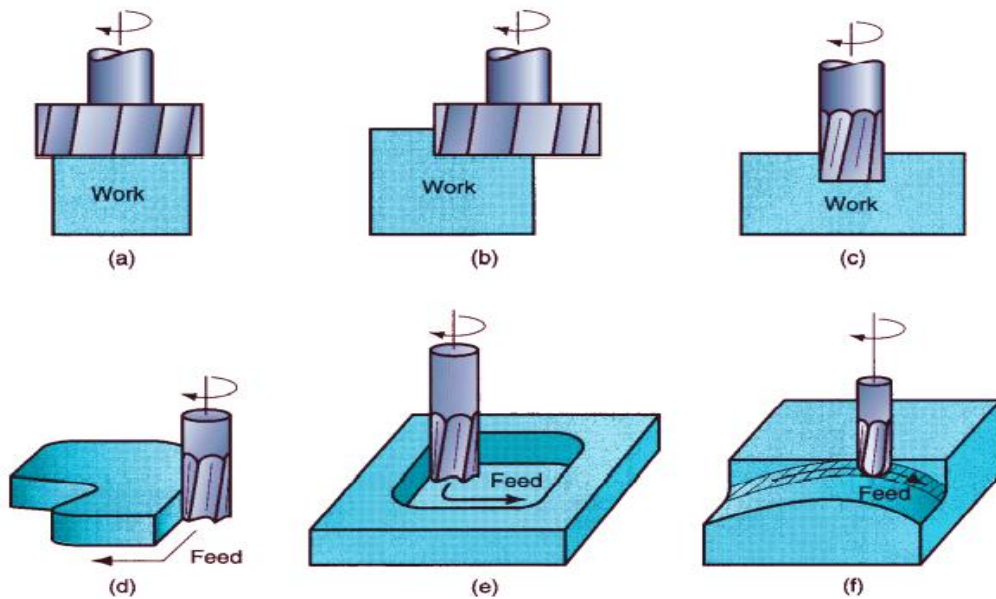


Figure 1.5 (a) Face milling, (b) Partial face milling, (c) End milling, (d) Profile milling, (e) Pocket milling, and (f) Surface countering.

1.2.2 Cutting Parameters in Milling Operation

Spindle speed can be converted to cutting speed at the outside diameter of the milling cutter using the following formula:

$$N = \frac{v}{\pi D} \quad (1.1)$$

N is the spindle speed (rev/min), v is the cutting speed (mm/min) and D is the cutter diameter (mm).

The feed in milling is given feed per cutter tooth which is called chip load. Chip load indicates the size of the chip formed by each cutting load. The equation for converting chip load to feed rate is as follows:

$$f_r = N n_t f \quad (1.2)$$

The f_r is feed rate (mm/min), n_t is the number of teeth on the cutter and f is chip load (mm/tooth).

The material removal rate in milling is the product of the cross-section of the machined area with feed rate which is the width of the workpiece (slap milling) or cutter diameter (end milling) multiply the depth of cut and feed rate.

$$R_{MR} = w d f_r \quad (1.3)$$

R_{MR} is material removal rate (mm/min), d is the depth of cut and w is the engaged cutter width for slap milling and replaced by cutter diameter for end milling (mm) where other milling operations can be used when considering the changes in the machined cross-section area.

The time required to mill a workpiece with a specific length L needs to be accounted for the approach distance A which is the distance that the milling cutter travels before fully engaged in the workpiece. For slab milling, the approach distance is given by:

$$A = \sqrt{d(D - d)} \quad (1.4)$$

For face milling, where the cutter is centered over a rectangular workpiece, the approach length is given as:

$$A = 0.5(D - \sqrt{D^2 - d^2}) \quad (1.5)$$

If $D = w$, then eq (1.5) is reduced to $A=0.5D$ and when $D \ll w$ as in slot milling then $A=0.5D$ also.

Then the time required to mill a workpiece in (min) is given by:

$$T_m = \frac{L+A}{f_r} \quad (1.6)$$

1.3 Important Measuring Factors in Machining Operation

Several important measuring factors in machining operations are crucial for assessing and optimizing the performance of the process. These factors help monitor and evaluate different aspects of the machining process to ensure quality, efficiency, and productivity. Here are some important measures commonly considered in machine operations:

1.3.1 Cutting Force Measurement

Cutting forces refer to the forces exerted on the cutting tool during the machining process, including components such as axial (thrust) force, radial force, and tangential (feed) force. Cutting force analysis plays a crucial role in understanding and optimizing machining operations. By measuring and analyzing cutting forces, valuable insights into the performance and efficiency of the process can be gained. Cutting forces are directly linked to the performance of cutting tools. Excessive cutting forces accelerate the wear rate of cutting tools, resulting in reduced tool life. By comprehending and controlling cutting forces, we can optimize tool life, decrease tooling costs, and ensure consistent tool performance. Additionally, cutting forces directly impact the surface finish and

dimensional accuracy of machined parts. High cutting forces can cause vibrations, tool deflection, and subpar surface finish. Furthermore, cutting forces are closely linked to energy consumption in machining operations. High cutting forces require more energy for the machining process. By optimizing cutting forces, energy efficiency can be improved, power consumption reduced, and sustainable manufacturing practices promoted. Overall, cutting force analysis provides valuable insights that enable informed decision-making, enhance machining performance, prolong tool life, improve surface finish, and achieve desired outcomes in the manufacturing process.

Most machining operations involve complex geometry. However, there is a simplified model called the orthogonal cutting model that effectively captures the mechanics of the process while neglecting many of the geometric complexities. The orthogonal cutting model enables the definition of various forces. These forces, in turn, allow for the determination of shear stress, coefficient of friction, and other related relationships.

In the context of 2D orthogonal cutting, several force components exert influence on the chip. Among these, two forces are applied by the tool and can be divided into mutually perpendicular components: friction force and normal force to friction. The friction force (F) acts as a resistance against the chip's movement along the tool's rake face, while the normal force to friction (N) is perpendicular to the friction force. In addition to the tool-applied forces, the workpiece also imparts two force components on the chip: shear force and normal force to shear. The shear force (F_s) induces shear deformation in the shear plane, and the normal force to shear (F_n) acts perpendicular to the shear force.

Directly measuring these four force components (F , N , F_s , and F_n) during machining is challenging due to their variable directions based on tool geometries and cutting conditions. However, a force-measuring device called a dynamometer can be employed to instrument the cutting tool. This enables the direct measurement of two additional force components: cutting force and thrust force. The cutting force (F_c) operates in the cutting direction, parallel to the cutting speed, while the thrust force (F_t) acts perpendicular to the cutting force and relates to the chip thickness before cutting. All the mentioned cutting force components are illustrated in Figure 1.6 where α is the rake angle and β is the friction angle and ϕ is the shear plane angle.

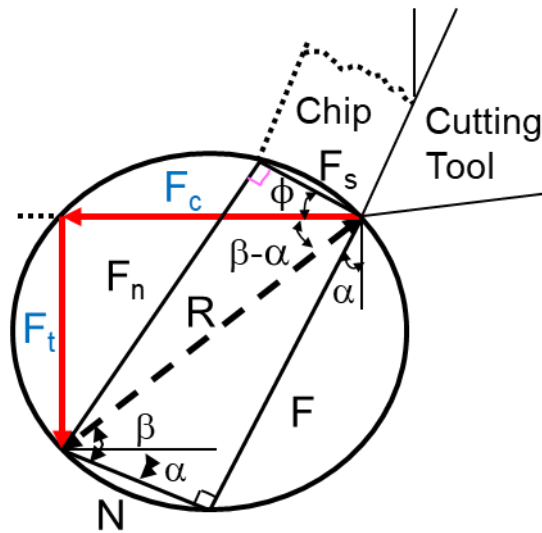


Figure 1.6 Force diagram showing geometric relationships between force components where R represents the resultant force.

Equations can be derived to establish relationships between the four force components that cannot be directly measured and the two forces that can. By utilizing the force diagram represented in Figure 1.6, trigonometric relationships can be derived to describe the interactions among these forces as follows:

$$F = F_c \sin \alpha + F_t \cos \alpha \quad (1.7)$$

$$N = F_c \cos \alpha - F_t \sin \alpha \quad (1.8)$$

$$F_s = F_c \cos \phi - F_t \sin \phi \quad (1.9)$$

$$F_n = F_c \sin \phi + F_t \cos \phi \quad (1.10)$$

1.3.2 Tool Wear and Tool Life

- **Tool Wear**

The intense forces and elevated temperatures experienced during machining generate an extremely challenging environment for the cutting tool. Excessive cutting force can result in tool fracture, while elevated cutting temperature can cause the tool material to soften and ultimately fail. If the tool withstands these conditions, continuous wear of the cutting edge eventually leads to its failure. Fracture and temperature-related failures both are undesirable modes of failure. Among the three potential tool failures, gradual wear is the preferred outcome since it allows for the longest possible utilization of the tool, offering economic advantages associated with prolonged tool usage.

Gradual wear is the gradual loss of material from its cutting edge during the machining process. This wear occurs due to repeated contact and friction between the tool and the workpiece. As the tool meets the workpiece material, microscopic abrasion, adhesion, and diffusion mechanisms contribute to the removal of material from the cutting edge. Over time, this wear leads to a change in the tool's geometry, affecting its performance and ultimately necessitating tool replacement or reconditioning.

Tool wear in cutting operations can appear in different forms including flank wear, crater wear, nose wear, and edge notch wear. Flank wear refers to the gradual wear of the tool's side or flank surface in contact with the workpiece material. Crater wear occurs at the tool's rake face due to the sliding action of the chip against the surface and is characterized by the formation of small cavities due to the intense heat and pressure generated during machining which can be expanded. Nose wear refers to the wear that occurs at the tip or nose of the cutting tool. It is particularly relevant for tools with a pointed or rounded tip geometry. Nose wear can result from the continuous contact and friction between the tool's nose and the workpiece material. Notch wear is characterized by the formation of notches or grooves on the cutting edge of the tool. It is typically caused by the repetitive impact and contact between the tool and hard or abrasive particles present in the workpiece material. Figure 1.7 illustrates all four types of wear.

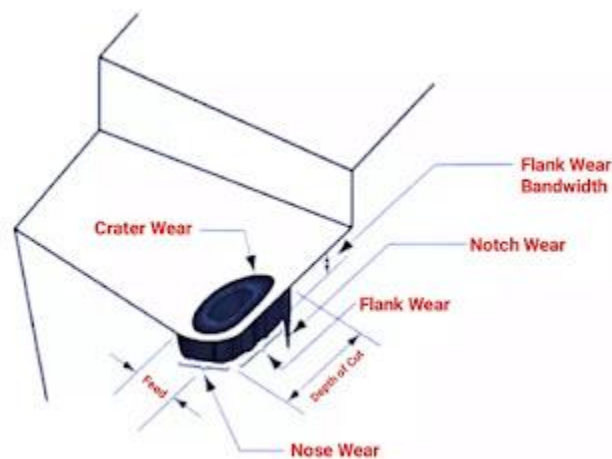


Figure 1.7 Different types of wear are illustrated in a single-point tool.

These different forms of tool wear are influenced by factors such as cutting parameters, workpiece material, tool material, cutting fluid or lubrication, and the overall cutting

conditions. Monitoring and managing tool wear are essential for maintaining optimal cutting performance, extending tool life, and ensuring consistent machining quality.

- **Tool Life**

As the cutting process progresses, the cutting tool experiences increasing levels of wear due to various wear mechanisms. The relationship between tool wear and cutting time is depicted in Figure 1.8. Although the graph illustrates flank wear, a similar pattern can be observed for crater wear.

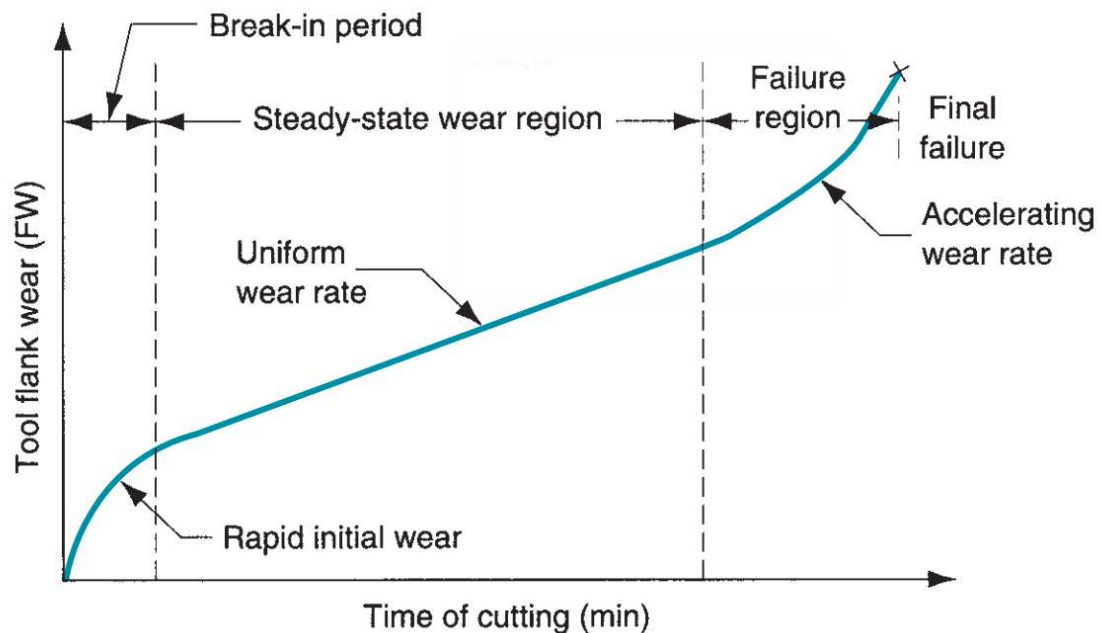


Figure 1.8 Tool flank wear VS time of cutting.

Generally, three distinct regions can be identified in the wear growth curve. The first region is the break-in period, characterized by rapid wear of the sharp cutting edge during the early stages of tool usage. This phase occurs within the first few minutes of cutting. Following the break-in period, wear proceeds at a relatively consistent rate, known as the steady-state wear region. In the Figure 1.8, this region is depicted as a linear function of

time, although some deviations from the straight line occur in actual machining. Eventually, the wear rate accelerates, indicating the onset of the failure region. In this phase, cutting temperatures rise, and the overall efficiency of the machining process declines. If allowed to continue, the tool eventually fails due to temperature-related issues.

Tool life is defined as the duration of the cutting time in which a tool can be effectively utilized. While one way to define tool life is to continue using the tool until it catastrophically fails, this approach is often disadvantageous in production due to challenges associated with tool resharpening and compromised work surface quality.

Tool life criteria refer to the predetermined measures used to determine when a cutting tool or tool insert should be replaced or reconditioned during machining operations. These criteria are established based on factors such as tool performance, cost-effectiveness, and the desired quality of the machined parts. Here are some common tool life criteria used:

- **Tool Wear Limit:** Tool wear is the primary factor used to assess tool life. The wear limit is the maximum allowable wear that a tool can experience before it needs to be replaced. This limit is typically defined by the manufacturer or based on empirical data and can be specified in terms of flank wear, crater wear, or other wear types specific to the tool and machining process. Table 1.2 shows some allowable wear land values in different machining operations and tool materials.

Table 1.2 Allowable flank wear for different tool materials at different machining operations [5].

Operation	Allowable Flank Wear Land	
	High-speed Steels Tool	Carbides Tools
Turning	1.5	0.4
Face Milling	1.5	0.4
End Milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

- **Cutting Forces:** Using cutting forces as a criterion for tool life is a common approach in machining operations [6]–[9]. As the tool wears, the cutting forces tend to increase. Tool life can be correlated with specific force thresholds. If the cutting forces exceed these thresholds, it indicates that the tool has reached its end of life or is approaching the end of its usable life. Also, comparative analysis can be used. Comparing cutting force data between new tools and worn tools can provide valuable information about tool wear and tool life. By establishing baseline force values for new tools, operators can monitor the changes in cutting forces as the tool wears. Significant deviations from the baseline values, such as substantial force increases, can indicate the need for tool replacement or reconditioning.

- **Tool Life Models:** Tool life models use mathematical equations and empirical data to estimate the remaining life of cutting tools. These models consider factors such as cutting parameters, tool material, workpiece material, and wear measurements to predict tool life [10], [11]. A commonly used model is Taylor's tool life equation which is given in Eq 1.11.

$$vT^n = C \quad (1.11)$$

Where v is cutting speed (m/min) or (ft/min), T is tool life in (min), and n and C are constants depending on cutting parameters, work material, and tooling.

It's important to note that tool life criteria can vary depending on the specific machining process, tool material, workpiece material, and other factors. Manufacturers, tool suppliers, or industry standards often provide guidelines or recommendations for tool life criteria based on their products and application-specific requirements. Regular monitoring, inspection, and measurement of tool wear and performance help ensure that tools are replaced or reconditioned at the appropriate time to maintain consistent production quality and efficiency.

1.3.3 Surface Roughness

Surface roughness refers to the irregularities or deviations in the surface texture of a machined or manufactured part. It is a measure of the small-scale variations in the surface profile, including the height, spacing, and distribution of surface features. Surface roughness is an important parameter that influences the functionality, appearance, and performance of a wide range of products across various industries.

Surface roughness is typically quantified and expressed using different parameters. The most used parameter is R_a (arithmetical mean roughness), which represents the average of the absolute values of the vertical deviations from the mean line within the sampling length. Other height parameters include R_q (root mean square roughness), R_v (maximum valley height), R_p (maximum peak height), R_z (average peak-to-valley height), R_t (maximum peak-to-valley height), and many more, each characterizing different aspects of the surface texture. Figure 1.9 shows different roughness parameters on the roughness signal.

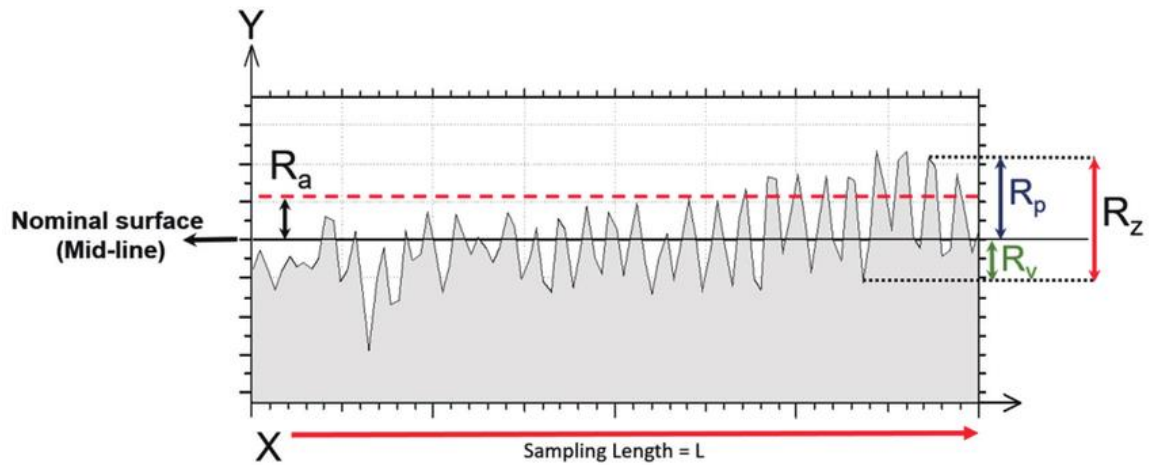


Figure 1.9 Different roughness parameters illustrated in roughness signal.

Measurement of surface roughness is typically performed using profilometers or surface roughness testers. These instruments use contact methods like a stylus or non-contact methods like optical or laser scanning to record the surface profile and calculate the roughness parameters.

Several factors can influence surface roughness, including the machining process, cutting parameters, tool geometry, workpiece material, and tool wear. Optimizing these factors

helps achieve the desired surface roughness for a given application. Finishing operations like grinding, polishing, or using specialized surface treatment techniques can further refine the surface roughness to meet specific requirements.

1.4 Cutting Fluid in Machining Operation

Machining processes generally encounter both high friction and high temperature due to the contact between the tool-chips and tool-workpiece which can affect the geometrical accuracy and surface finish of the produced part, tool life, and machine power required. Thus, reducing the friction forces and temperature during machining is crucial to have better-machined parts at a lower cost. To cool and lubricate the cutting tool and workpiece during the machining process, cutting fluid is frequently used. A good cutting fluid should have good lubrication and cooling properties. In the following subsections, I will discuss cutting fluids according to their functions as lubricants and coolants. Cutting fluids offer additional advantages in addition to removing heat and decreasing friction, including washing away chips (especially in grinding and milling), lowering the work piece's temperature for easier handling, lowering cutting forces and power requirements, enhancing the work piece's dimensional stability, and enhancing surface finish.

1.4.1 Lubricant

Any relative motion between two contacted surfaces causes friction to occur due to the high surface shear strength of the solid surfaces which is the case during machining when the tool cuts the workpiece. The separation of the contacted surface can reduce the solid-solid contact which as a result will decrease surface shear strength and then friction. The presence of lubrication between any surfaces in contact reduces friction and wear by

minimizing the surface shear strength of the surface. So, the main purpose of lubrication is to lower the friction and wear in the system. Lubrication can be applied to both solid lubrication and fluid lubrication.

- **Solid Lubricant**

Solid lubricant, also known as a dry lubricant, is any material used as powder and forms a film between any contacted surfaces during a relative motion to reduce friction and wear. Solid lubricant exhibits very low friction and moderate to low wear during sliding. The most common solid lubricants are graphite, and molybdenum disulfide (MoS_2). Their lamellar structures make them efficient lubricants because lamellas are directed parallel to the surface in the direction of motion which allows preventing contact even with highly loaded stationary surfaces. Therefore, lamellas readily shear over one other in the direction of motion, resulting in low friction. Other solid lubricants were used such as polytetrafluoroethylene (PTFE), fullerenes or Buckyballs (C_{60}), talc, BN, CaF_2 , WS_2 , H_3BO_3 , CeF_3 , and B_2O_3 [12], [13]. Solid lubricants are mostly used when liquid lubricants are not preferred such as in space applications where the liquid would evaporate and in high-temperature applications where liquid lubricant may decompose or oxidize. Solid lubricant materials can be used in their dry state, as dry powder solids impregnated with solid lubricants, or dispersions (suspensions in lubricating oils and greases). Solid lubricants are considered environmentally friendly lubricants because they do not contain hazard additives.

- **Fluid Lubricant**

Fluid lubricant provides a film between contacted surfaces in relative motion to prevent solid-solid contact to reduce friction and wear. Fluid lubricants can be in liquid or gaseous forms. A thick film of air between sliding surfaces can be considered good lubrication. Liquid lubricants are the common type of lubricant used in machining operations, and they are generally oil-based fluids because oil has good lubricity properties. Different additives can be added to liquid lubricants to improve their thermal properties, wear resistance, and bearing load capacity such as sulfurous and phosphorous compounds. However, although these additives improve some properties of liquid lubricant, they make the lubricant toxic and cause environmental pollution and health hazards [12]. Liquid-type cutting fluid is desirable to be used at lower cutting speeds because at higher speeds they lose their effectiveness. This happened due to different reasons. High-speed motion prohibits lubrication to reach tool-chip and tool-workpiece interfaces. Furthermore, the rise in cutting temperature at HSM may cause the oil to evaporate before it can lubricate. Although the primary goal of lubricants is to minimize friction, they can also lower temperature through a variety of techniques. They have some thermal properties that remove heat during operation. Moreover, they reduce friction and cutting forces, eventually reducing the heat generated and cutting temperature.

1.4.2 Coolant

Coolant is a fluid that is aimed to provide good heat transfer properties to reduce or regulate the temperature in the system. Coolant has good thermal capacity and low viscosity to be able to carry the heat generated away faster. Thermal capacity depends mainly on specific heat and thermal conductivity. Coolant-type cutting fluid is water-

based fluid because water has high specific heat and thermal conductivity compared to other fluids. Coolant-type cutting fluid is more effective to be used at a high cutting speed where high temperature and heat are generated especially if the cutting tool is more sensitive to temperature failure such as high-speed steel tools. Water-based coolants can be divided into three types:

- **Emulsified Oils:** They consist of oil droplets suspended in water. Emulsifying agents are used to integrate and stabilize the emulsion when the oil droplets are combined with the water. Some additives can be added to improve cooling and lubrication properties.
- **Chemicals Fluids:** These fluids contain chemicals mixed with water solution instead of oil droplets. Sulfur, chlorine, and phosphorus compounds with wetting agents are among the dissolved chemicals.
- **Semichemical Fluids:** These are a form of fluid that is a cross between chemical fluids and emulsified oils.

1.4.3 Nanofluid

A new advancement in cutting fluid is the use of nanoparticles. A nanofluid is a colloidal suspension of dispersing nanoparticles in a base fluid. In other words, it is a fluid containing a suspension of nano-sized particles. The base fluid can be water, ethylene glycol, and oil. Nanoparticles can be metal, ceramic, oxide, or carbon particles [14]. For cutting fluid, the addition of nanoparticles to the fluid is meant to enhance the properties of the integrated fluid. Thermal transfer properties of the fluid can be improved by the addition of the percentage of nanoparticles. The wear resistance of the fluid can be enhanced by adding anti-wear particles. Also, Lubricity can be increased by the present

of nanoparticles in which the nano fluid combined the lubricity of solid lubricant and liquid lubricant. The mixture of dry powdered nanoparticles with base fluid is usually done using a sonication technique. The size of the particles grows as they aggregate and agglomerate, and the thermal conductivity of nanofluids decreases. Thus, stability emerges as the main concern affecting the use and value of nanofluids. The stability of nanofluid can be improved using different techniques such as surfactant additives, surface modification techniques, and stability mechanisms [14].

1.4.4 Different Delivery Techniques for Cutting Fluid

Cutting fluids are applied to machining operations by different methods. The most common methods are discussed in the following sub-sections.

- **Flooding Method**

Flooding is the most common method of applying cutting fluid where a stream of fluid is directly delivered to the tool-workpiece and tool chip interfaces during machining operation. The flooding method usually has good heat removal and lubrication properties compared to other methods because it provides more cutting fluid than what is required for the machining operation [15], see Figure 1.10. On the other hand, the amount of fluid used is very large, which is not cost-effective. Moreover, the health hazards associated with cutting fluid are another issue. Cutting fluids contain hazardous additives that enhance their effectiveness but also make them more toxic. Also, the excess cutting fluid will contaminate easily over time because it will be exposed to other substances and removed chips which will cause a reduction in the properties of cutting fluids. Changing the cutting fluid regularly is mandatory to ensure good quality cutting fluid. A filtration

system is utilized to clean and extend the lifespan of the cutting fluid by removing impurities.



Figure 1.10 Flooding cutting fluid technique in the end milling process.

- **Mist Method**

The misting method is another method of cutting fluid delivery to the machining operation [16]. In this method, high-speed atomized cutting fluid is produced due to the Venturi effect and directed to the cutting region through a nozzle with a tiny hole using a pressurized air stream. Generally, the mist method is not as effective as the flooding method in cooling and lubrication, but they are comparable and more economically and environmentally effective [17]. Also, the mist method can reach difficult areas that the flooding method might not be able to. A more common name for the mist method is minimum quantity lubricant (MQL). This naming comes from the idea of supplying a minimum amount of lubricant during operation which provides sufficient lubrication. This reduces environmental and economic issues of the flooding type. MQL can be delivered by two techniques: External and internal methods. External MQL refers to a method of delivering a small amount of lubricant to the cutting zone from an external source while internal MQL involves the application of a small amount of lubricant

directly to the cutting tool or workpiece supplied through internal channels or passages in cutting tools [18]. Figure 1.11 shows the internal and external methods of delivering MQL.

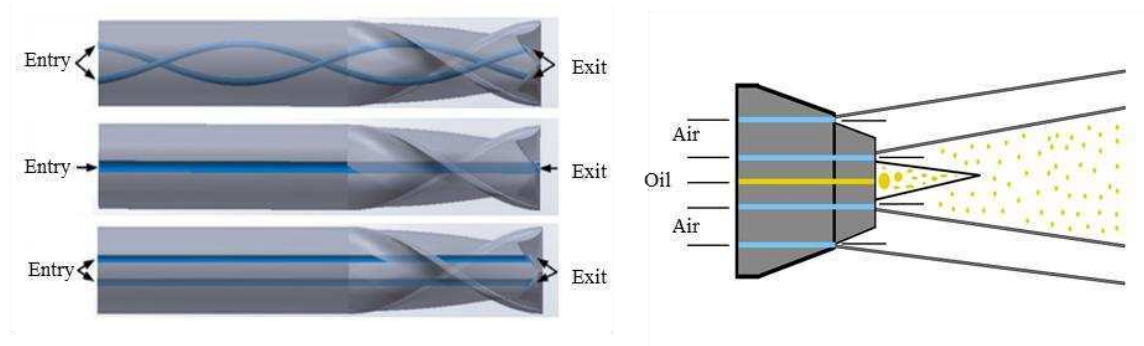


Figure 1.11 (Left) Different configurations of internal channels inside cutting tool for MQL [9], (Right) external nozzle for MQL.

- **Cryogenic Cooling Method**

Cryogenics is the science of very low temperature 100K (-173°C) applications. Various cryogenic coolants are used such as helium, hydrogen, neon, nitrogen, oxygen, argon, krypton, methane, ethane, and carbon dioxide but when referred to as cryogenic CO₂ and LN₂ are used for machining [19]. Cryogenic cooling is a method that usually employs liquid nitrogen or CO₂ instead of conventional cutting fluids [20]. This technique involves directing liquefied gases into the cutting area to achieve cooling of both the tool and workpiece. The cryogenic medium absorbs the heat generated in the cutting zone, subsequently evaporating into the atmosphere. By efficiently extracting heat from the cutting zone, the temperature of the cutting process is reduced. This alteration in temperature has an impact on the frictional properties at the interfaces between the tool and chip, as well as on the characteristics of both the workpiece and the tool material [21].

CHAPTER 2

LITERATURE REVIEW

During the past decade, there were more concerns about the issues of the heat generated from high cutting speed in high-production machining. Friction and wear of cutting tool is also another concern. Cutting fluids were utilized during the machining operation to reduce the effects of these concerns. Cutting fluids have two main functions, namely lubrication and cooling to reduce friction in tool, chip, and workpiece contacted areas along with providing good heat transfer properties. Due to the severe friction and wear conditions, the combined functions of cutting fluids are required.

This chapter provides the reader with literature information about the subjects discussed in this thesis. The sections in this chapter are directly related to the planned work presented to provide sufficient information about the subject.

2.1 Concerns about Cutting Fluid

Despite the many advantages of cutting fluids, flood coolants, which are the most common type of cutting fluid, present both economic and environmental issues.

2.1.1 Environmental Impact

Most cutting fluids contain toxic additives such as sulfur, chlorine, and phosphorus compounds. Although these additives are added to improve the wear resistance and loading capacity ability of the cutting fluid, they bring hazard problems during the utilization of these fluids. In addition, the flooding cutting fluid provides a larger amount

of fluid than is needed for the machining operation. The excess cutting fluid might be filtered again and reused several times until its properties are degraded. In the end, a huge amount of cutting fluid will be waste disposal which severely impacts the working environment and the disposal environment as well as pose a health risk to workers. Thus, the utilization of more environmentally friendly cutting fluid is intended [13].

2.1.2 Economic Impact

Cutting fluids are usually used in most machining operations. Costs involved in cutting fluids are responsible for approximately 12% of the total machining costs [22], [23]. The flooding delivery technique provides excess fluid during the machining process that generally ends up as waste. The high costs related to the usage of cutting fluids, as well as the likelihood of rising expenses if stronger environmental regulations are implemented need to be considered [22], [23]. As a result, minimizing the amount of cutting fluids used can be a substantial cost-saving measure.

2.2 Environmentally Friendly Machining Techniques

Dry cutting will be an ideal solution for reducing the negative impact of cutting fluids, but as a result cutting temperature, friction, and adhesion in the cutting tool-workpiece region will be more, which will cause a reduction in tool life. Different environmentally friendly machining techniques were introduced to replace the flooding lubricant techniques such as solid lubricant assistance machining and MQL. These techniques are discussed in the following sub-sections.

2.2.1 Solid Lubricant Assistance Machining

An innovative idea for regulating the temperature of the machining zone without harming the environment is solid lubricant-assisted machining. The two most common solid particles used as solid lubricants are graphite and molybdenum disulfide. Solid lubricants are used as a dry powder and delivered to the machining zone. Different studies on solid lubricants to assist machining were conducted [24], [25]. The observations showed that solid lubricants gave better results in cutting tools, surface finish, and heat removal compared to dry machining and comparable results with conventional fluid machining. The main advantage of this type is the elimination of fluid coolants because solid lubricants are environment-friendly and produce no harmful effect on the newly generated work surface compared to fluid lubricants.

2.2.2 MQL Machining

The use of flood-type cutting fluids during operations involves excessive fluid consumption, which presents significant environmental and economic issues. Therefore, the alternative is to reduce the utilized cutting fluids to a minimal level while maintaining or enhancing the characteristic of lubrication and cooling. Near-dry lubrication or mist lubrication showed good results compared to flood lubrication [22]. Researchers Liew et al. [26] described that the atomized mist form oil showed effective feeding to cutting region in comparison to the regular flood method. The reason for that might be because flood lubrication may splash off when the cutting tool rotates while cutting oil in the form of mist may stick to the surface of the tool part which can help with the cutting process.

2.3 Nano-oil

2.3.1 The Effect of Solid Particles in Nano-oil

Oil lubrication with nano particles additives has been introduced to improve oil lubrication properties by many researchers with various application methods [27]–[29]. Reducing friction in the cutting region with adequate lubricant amount will reduce the heat generated as well as reduce the used cutting fluid. Nanoparticles work as rolling and sliding bearings that facilitate the movement between the frictional surfaces, resulting in a considerable reduction in friction behavior. Physical analysis of nano-based solid particles [27] showed that nano-based solid dispersion worked as elastohydrodynamic lubrication and it can penetrate the rubbing surfaces easily preventing direct contact and reducing friction and wear. Nanoparticles have low friction with contacted surfaces which effectively minimizes the effect of high friction in the interface area between tool and workpiece, reducing cutting forces. Furthermore, as nano-oil concentration increases, nanoparticles' existence in the tool-workpiece interface will increase which will serve as a spacer to eliminate the contact between the cutting tool and workpiece [30].

Researchers D.X. Peng et al. [27] indicated that the coefficient of friction of nano-based solid particles in oil decreases to some extent and then increases back with a further increase in nanoparticle concentration. During high-speed machining, Elastohydrodynamic lubrication will be changed into boundary lubrication due to the high generated heat in cutting. The presence of nanoparticles between tool-workpiece zones may cause a reduction of friction between the contacted surfaces [28], [29]. A thin protective film can be formed on the surface of the workpiece that works as a contact resistance film due to the high pressure in nano oil with the present of the tool and

workpiece gap [30]. With more nano-oil concentration increases the thin protective film can be formulated more on the machined surface which might occur due to the breaking process. As a bigger number of nanoparticles will continue to rub on the asperities in the surface of the workpiece during the machining process, the chemical interaction formed between the new surface and nano-lubricant will be stronger, and as a result, the film formed will be more intensive. So, the properties of the machined surface will improve with a lower friction coefficient which in the end increases the quality of the produced surface [28], [30].

2.3.2 Types of Solid Particles for Nano-oil

Many types of nano-solid particles are available in the markets which are suitable to be used for nano-lubrication such as Graphite [31], MoS₂ [32], Al₂O₃ [33], SiO₂ [34] and Carbon Nano Tube (CNT) [18], [35] to be used with proper sonification method to disperse the particle homogeneously in mineral oil with proper concentration. To achieve optimum nano lubrication performance, it is vital to conduct a detailed analysis with the correct nano lubrication parameters setting during the machining process. Various investigations of the effectiveness of different nanoparticle types have been conducted on machining performance. During the drilling of AISI 4340 steel material by uncoated carbide cutter with the addition of solid lubricant (graphite mixed with SAE 40 oil), force component was considerably minimized because of the ability of graphite lattice structure to slide over each other, which works as an effective lubricating film. It was also found to dramatically improve the tool life, reduce surface roughness, and reduce chip thickness ratio because of the ability of solid lubricant mixture in penetrating the chip-tool interface [31].

According to the statistical analysis of Baskaran et al. [36] wet machining using waste cooking oil and molybdenum disulfide nanoparticles lowered cutting force by 27.53% on average compared to dry machining. Alumina nano-based solid suspended in an aqueous acetate buffer solution was investigated and it was found that a 10% volume of alumina nano-based solid lubricant resulted in a double reduction in the friction coefficient and 10 times reduction in stainless-steel wear [33]. In addition, the hybrid nano lubricant of MWCNT and ZnO was examined, and the results showed good improvement in the thermal conductivity of nano-oil compared to the base oil [37]. Different sustainability assessments were done on nano-oil based on the MQL system that is not limited to only machine quality but also including other factors such as environmental, safety, and health issues [38]–[40].

2.3.3 Carbon Nano Tubes Particles in Nano-oil

The nanoparticles of Carbon nanotubes (CNTs) are known to have good hardness, exceptional strength, and stiffness in addition to their availability on the markets [41], [42]. CNTs are allotropes of carbon formed by rolling up graphene sheets in cylindrical nanostructure shape which can be as single-walled CNT (SWCNT) or multiple-walled CNT (MWCNT). The features of these cylindrical carbon molecules are uncommon, making them useful in materials research and industry. CNT nanoparticles can be found in very small sizes, ranging from 5-100nm. Moreover, because of their excellent thermal conductivity, and mechanical and electrical properties, carbon nanotubes are used as nano-solid lubricant additives for mineral oil in appropriate concentrations to produce nano-lubricant [18], [43], [44]. A study by Mahendran et al. [35] was conducted on CNT nano-oil to analyze the metrological and tribological characteristics of this nanofluid.

They observed that the carrying loading capacity and the anti-wear of the oil were improved with the nanoparticles while on the other hand, more concentration of nanoparticles can cause harmful friction for the contacting surfaces.

2.4 Motivations and Objectives of the Thesis Work

According to the literature above, it was found that the selection of an effective lubricant during the machining process is crucial for the machining process. Any elimination or reduction of cutting fluid will greatly reduce the cost of the machining process as well as reduce the environmental concerns of cutting fluids. In this study, we examined the functionality of the CNT nano-lubricant on machining performance by considering high-speed machining through an established optimization technique. The effective parameters of the CNT nano-lubrication system were selected in conjunction with the most reliable cutting parameters for high-speed heavy-duty machining to ensure the data collection is very useful, informative, and can contribute to the manufacturing industry. Cutting forces were tested at different controlled MQL factors. After that, the wear of the cutting tools was investigated. Scanning electron microscopy (SEM) images in conjunction with energy-dispersive X-ray EDX and surface roughness images were taken to study the topography of the machined surfaces. We summarize the research objectives as follows:

- To develop an effective CNT nano-lubrication system and determine the optimum CNT nano-lubricant parameters under different concentrations of nanoparticles, output oil rate, and airflow rate.
- To study the CNT nano-lubricant effects on high-speed heavy-duty machining performance (cutting force, tool wear, the topography of machined surface) by considering the high production rate and product quality.

CHAPTER 3

METHODOLOGY

3.1 Preparation of Homogeneous Dispersion CNT Nano-lubrication

CNT was functionalized chemically with COOH to improve its stability when mixed with oil. The base lubricant oil used is Coolube® 2210 which is environmentally friendly and suitable for MQL applications. Functionalized CNT nanoparticles that have an average size of 5-50 nm as shown in Figure 3.1 were added to lubrication oil and sonication by ultrasonic processing to suspend the CNT particles in homogenous distribution in the nanoparticle-oil mixture. Figure 3.2 shows the CNT nano-oil preparation process.

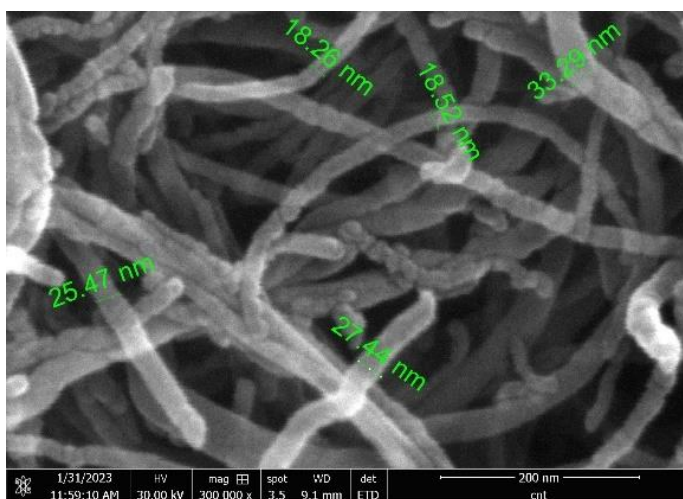


Figure 3.1 Scanning electron microscopy (SEM) image of CNT nano particles showing their diameters sizes.

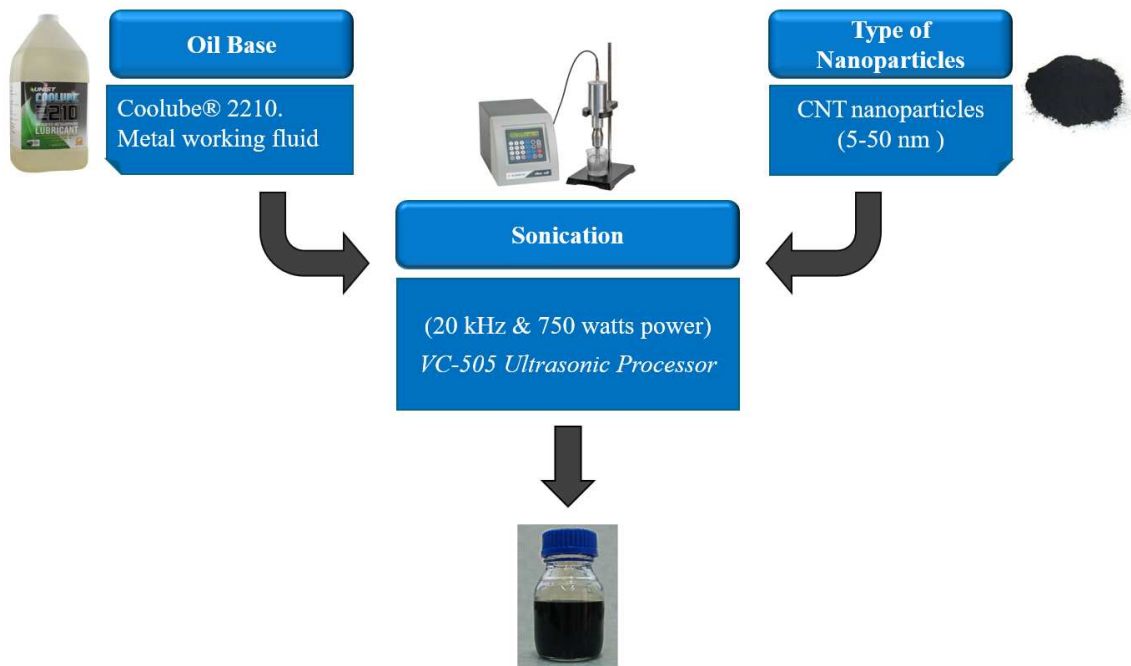


Figure 3.2 Preparation process of CNT nano-oil.

3.2 MQL System

CNT was MQL systems, or minimal quantity lubrication, are intended to apply a very thin amount of high-quality lubricating oil to metal cutting/machining processes. Figure 3.3 shows a typical MQL application system, which includes a reservoir, pump, valves, hoses or tubing, and a nozzle that distributes the oil to the cutting surface in an atomized spray. MQL is a phrase and method that is used in machining and metal-cutting activities.

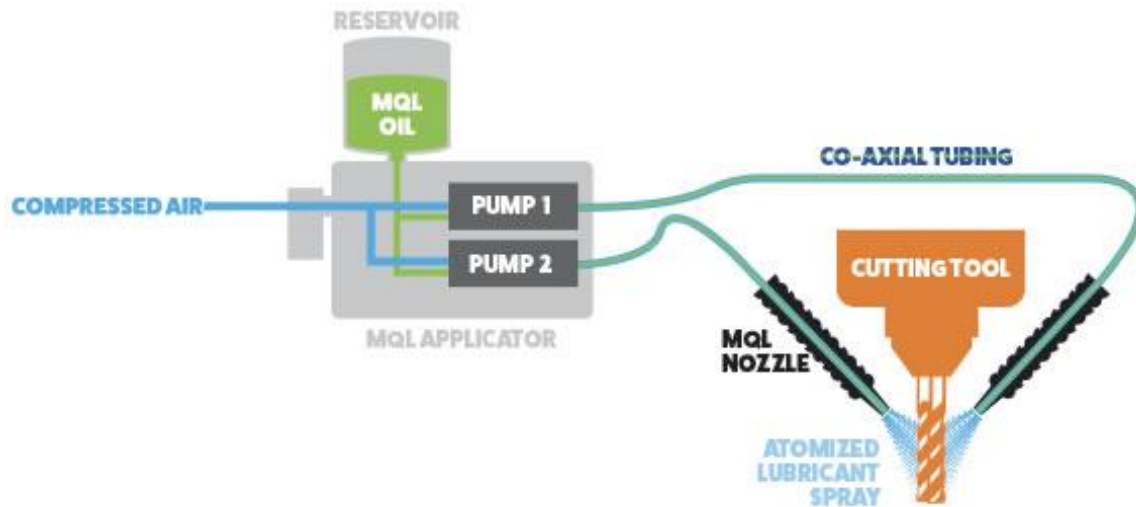


Figure 3.3 Schematic diagram shows MQL components.

The MQL system used is from Unist company with co-axial tubing. It delivers the oil consistently and repeatedly using positive displacement pumps that move the specific volume of oil in each pump stroke without considering the temperature. The components of Unist MQL are shown in Figure 3.4 named in Table 3.1. And the specifications of Unist MQL are shown in Table 3.2.

Table 3.1 Names of Unist MQL components.

A- Air filter.	F- Pump stork adjustment knob.
B- Control valve.	G- 16 oz [473 ml] fluid reservoir.
C- Positive Displacement metering pump.	H- Rugged steel enclosure.
D- Pneumatic pulse generator.	L- Drain plug.
F- Air metering screw.	J- Outlet port.



Figure 3.4 Unist MQL components.

Table 3.2 Specification of Unist MQL.

Supply air pressure	Clean and dry compressed air with 0-100 psi [4-7 bar]
Pumps	Oil output at a full stroke is 0.033ml. The viscosity of the oil is 50-1000 SUS*. The output rate is 0-396 ml/hr depending on the number of pulses generated per minute
Air flow rate	0-4 SCFM** [0-113 LPM***] for each air and oil output. The recommended is 1-2 SCFM [28-56 LPM]
Pulse generating frequency	Ranged 0-200 pulse/min and recommended 5-50 pulse/min.

* Saybolt Universal Seconds, ** Standard Cubic Feet per Minute, *** Liter per minute.

3.3 Experimental Set-up

In this research work, we used Coolube® 2210 lubricant oil as base oil. Unist MQL system is used to help us deliver the CNT nano-lubricant to the tool–chip contacted area. The thin-pulsed jet nozzles in the MQL system are responsible for spraying the CNT nano-lubricant in the tool-workpiece interface during the experimentation. The nozzle contains an internal tube that pumps the oil and an external tube that pumps the air which is mixed in the nozzle exit and then delivered into the cutting region which is capable of minimizing oil consumption by up to 25% as compared to ordinary MQL lubrication system, see Figure 3.5.

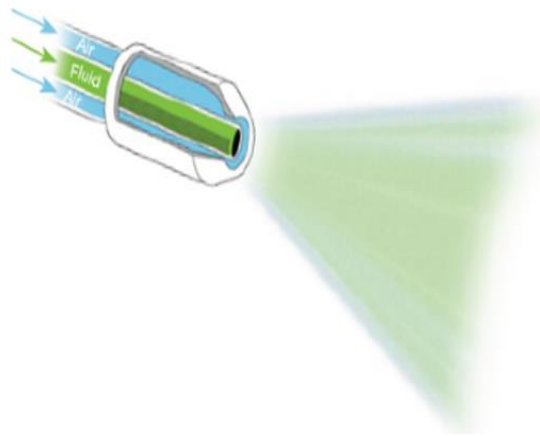


Figure 3.5 MQL nozzle with two internal tubes: One for air and the other for oil.

Each nozzle has an opening of 1 mm diameter and will be connected to a flexible fixture placed on the spindle of the CNC machine. The location and orientation of the nozzle can be controlled using a flexible design attached to the nozzle that gives more freedom in locating the injection nozzle at any orientation. During machining, the air supply pressure is set to 80 psi [5.52 bar].

The experimental set-up and equipment are illustrated in Figure 3.6 and named in Table 3.3. A Spinner U-620 CNC milling machine was used in this study. A workpiece of mild steel AISI 1020 was selected as a case study for this research and its elemental composition is shown in Table 3.4. The tested cutting process is slot milling (straight slot with two open ends). The Kistler three-axis dynamometer (type 9257B) is utilized to measure cutting forces signals in three axes (X, Y, and Z directions).

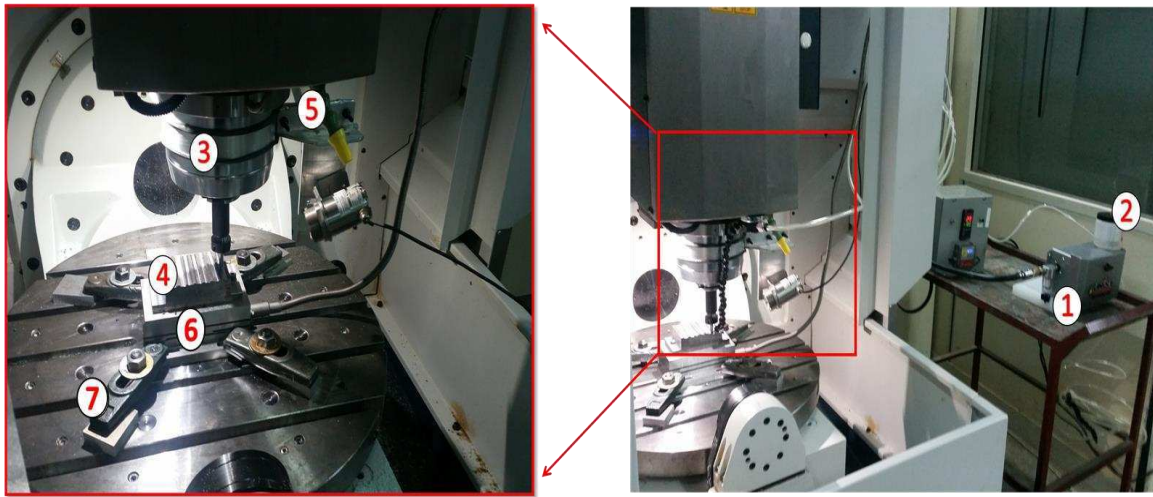


Figure 3.6 The set-up and equipment for the experiment.

Table 3.3 Names of the equipment in the experiment set-up

No	Item	No	Item
1)	MQL System	5)	MQL Nano-Oil Nozzle
2)	Oil Tank	6)	Kistler Dynamometer
3)	High-Speed Spindle with Cemented Carbide Cutting Tool	7)	Clamps to Hold the Dynamometer
4)	Mild Steel Workpiece		

Table 3.4 Elemental composition of mild steel workpiece.

Element	Composition (wt%)
Fe	97.9
Mn	0.975
Si	0.221
C	0.205
Cr	0.199
Mo	0.13
Ni	0.096
Others	<0.275

The cutting tool to be used is SANDVICK-Solid Carbide, Model: 1P230-1000-XA 1630, a two-flute flat end mill with a 10 mm diameter which is suitable for slot milling process. The workpieces' dimensions are $76 \times 105 \times 38$ mm. Figure 3.7 illustrates the shape of the workpiece and cutting tool used in the experiment.

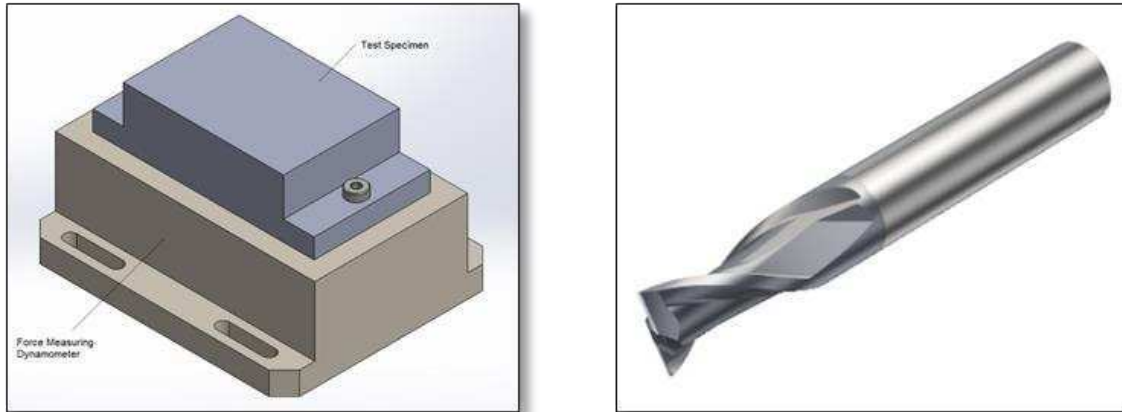


Figure 3.7 (Left) 3D model represents the workpiece above the dynamometer, (Right) cutting tool with two flutes end mill.

All the machines and devices used in the experiments are illustrated in Table 3.5 & Table 3.6. The cutting parameters such as cutting speed, feed rate, and depth of cut were chosen according to the tool manufacturer's recommendations. Figure 3.8 shows the relation between the life of the tool and speed of cut in (a) and feed per tooth in (b) according to the SANDVICK tool manufacturer's recommendations whereas the cutting data are shown in Table 3.7.

Table 3.5 Machining system components.

Machining System Components	Name
Machine Tool	Spinner U-620 CNC milling machine.
Tool	SANDVICK-Solid Carbide: two-flute flat end mill with 10 mm diameter.
Workpiece	Mild steel: AISI 1020 with 209 HB with dimensions of $76 \times 105 \times 38$ mm.

Table 3.6 Testing devices used in the experiments.

Measured Parameter	Test Device
Cutting Force Signal	Kistler three-axis dynamometer (type 9257B).
Cutting Tool Wear	Optical microscope: Olympus DSX510.
SEM & EDX	JSM-6610LV Machine.
Surface Roughness	3D Optical profilometer: ContourX-100.
Rockwell Hardness	Tinius Olsen Rockwell Hardness Tester.

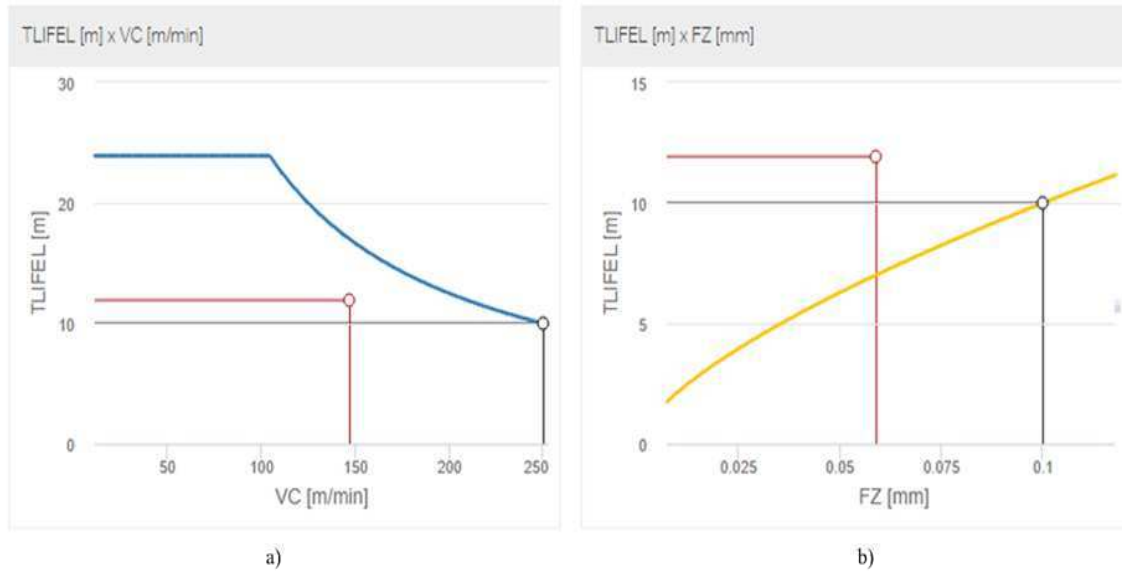


Figure 3.8 Tool life Vs cutting speed in (a) and tool life Vs feed per tooth in (b) according to tool manufacturer's recommendations.

Table 3.7 Cutting parameters for the experiment from the tool manufacturer's recommendations.

Parameter	Value	Parameter	Value
Cutting speed	250 m/min	Feed per tooth	0.1 mm
Spindle speed	7960 rev/min	Feed speed at the machined diameter	1590 mm/min
Depth of cut	2 mm	Material removal rate	31.9 cm ³ /min

3.4 Design of Experiment

The control factors of nano-lubricant and their levels are shown in Table 3.8. The number of experiments and their factor level is presented in Table 3.9 according to the standardized Taguchi-based experiment design L16(43) orthogonal array. The output parameter that is measured is cutting force, other measured parameters will be discussed in the results section later.

Table 3.8 Controlled parameters with their levels in the experiments.

Controlled Parameters		Level			
		1	2	3	4
A	Nanoparticle concentration (wt %)	0	0.1	0.3	0.5
B	Output Oil rate (pulse/min)	10	25	40	55
	Output Oil rate (ml/min)	0.33	0.825	1.32	1.815

C	Airflow rate (turn of adjustment knob)	0.5	1	1.5	2
	Airflow rate (SCFM)	0.5	0.75	1.25	2.25

Table 3.9 Standard L16(4)³ experimental array from Taguchi optimization.

Exp No.	Control parameters and levels		
	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	1	4	4
5	2	1	2
6	2	2	1
7	2	3	4
8	2	4	3
9	3	1	3
10	3	2	4
11	3	3	1

12	3	4	2
13	4	1	4
14	4	2	3
15	4	3	2
16	4	4	1

3.5 Taguchi Optimization Method: S/N and ANOVA Analysis

In engineering analysis, Taguchi techniques are frequently used to select design parameters to improve performance characteristics [13]. In an empirical investigation, the Taguchi approach combines statistical and mathematical methods. It is economical for describing difficult and long procedures. It employs fewer experiments than are necessary to explore all input parameter values, and it filters out certain effects brought on by statistical variance. Once the experimental runs are completed and the cutting force data is collected, analyzing data is performed with the help of signal-to-noise (S/N) response analysis and analysis of variance (ANOVA).

The S/N ratio is a statistical measure used as an objective function in the Taguchi-based experiment to evaluate the performance of the nano-oil in terms of cutting force reduction. It represents the ratio of the desired signal (in this case, the reduced cutting force) to the noise (the variability or error in the measurements). By maximizing the S/N, the experiment aims to find the parameters combination that provides the most consistent and significant reduction in cutting force. The S/N ratio is divided into three main

categories depending on what the desired characteristic is: greater, nominal, or smaller is better. In our case, we want cutting force to have smaller values to give better machining performance, so Eq. (3.1) of the S/N ratio is used for smaller the better characteristics (in dB):

$$\frac{S}{N} = -10 \log\left(\frac{1}{n} \sum y_i^2\right) \quad (3.1)$$

Where S/N is signal to noise ratio, n is the total number of repetitions, y is the control factor and i represents the number of repetitions such as ($i= 1, 2, \dots n$).

The ANOVA is a statistical analysis method used to determine the statistical significance of parameters and their levels for cutting force reduction. It helps identify which parameters have a significant impact on the response variable, which in this case is the cutting force. By analyzing the ANOVA results, we can identify the most influential parameters and their respective optimal levels, as well as their contributions to cutting force reduction.

3.6 Flow Chart of Research Activities

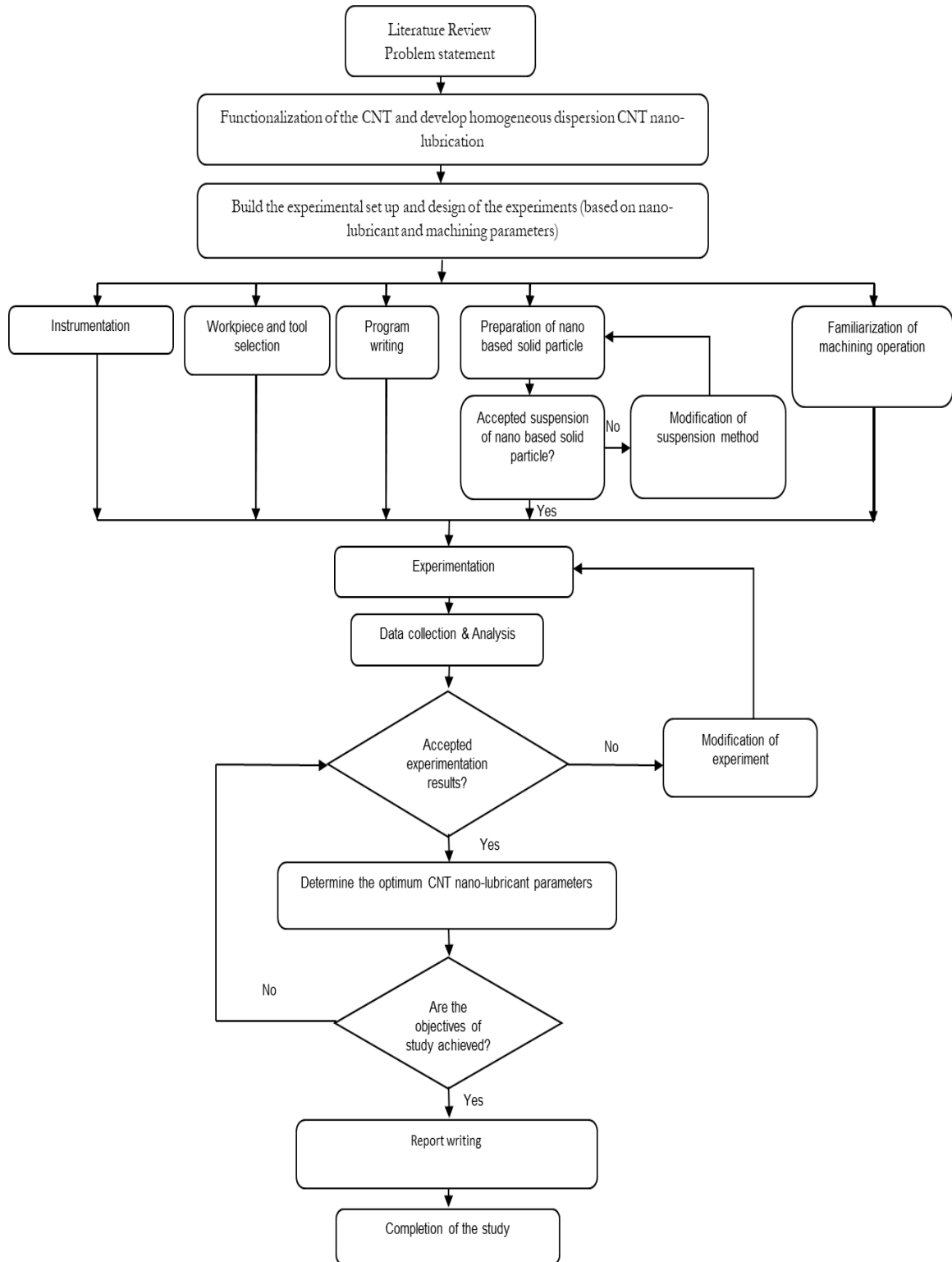


Figure 3.9 Flow chart of research activities.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Experimental Results (Cutting Force)

Three slot milling experiments were conducted under different cutting conditions. In experiment (1), we optimized MQL parameters under the recommended cutting conditions from the cutting tool manufacturer. For experiment (2), we optimized MQL parameters under severe cutting conditions. For experiment (3), we cut the workpiece until the end of the tool life in severe conditions. The cutting parameters for all three experiments are summarized in the following Table 4.1. In each experiment, we measured the cutting forces using Dynamometer and calculated the total cutting force using the following equation.

$$F_c = \sqrt{F_x^2 + F_y^2} \quad (4.1)$$

Where F_c is the total cutting force, F_x is the cutting force from the x-axis and F_y is the cutting force on the y-axis measured by the dynamometer. The vertical force F_z is not included because it represents the thrust force.

Table 4.1 Cutting parameters in the experiments.

Cutting Parameter	Experiment (1)	Experiment (2)	Experiment (3)
Spindle Speed	8000 rpm	12000 rpm	12000 rpm
Feed Rate	1600 mm/min	200 mm/min	200 mm/min
Depth of Cut	2 mm	5 mm	5 mm

4.1.1 Experiment (1)

In Experiment (1), we used the recommended cutting parameters from the cutting tool manufacturer with the highest recommended spindle speed and feed rate (8000 rpm spindle speed, 1600 mm/min feed rate, and 2 mm depth of cut). Figure 4.1 shows a sample of filtered cutting force signal (other cutting force signals for the remaining runs are shown in **Appendix A**). The means of cutting force and S/N results are shown in Table 4.2. The summary of cutting forces of the 16 tests of the experiment (1) is illustrated in Figure 4.2

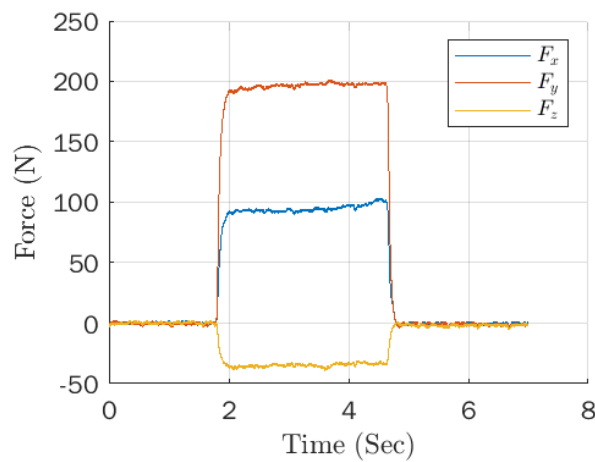


Figure 4.1 A filtered cutting force signal for the experiment (1) test 1 trail 1.

Table 4.2. Total cutting forces with S/N results.

Run No.	Control Factors Levels			Total Cutting Force (N)			S/N
	A	B	C	Trial 1	Trial 2	Average	
1	1	1	1	214.98	213.32	214.15	-46.61
2	1	2	2	214.14	216.43	215.28	-46.66
3	1	3	3	212.98	213.52	213.25	-46.58
4	1	4	4	206.66	218.82	212.74	-46.56
5	2	1	2	206.64	218.88	212.76	-46.56
6	2	2	1	204.55	222.57	213.56	-46.60
7	2	3	4	213.78	218.40	216.09	-46.69
8	2	4	3	214.61	216.71	215.66	-46.68
9	3	1	3	219.54	217.12	218.33	-46.78
10	3	2	4	213.83	217.44	215.64	-46.67
11	3	3	1	221.18	216.11	218.65	-46.80
12	3	4	2	212.90	220.31	212.90	-46.71
13	4	1	4	215.96	216.65	216.30	-46.70
14	4	2	3	211.46	218.60	215.03	-46.65

15	4	3	2	211.73	216.60	214.16	-46.62
16	4	4	1	204.60	218.00	211.30	-46.50

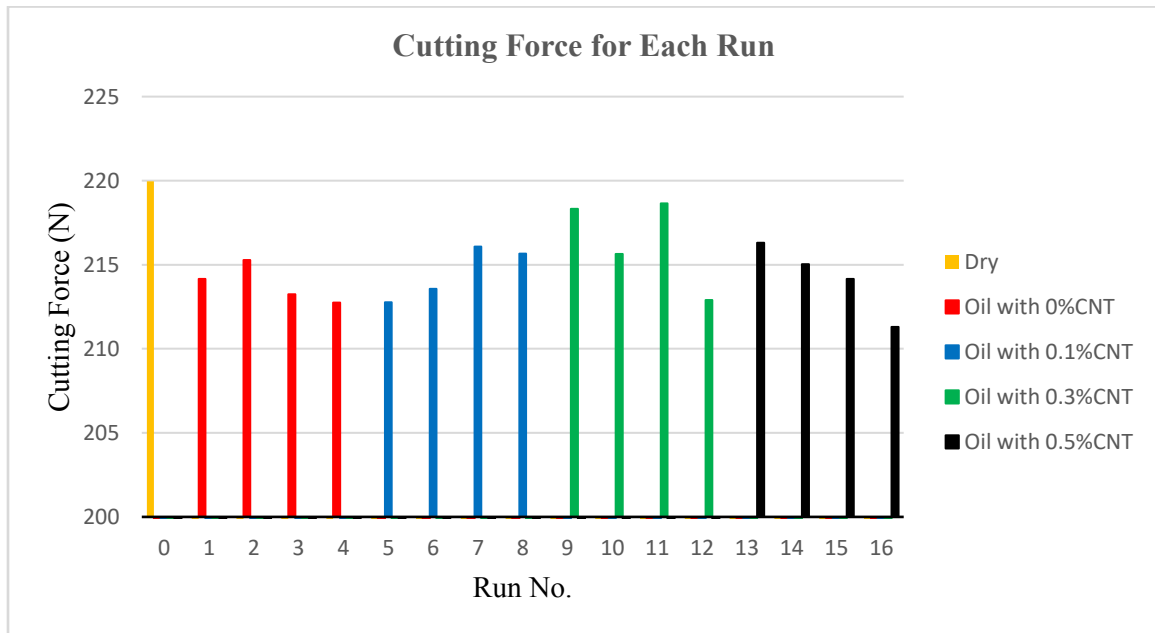


Figure 4.2 Cutting forces for each run of experiment (1).

Using the S/N & ANOVA analysis as shown in Table 4.3, we found that the combination of 1A, 4B, and 2C gives the lowest cutting force. Also, factor A which is nano-oil concentration is the most significant factor with 73.25% while the other two factors show similar significance with 12.23% for factor B and 14.52% for factor C.

Table 4.3 S/N & ANOVA analysis for the experiment (1).

S/N				ANOVA			
					A	B	C
	A	B	C	Level 1	-46.60	-46.66	-46.63
Level 1	-46.60	-46.665	-46.628	Level 2	-46.63	-46.65	-46.61
Level 2	-46.63	-46.646	-46.610	Level 3	-46.74	-46.67	-46.67
Level 3	-46.74	-46.670	-46.672	Level 4	-46.62	-46.61	-46.66
Level 4	-46.62	-46.613	-46.657	Total Sum	-186.6	-186.6	-186.57
Lowest Rank	-46.60	-46.613	-46.610	Square Difference	0.05	0.01	0.01
Optimum Level	1	4	2	Total Sum Square Difference	0.07		
				Contribution Ratio %	73.25	12.23	14.52

4.1.2 Experiment (2)

- Pre-experiment Tests

Before running experiment (2), we did some tests and modifications for HSM. In the beginning, we simulated a different combination of the recommended cutting parameters to get the lowest tool life in (m) which means that the lowest length of material needed for the cutting tool to fail, see Table 4.4.

Table 4.4 Simulation of different combinations of cutting parameters on tool life.

Sim. #	Speed (m/min)	Spindle speed (rpm)	Feed/tooth (mm)	Feed speed (mm/min)	MRR (cm ³ /min)	Tool life (m)	Tool life (min)	Cutting time (sec)
1	147	4680	0.059	551	27.5	10.43	19	8.82
2	104	3310	0.059	391	19.5	14.68	38	12.4
3	249	7930	0.059	936	46.8	6.1	6.6	5.2
4	147	4680	0.118	1100	55.2	16.55	15	4.4
5	147	4680	0.00811	75.9	3.8	2.7	36	62.4
6	249	7930	0.00811	129	6.43	1.6	13	37.8
7	249	7930	0.118	1870	93.3	9.8	5.2	2.6

As we see from the simulation results in Table 4.4, the lowest tool life in (m) is achieved by increasing the cutting speed and decreasing the feed speed as seen in simulation #6 with only 1.6 m tool life. This means that high cutting speed with a low feed rate is the most severe condition for cutting tool life.

The maximum spindle speed of the Spinner U-620 CNC milling machine which can be reached is 12000 rpm. A low feed rate of 200 mm/min can be used. So, we exceeded the values of the cutting tool's manufacturer, and we selected 12000 rpm spindle speed, 200 mm/min feed rate, and 5 mm depth of cut as cutting parameters to get more severe conditions for the cutting tool.

Next, we conducted different tests at different CNT nano-oil concentrations (0%, 0.1%, 0.3%, 0.5%, 0.7% & 1%) with 55 pulses per min and 2 full turns of adjustment knob for air supply in the MQL system to determine which are the best concentrations to select. The cutting parameters are (12000 rpm, 200 mm/min, and 5mm depth of cut). We were not able to use CNT nano-oil with 1% concentration because it is very thick and viscous and the MQL system could not pump the CNT nano-oil, so this option was eliminated. Figure 4.3 shows the cutting forces of different CNT nano-oil concentrations for a 200 mm/min feed rate. The cutting force signals are shown in **Appendix A**.

We selected 0%, 0.1%, 0.3%, and 0.5% CNT nano-oil concentrations for the next experiment because these levels showed satisfactory values for cutting force and no need to go with 0.7%. Currently, the best cutting force result was shown at 0.3% wt CNT nano-oil.

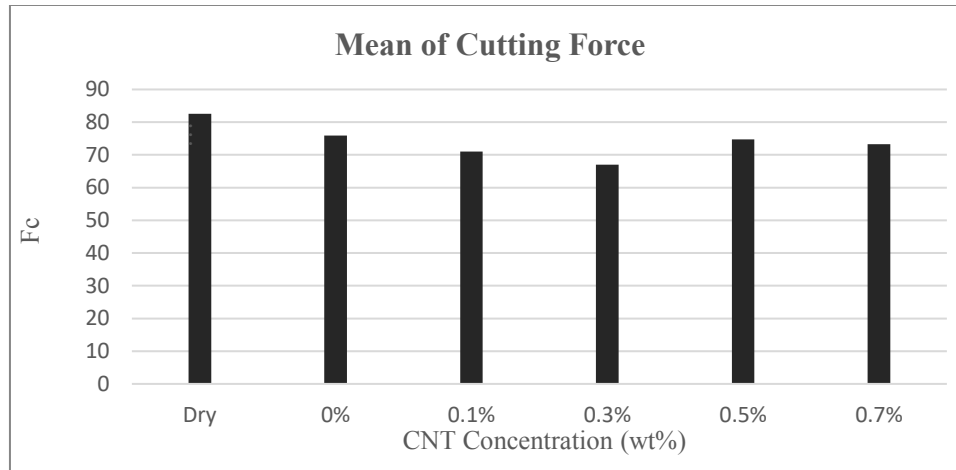


Figure 4.3 Mean cutting force at different CNT concentrations.

Finally, we are ready to experiment (2) with the following cutting parameters (12000 rpm spindle speed, 200 mm/min feed rate, and 5 mm depth of cut) and with 0%, 0.1%, 0.3% & 0.5% CNT concentration levels.

- Experiment Results

The cutting forces and S/N results are shown in Table 4.5. All the cutting force signals are shown in **Appendix A**.

Table 4.5 Cutting force and S/N results under different control factors.

Exp. #	Control factors and levels			Total Cutting Force (N)	S/N
	A	B	C		
1	1	1	1	75.463	-37.555
2	1	2	2	77.501	-37.786
3	1	3	3	72.110	-37.160

4	1	4	4	71.819	-37.125
5	2	1	2	77.045	-37.735
6	2	2	1	76.303	-37.651
7	2	3	4	73.331	-37.306
8	2	4	3	68.216	-36.678
9	3	1	3	72.876	-37.252
10	3	2	4	63.279	-36.025
11	3	3	1	68.251	-36.682
12	3	4	2	66.078	-36.401
13	4	1	4	72.712	-37.232
14	4	2	3	66.364	-36.439
15	4	3	2	65.782	-36.362
16	4	4	1	68.402	-36.701

Using the S/N & ANOVA analysis shown in Table 4.6, we found that the combination of 3A, 4B, and 3C gives the lowest cutting force. Also, factor A is the most significant factor with 62.26%, and then factor B with 32.47% while factor C is the least significant with only a 5.28% contribution ratio.

Table 4.6 S/N & ANOVA analysis for the experiment (2).

S/N				ANOVA			
					A	B	C
	A	B	C	Level 1	-37.41	-37.44	-37.15
Level 1	-37.41	-37.44	-37.147	Level 2	-37.34	-36.98	-37.07
Level 2	-37.34	-36.98	-37.071	Level 3	-36.59	-36.88	-36.88
Level 3	-36.59	-36.88	-36.882	Level 4	-36.68	-36.73	-36.92
Level 4	-36.68	-36.73	-36.922	Total Sum	-148.0	-148.0	-148.0
Lowest Rank	-36.59	-36.73	-36.88	Square Difference	2.20	1.15	0.19
Optimum Level	3	4	3	Total Sum Square Difference	3.54		
				Contribution Ratio %	62.26	32.47	5.28

Because the experiment with 3A, 4B, and 3C is not from the experiment list of the Taguchi optimization method. All tests from 1-16, the optimized test with an (O1) symbol and the dry test with a number (0) are shown in Figure 4.4.

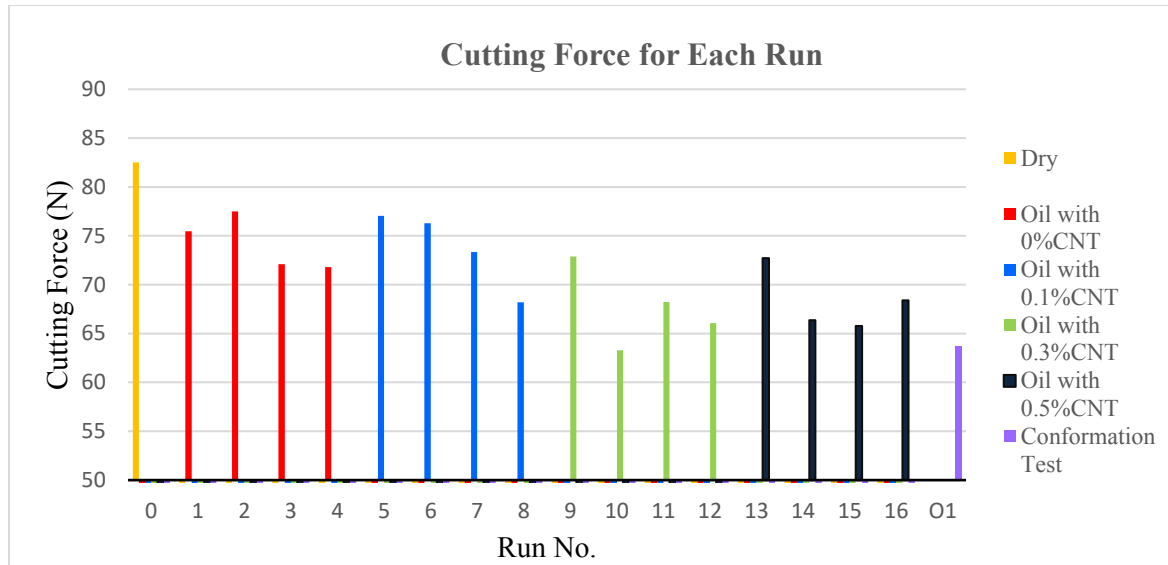


Figure 4.4 Mean cutting forces for all runs in experiment (2).

4.1.3 Experiment (3)

After finishing the S/N and ANOVA analysis of Experiment (2) and finding the optimized level for each parameter, we conducted a long-run slot milling test in which cutting is performed until the end of the life of the cutting tool. Three different conditions were tested: dry condition, lubrication condition with oil of 1A, 4B, and 3C levels, and lubrication condition with CNT nano-oil of 3A, 4B, and 3C. Note that the slot milling cutting is not continuous, and there are interruptions during the measurement of cutting force. This is because, for long milling runs, a large workpiece is required, which cannot be held on the dynamometer. We used cutting force as an indication about tool life which can give similar response to flank wear measurement. The results of this test are shown in Figure 4.5, (All force signals are shown in **Appendix A**). The tool life of the ordinary oil case reached about 4 min while the tool life of the CNT nano-oil case reached out to 6.5 min. CNT nano-oil showed better results in which it was able to prolong the cutting tool

life compared to the oil alone. This showed the ability of CNT nano oil to transfer heat and reduce the friction from the tool/workpiece and tool/chip interface.

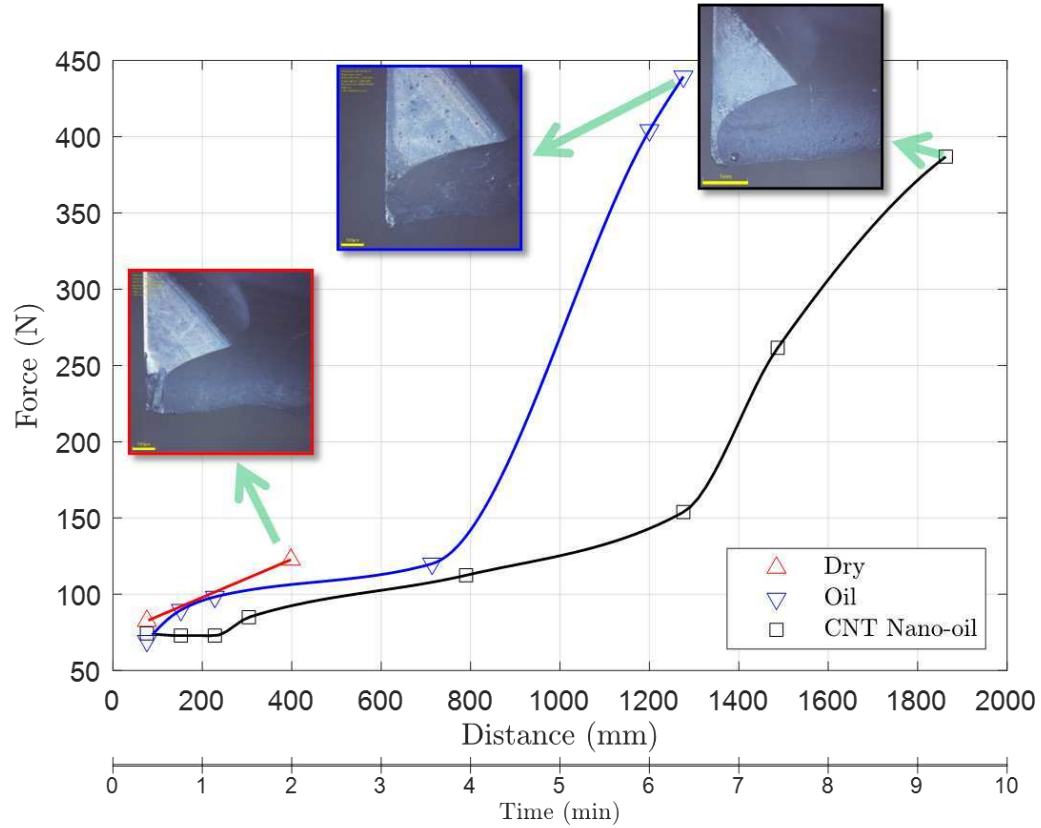


Figure 4.5 Mean force for dry, oil lubricant, and CNT nano-oil conditions in the long run.

4.2 Cutting Tool Wear

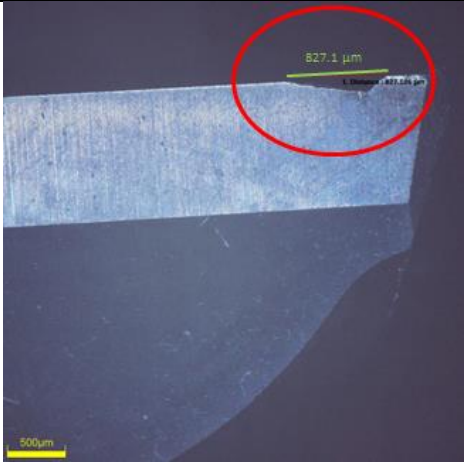
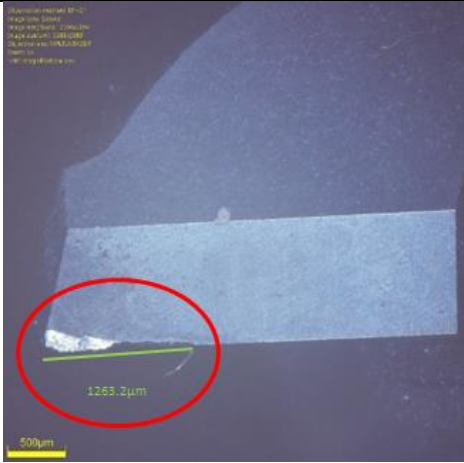
The wear of cutting tools was investigated after the long run test using an optical microscope Olympus DSX510 for the three cutting tools: dry, oil, and CNT-nano oil lubrication. The orientations at which images were captured for each cutting tool are illustrated in Figure 4.6 while the images are shown in Table 4.7.

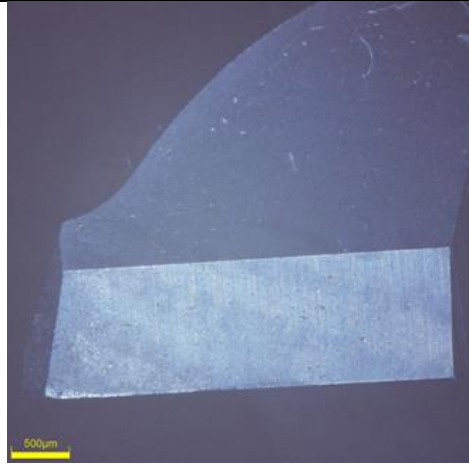


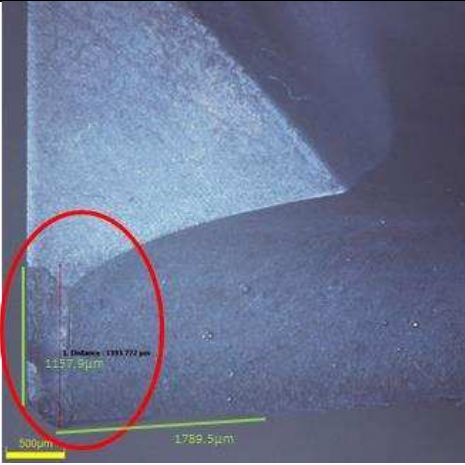
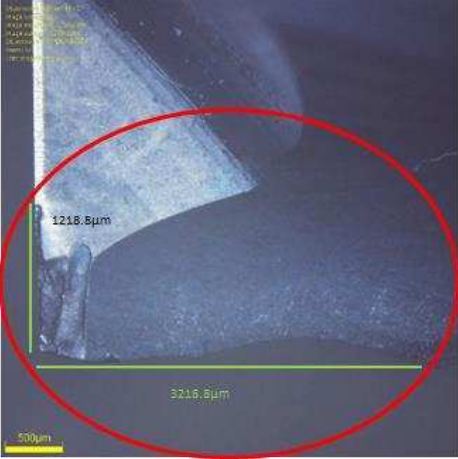
Figure 4.6 The directions at which the wear of the cutting tool was investigated.

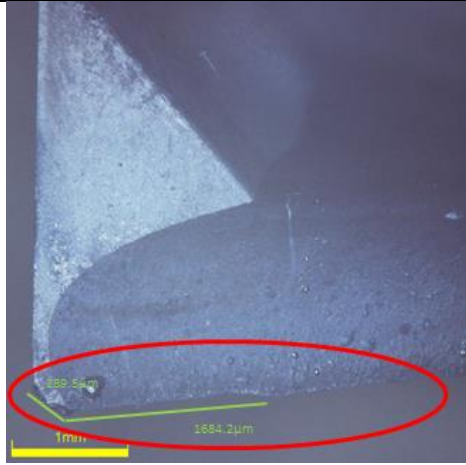
Table 4.7 Cutting tool wear at different locations for dry, ordinary oil, and CNT nano-oil.

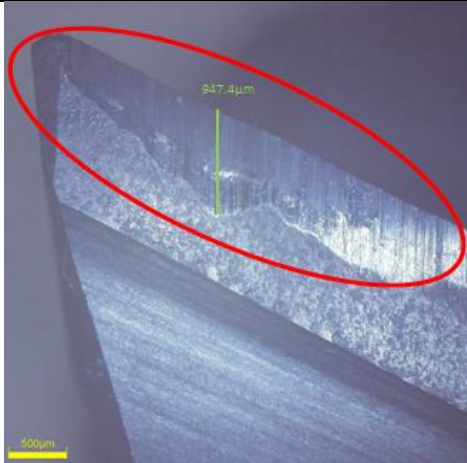
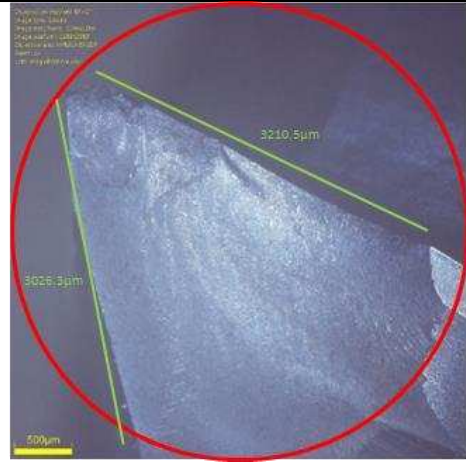
Direction	Cutting Tool Condition	
Top (Right)	Dry: After a 400 mm cutting length.	Oil: (3 4 3) After a 1276 mm cutting length.
		
	CNT nano-Oil: (3 4 3) After a 1276 mm cutting length.	CNT nano-Oil: (3 4 3) After an 1863 mm cutting length.

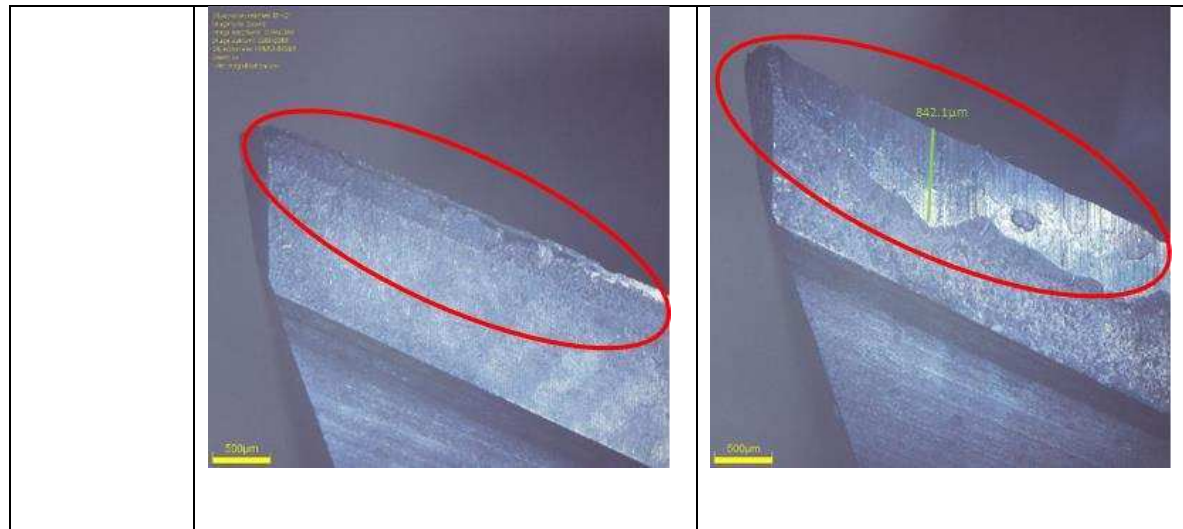
		
Top (Left)	Dry: After a 400 mm cutting length.	Oil: (3 4 3) After a 1276 mm cutting length.
		
	CNT nano-Oil: (3 4 3) After a 1276 mm cutting length.	CNT nano-Oil: (3 4 3) After an 1863 mm cutting length.

		
	Dry: After a 400 mm cutting length.	Oil: (3 4 3) After a 1276 mm cutting length.
Side (Right)		
	CNT nano-Oil: (3 4 3) After a 1276 mm cutting length.	CNT nano-Oil: (3 4 3) After an 1863 mm cutting length.

		
	Dry: After a 400 mm cutting length.	Oil: (3 4 3) After a 1276 mm cutting length.
Side (Left)		
	CNT nano-Oil: (3 4 3) After a 1276 mm cutting length.	CNT nano-Oil: (3 4 3) After an 1863 mm cutting length.

		
	Dry: After a 400 mm cutting length.	Oil: (3 4 3) After a 1276 mm cutting length.
Corner (Right)		
	CNT nano-Oil: (3 4 3) After a 1276 mm cutting length.	CNT nano-Oil: (3 4 3) After an 1863 mm cutting length.

		
Corner (Left)	Dry: After a 400 mm cutting length.	Oil: (3 4 3) After a 1276 mm cutting length.
		
	CNT nano-Oil: (3 4 3) After a 1276 mm cutting length.	CNT nano-Oil: (3 4 3) After an 1863 mm cutting length.



As seen in Table 4.7, the amount of wear in the cutting tool in the dry condition is more than the wear in other situations although it cut a shorter distance of only 400 mm which is expected because it is exposed to high temperature and friction. If we compare the lubrication cases (ordinary oil and CNT Nano-oil), we notice that at the same cutting length (~1200 mm), the cutting tool under CNT nano-oil has less wear compared to the ordinary oil case which is because CNT nano-oil can dissipate more heat from cutting tool compared to ordinary oil that reduces the temperature of cutting tool and thus reduce the wear. As a result, using CNT nano-oil increases the life of the cutting tool and reduces its wear.

4.3 SEM & EDX

The samples were prepared to be in 1-inch cubic shape so that they can be fit in the holder of the Scanning Electron Microscopy (SEM) machine. Samples were cleaned with acetone before they entered the SEM chamber to ensure the sample was not affected by external impurities. Figure 4.7 shows the prepared sample of CNT nano-oil inside the SEM chamber. The SEM machine used is JSM-6610LV. SEM and EDX images for both

oil and CNT nano oil cases were taken on the machined surface after cutting length of 1276 mm, see Figure 4.8 for clarification.



Figure 4.7 Machined sample under CNT nano-oil is inside SEM chamber.

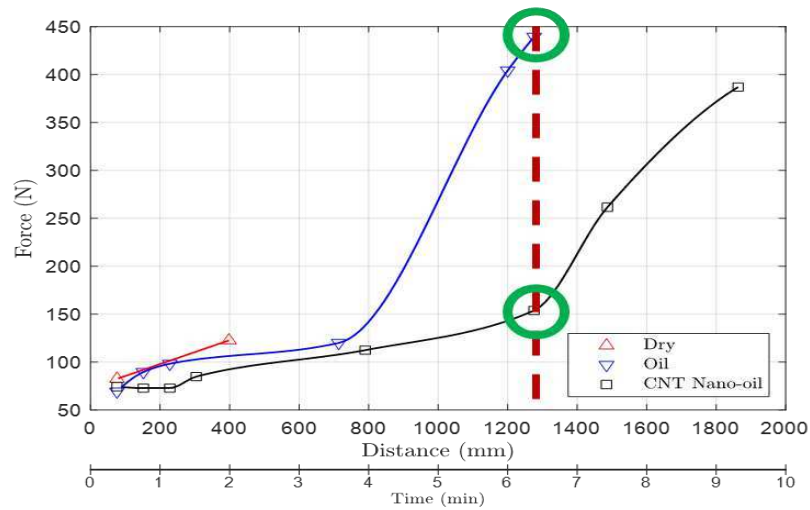


Figure 4.8 Force Vs cutting distance graph where SEM & EDX were taken at 1276 cutting length of the machined surface.

SEM images for oil and CNT nano-oil samples at different magnifications are displayed in Figure 4.9. For the CNT nano-oil case, there is no CNT film appeared. If we compare the SEM images of the ordinary oil case with the CNT nano-oil case, we noticed that for

the oil case, the lines of paths are not as straight as CNT nano-oil case because part of the surface material was melted and disturbed the lines which mean temperature was more compared to CNT nano oil case.

Energy dispersive X-ray (EDX or EDS) mapping analysis of composites shows the elemental composition of the surface of the samples, see Table 4.8. The carbon percentage increased a little bit in CNT nano-oil compared to oil and dry cases which means that some CNT particles are stuck on the surface although there is no clear film layer was noticed.

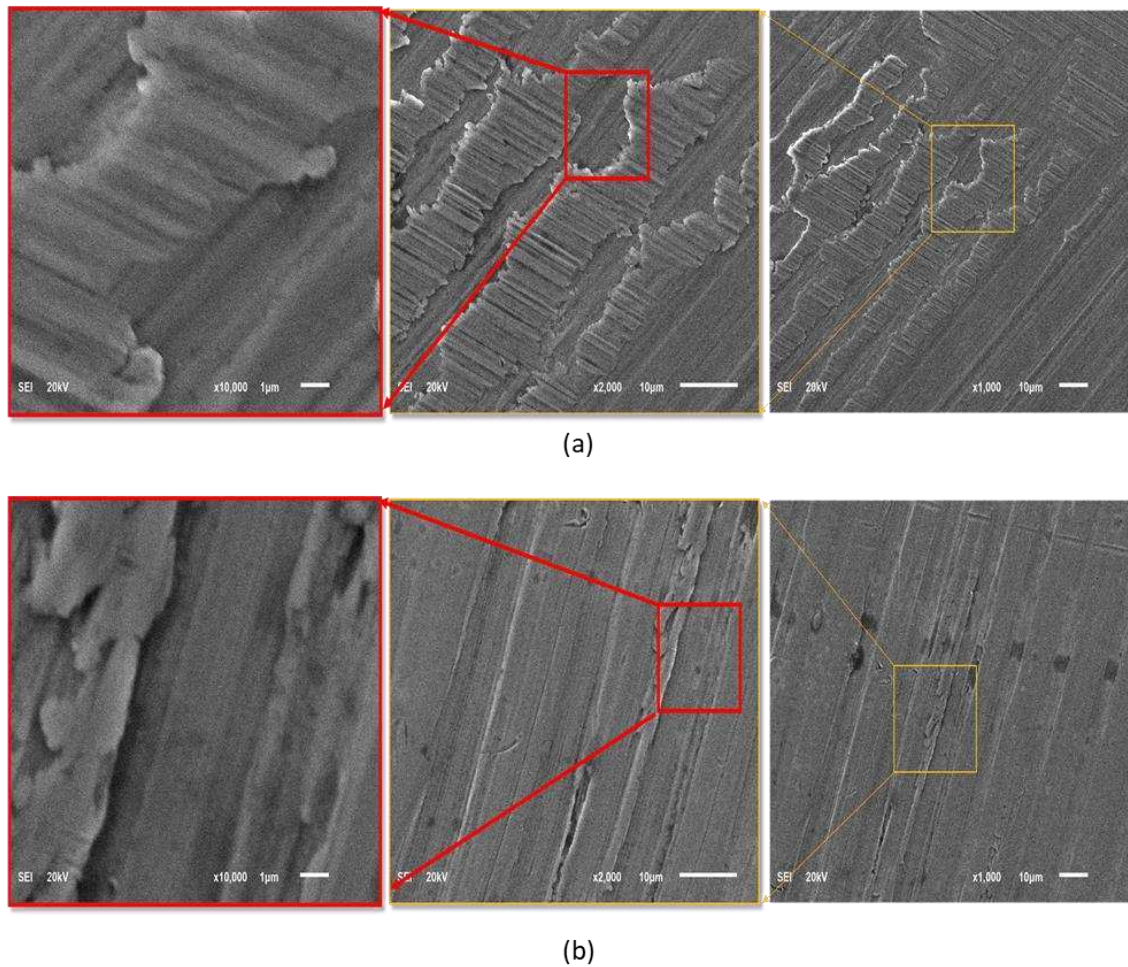
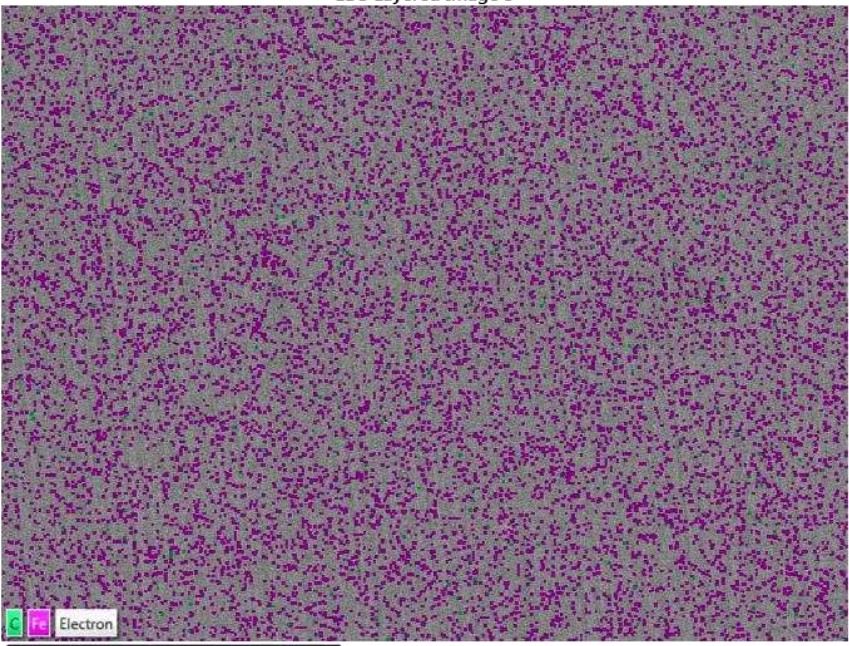
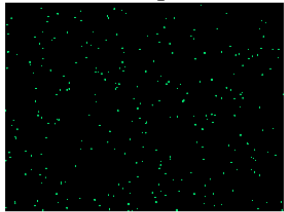
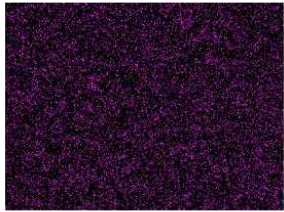
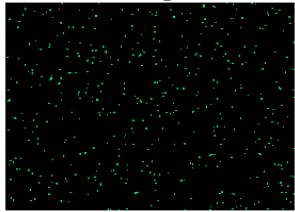
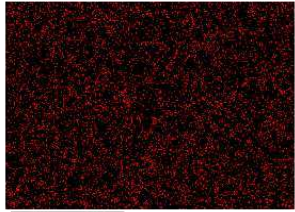
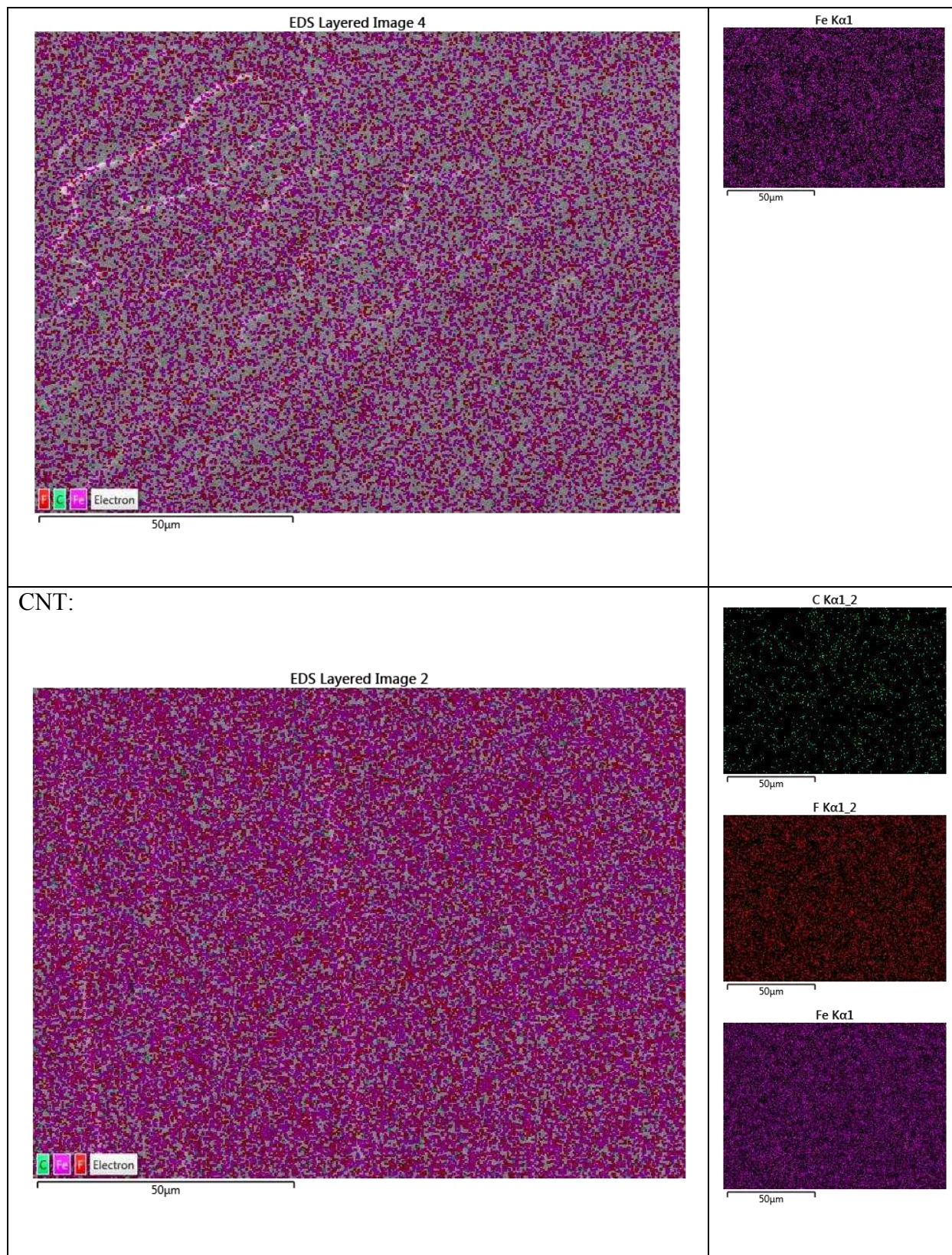


Figure 4.9 SEM images at different magnifications for (a) oil condition and (b) CNT nano-oil condition

Table 4.8 EDX Images for dry, oil, and CNT nano-oil.

EDX mapping	Individual element composition
Dry: EDS Layered Image 3  50µm	C Kα1_2  50µm Fe Kα1  50µm
Oil:	C Kα1_2  50µm F Kα1_2  50µm



4.4 Hardness of Workpiece

A hardness test is a mechanical test performed on a material to evaluate its resistance to indentation or deformation. It is an essential measure of a material's strength, durability, and suitability for specific applications. We used Tinius Olsen Rockwell hardness tester Scale B to measure the depth of penetration of an indenter into the material under a specific load. It is commonly used for metallic materials and provides a direct hardness value. We measured the Rockwell hardness of the workpiece before cutting and compared it with the hardness after milling under both oil lubricant and CNT nano lubricant. The hardness results are shown in Table 4.9. The results showed that there was almost no change in the hardness of the workpiece in all three cases, even in the CNT nano lubricant case. This means that there are no or very few CNT nanoparticles present on the machining surface of the workpiece, as also indicated in the EDX images in the above section.

Table 4.9 Results of Rockwell hardness of workpiece under different conditions.

Condition of workpiece	Rockwell Hardness HRB						
	1	2	3	4	5	6	Average
Original workpiece	90.64	89.8	90.07	88.54	91.33	88.33	89.79
The machined surface under oil lubrication	91.01	90.01	89.43	91.54	87.01	90.8	89.97
The machined surface under CNT nano lubrication	90.59	88.75	91.01	91.28	89.22	89.8	90.11

4.5 Surface Roughness

Surface roughness for the machined surface is measured using a 3D Optical Profilometer: ContourX-100 under both oil and CNT nano oil lubrication. The 3D surface topography of machined surfaces with oil and CNT (carbon nanotube) after a long run of 1200 mm, are illustrated in Figures 4.10, and 4.11. In the case of oil, the surface has a maximum peak height of 2.666 μm , which is worse than the CNT nano-oil case which shows a better surface finish with a maximum peak height of only 1.941 μm .

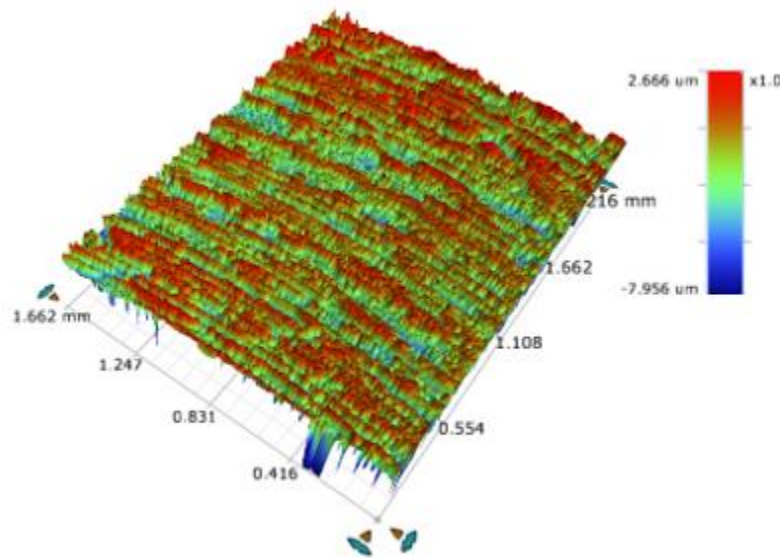


Figure 4.10 Topography of machined surface with oil.

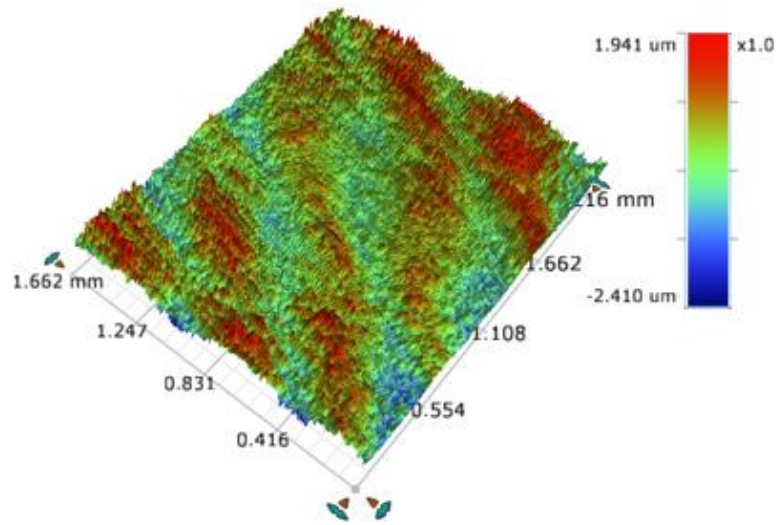


Figure 4.11 Topography of machined surface with CNT nano-oil.

The surface roughness parameters for the two cases are shown in Table 4.10. The surface roughness of the CNT nano-oil case showed better results than the oil case. This is logical because in the oil case, the cutting tool was damaged faster and with the damaged cutting tool the surface roughness become worse.

Table 4.10: Surface roughness parameters for two different cases: Oil and CNT Nano-oil.

Surface roughness parameters	Oil	CNT Nano-oil
R_a (μm)	0.621	0.296
R_q (μm)	0.741	0.375
R_v (μm)	-7.956	-2.41
R_p (μm)	2.666	1.941
R_t (μm)	10.622	4.351

CHAPTER 5

CONCLUSION

5.1 Summary

Functionalized COOH CNT was mixed with oil to prepare a nano-oil mixture and used for slot milling lubrication of mild steel. CNT nano-oil was delivered to the tool/chips/workpiece interfaces using the MQL system. Different experiments were done under different cutting parameters to evaluate the CNT nano-oil effectiveness. CNT nano-oil performs better with more severe conditions (high cutting speed and low feed rate). Different MQL-controlled parameters were varied to determine the best combination that shows the minimum cutting force using the Taguchi optimization method. For cutting conditions of 12000 rpm, 200 mm/min, and 5mm depth of cut, oil with a CNT concentration of 0.3% shows the best results in reducing the cutting force. For the long run test, CNT nano oil was able to prolong the tool life compared to the utilization of oil alone. SEM images showed that machined surfaces with oil lubrication are worse compared to the CNT nano-oil case. EDX images of CNT nano-oil showed that there are some CNT particles stuck on the machining surface in a very small amount. The surface roughness of the CNT nano-oil case showed better results than the oil case. This is logical because in the oil case, the cutting tool was damaged faster and with the damaged cutting tool the surface roughness become worse.

5.2 Recommendation for Future Work

Different aspects of this thesis can be studied in future work, including:

- **Investigation of Different Materials:** In the experiments conducted, only mild steel workpieces were used. It would be valuable to test other materials to explore the effect of CNT nano-oil on a wider range of materials. This would provide insights into how the nanofluid performs and interacts with different material compositions.
- **Nanofluid Stability Measurement:** Although not covered in this thesis, it would be beneficial to include a study on the stability of the nanofluid. This would involve evaluating the stability of the CNT nano-oil over time and assessing factors such as sedimentation, agglomeration, and any changes in its physical properties. Understanding the stability of the nanofluid is crucial for its practical application and long-term performance.
- **Temperature Measurements:** Another area that can be explored in future research is the study of temperature. Investigating the influence of temperature on the performance of CNT nano-oil during cutting processes would provide valuable insights. This could involve measuring and analyzing the temperature distribution during machining operations using CNT nano-oil, and studying its effect on cutting performance, tool wear, and surface integrity.
- **Varying Cutting Speeds:** It is recommended to explore the utilization of different cutting speeds in future studies. Comparing the performance of CNT nano-oil at higher cutting speeds to lower speeds would help determine its

optimal operating range. This investigation could shed light on whether the benefits of CNT nano-oil are more pronounced at higher cutting speeds and could lead to improved machining efficiency and performance.

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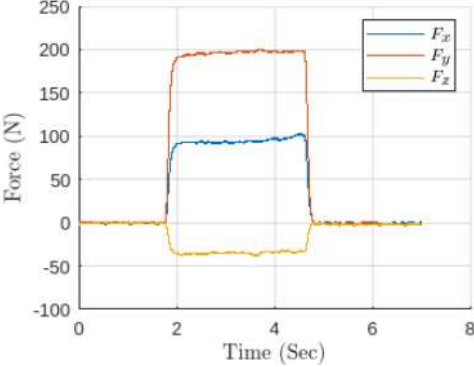
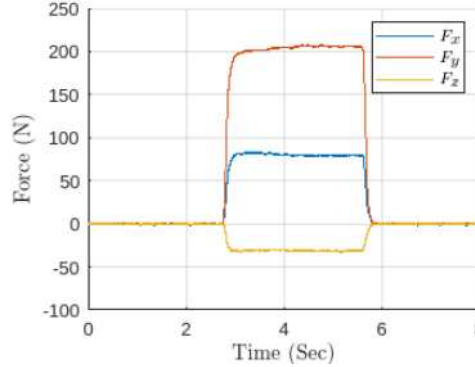
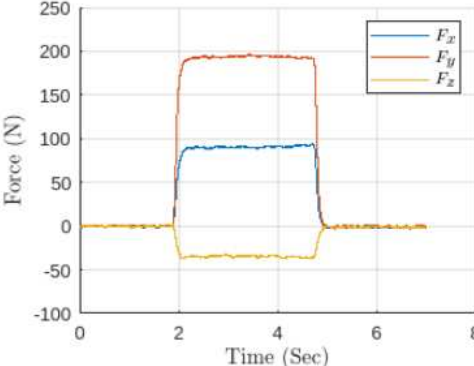
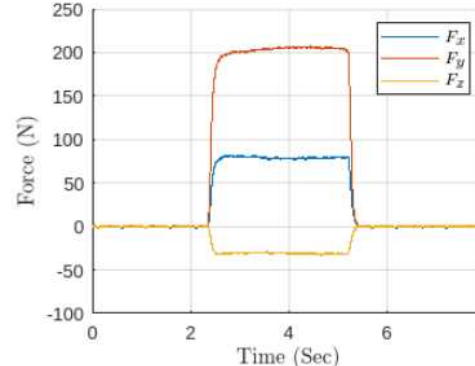
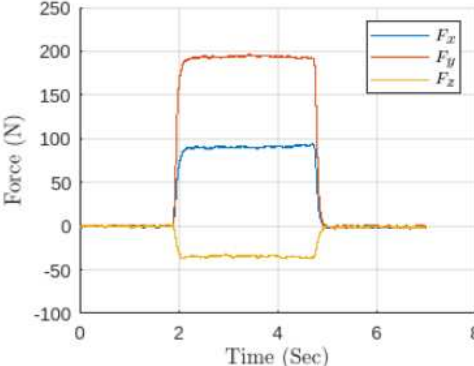
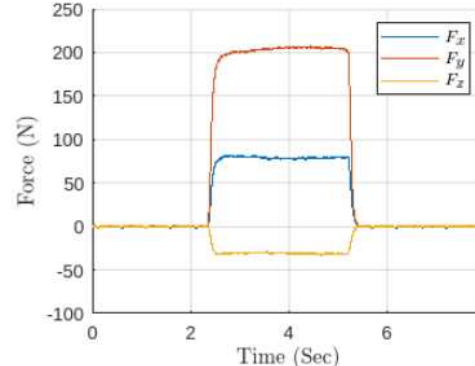
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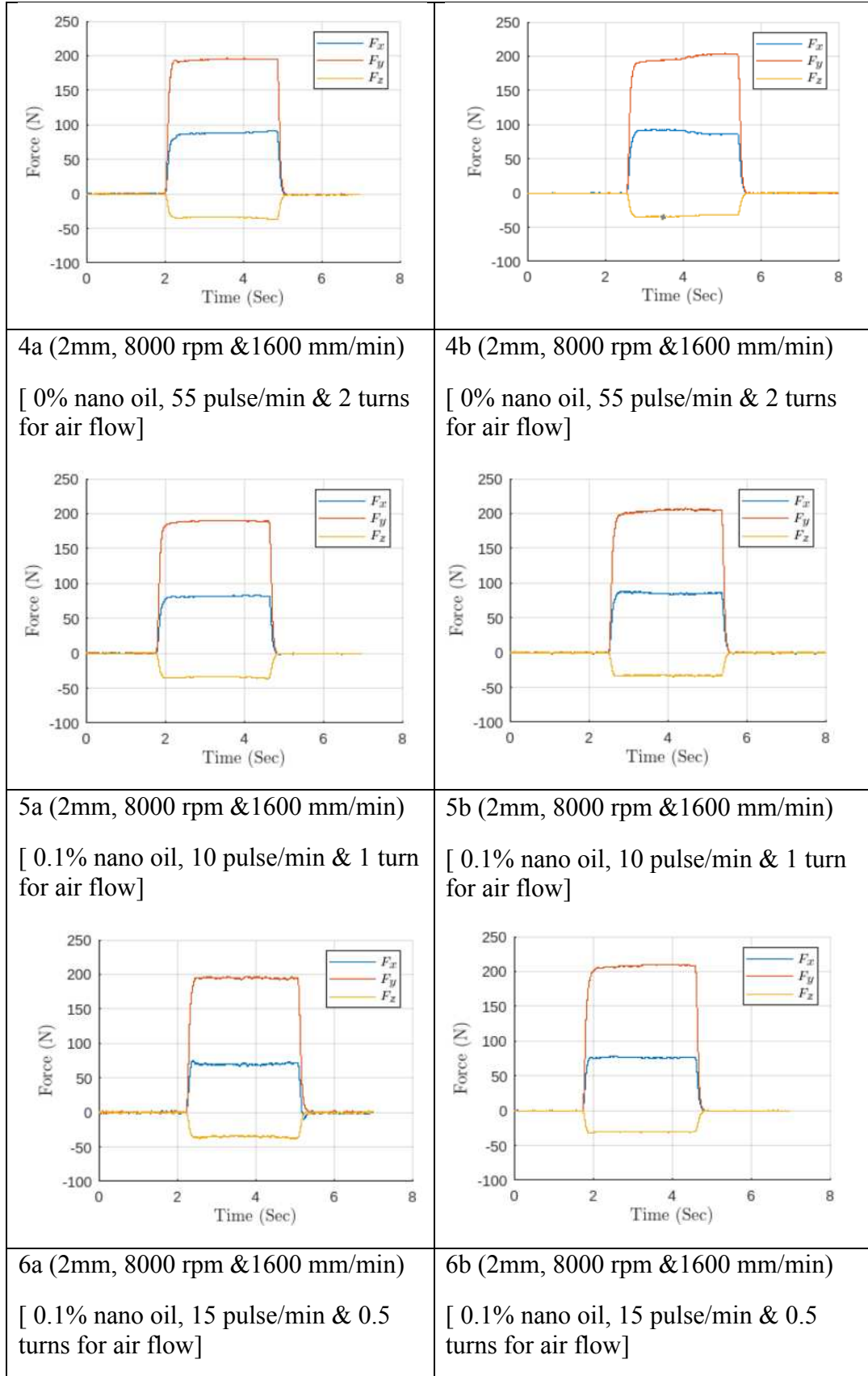
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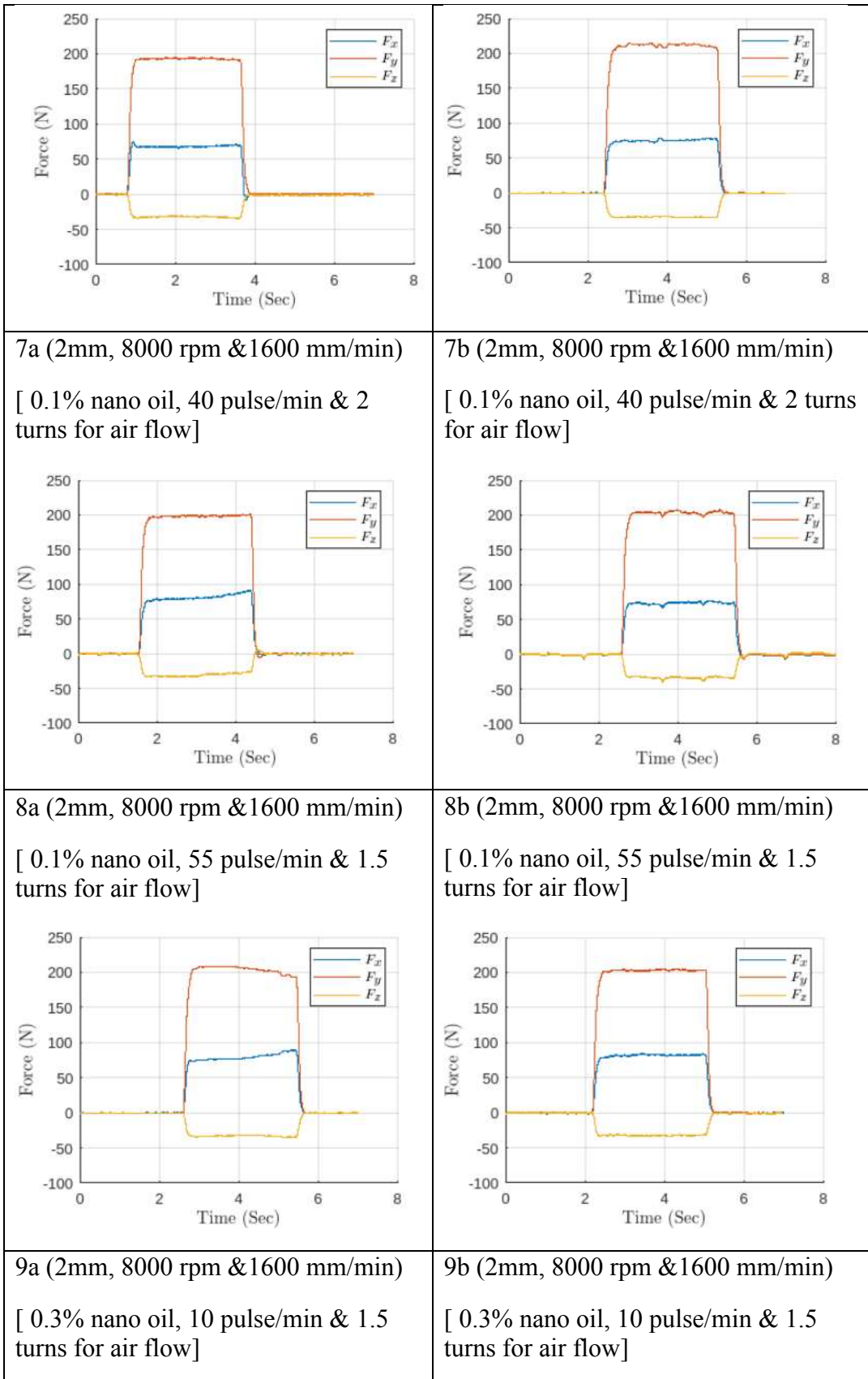
Appendix A

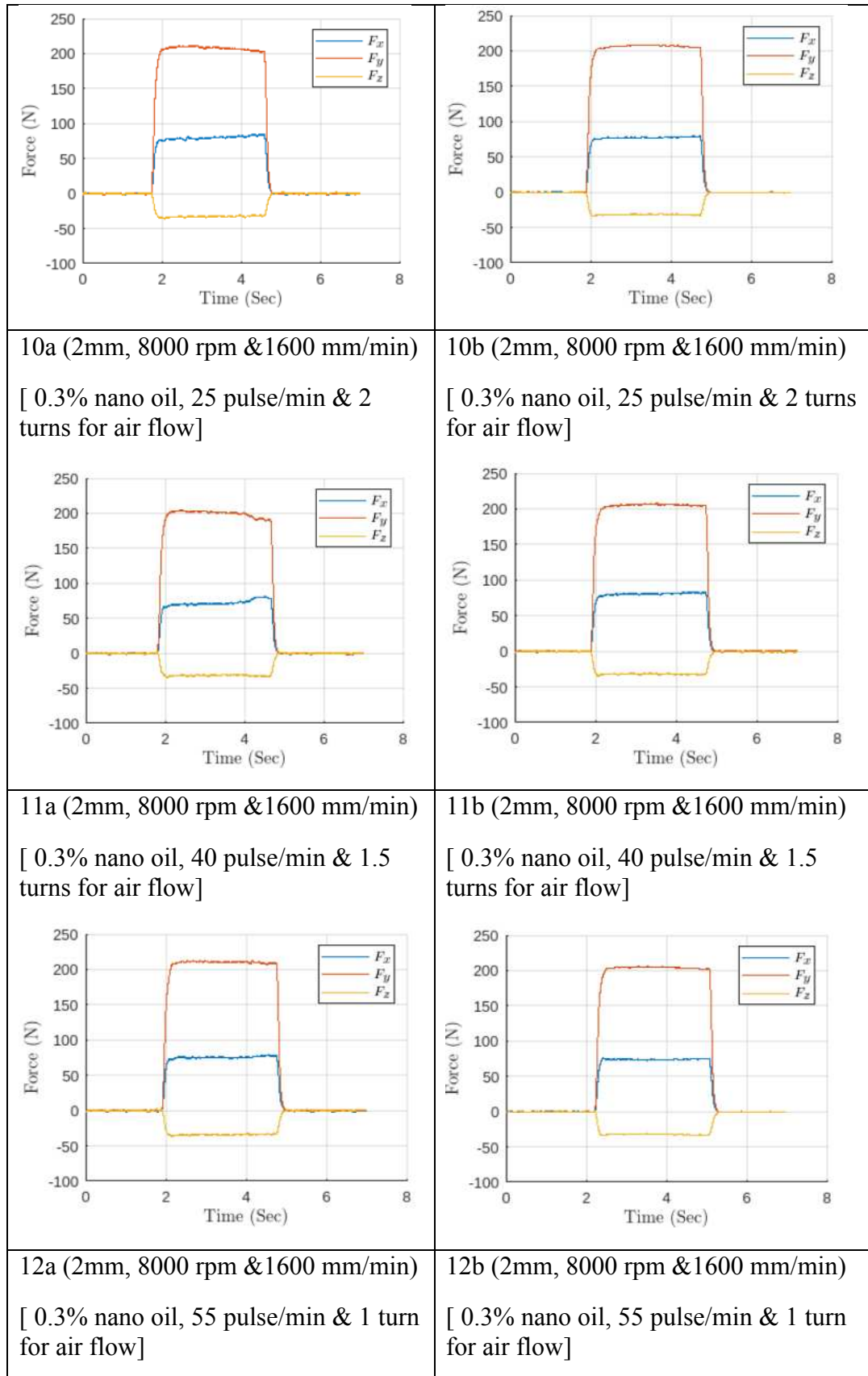
1- Cutting Force Signals of Experiment (1):

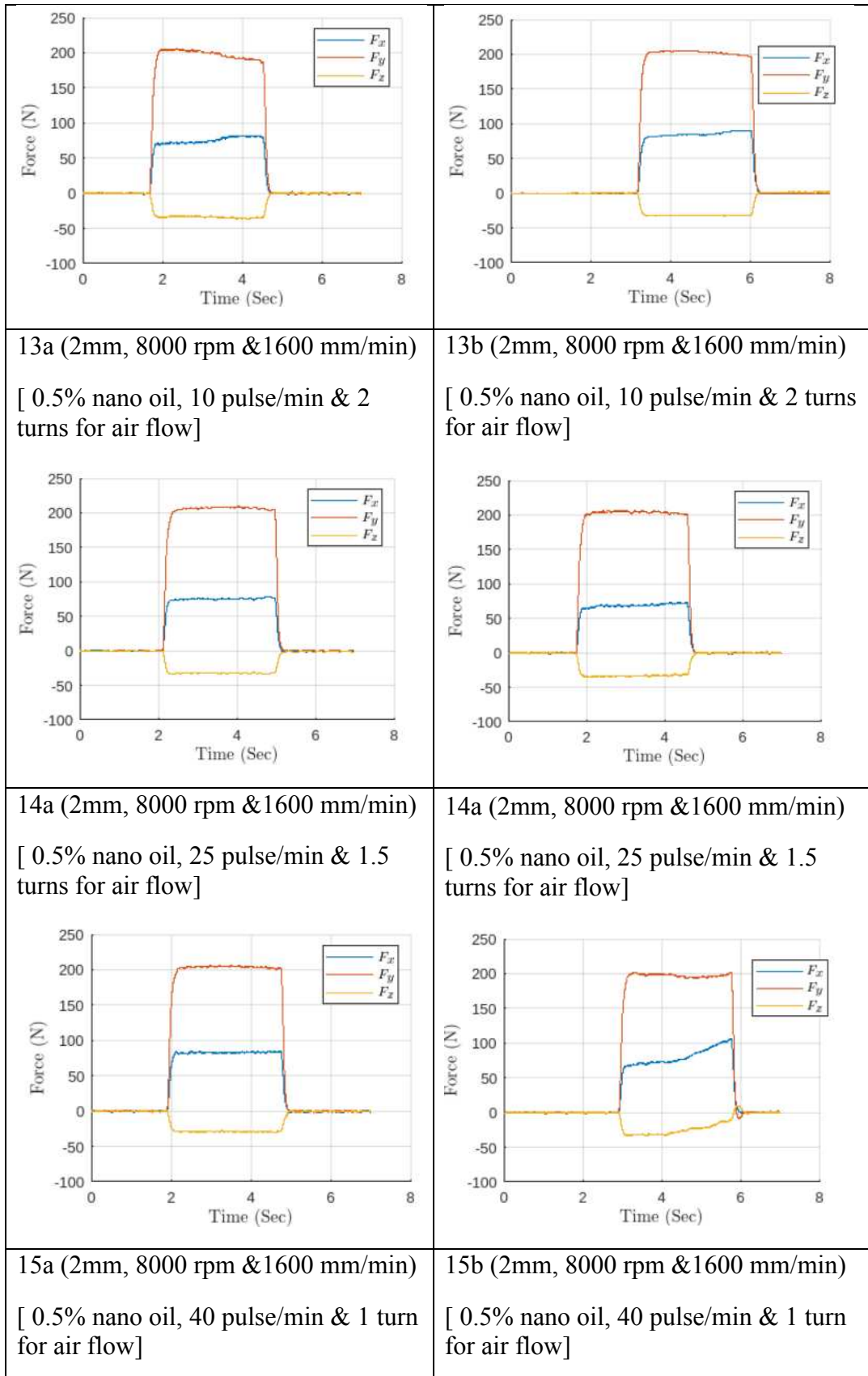
Table A.1 The mean cutting force signals for the experiment (1).

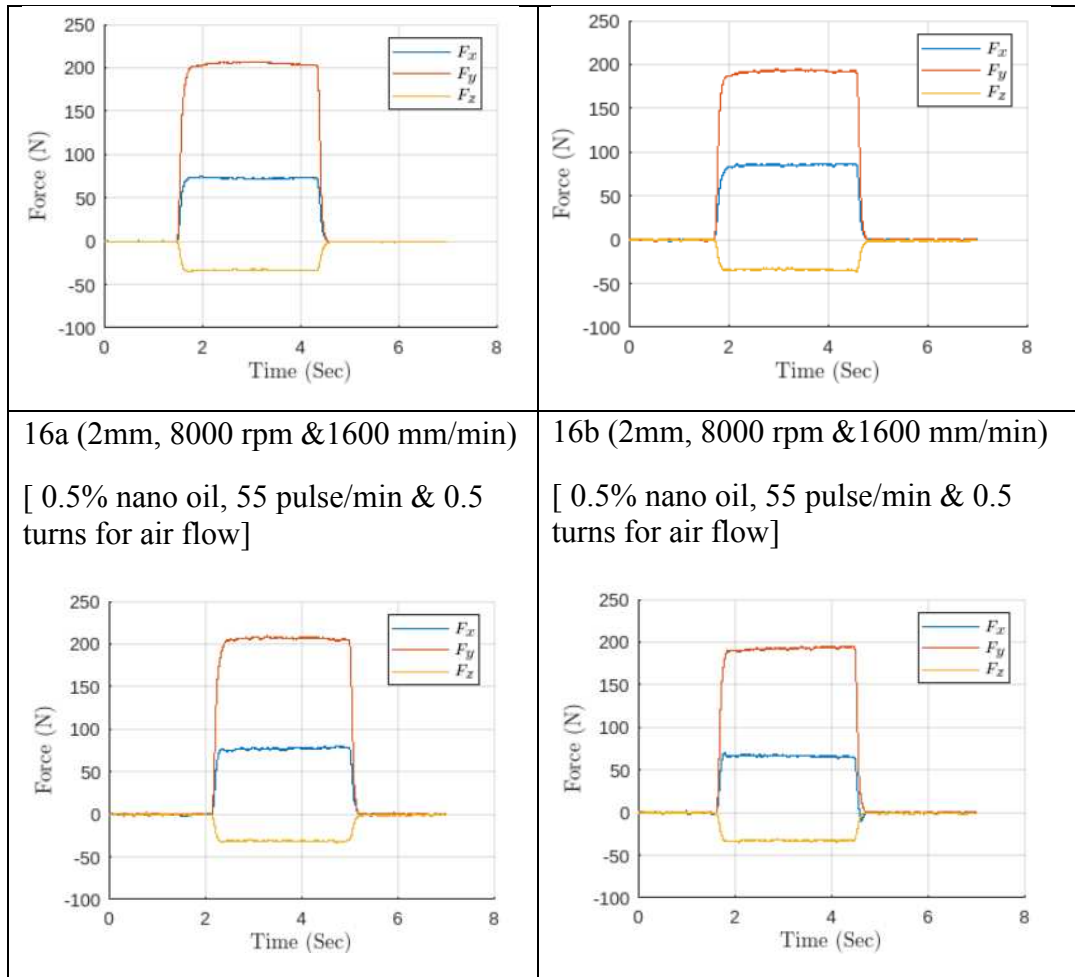
1a (2mm, 8000 rpm & 1600 mm/min) [0% nano oil, 10 pulse/min & 0.5 turns for air flow] 	1b (2mm, 8000 rpm & 1600 mm/min) [0% nano oil, 10 pulse/min & 0.5 turns for air flow] 
2a (2mm, 8000 rpm & 1600 mm/min) [0% nano oil, 25 pulse/min & 1 turn for air flow] 	2b (2mm, 8000 rpm & 1600 mm/min) [0% nano oil, 25 pulse/min & 1 turn for air flow] 
3a (2mm, 8000 rpm & 1600 mm/min) [0% nano oil, 40 pulse/min & 1.5 turns for air flow] 	3b (2mm, 8000 rpm & 1600 mm/min) [0% nano oil, 40 pulse/min & 1.5 turns for air flow] 







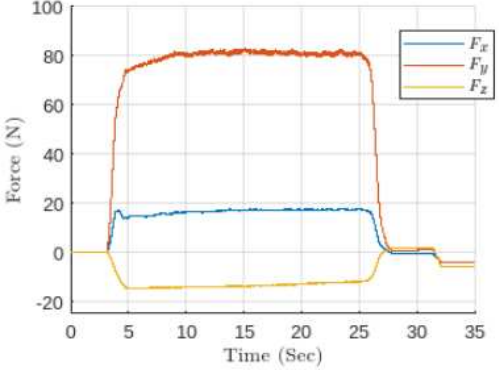
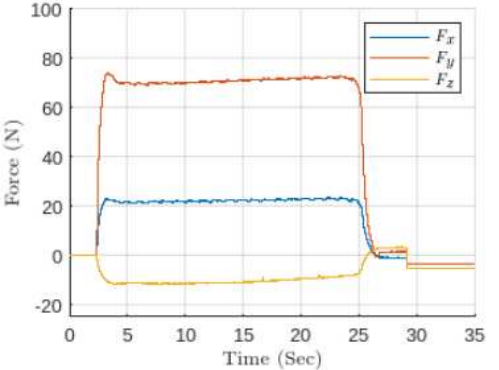
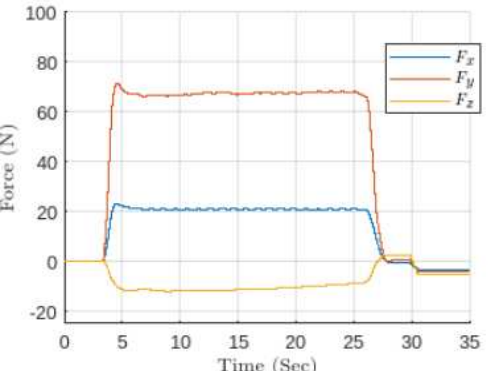
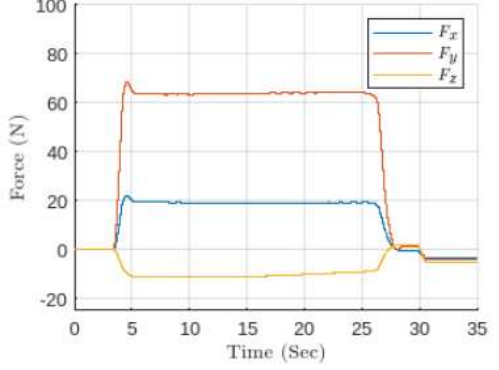


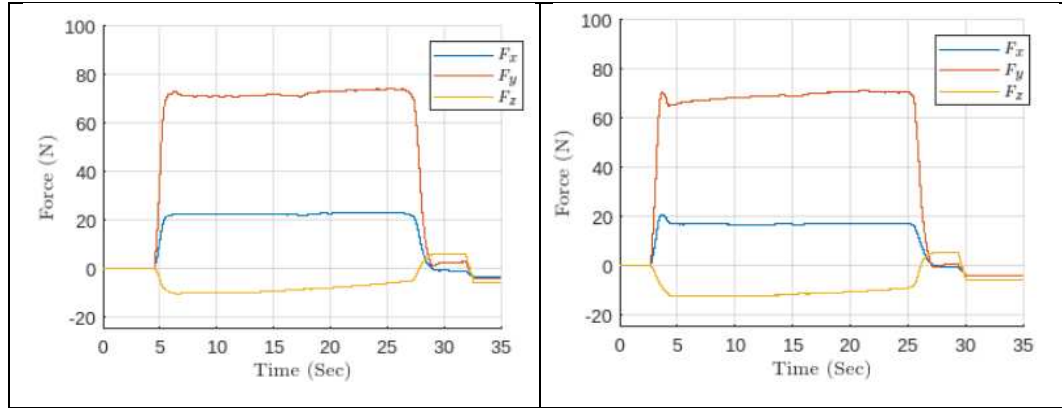


2- Cutting Force Signals of Experiment (2):

- Pre-Experiment

Table A.2 The mean cutting force signals for the pre-experiment tests.

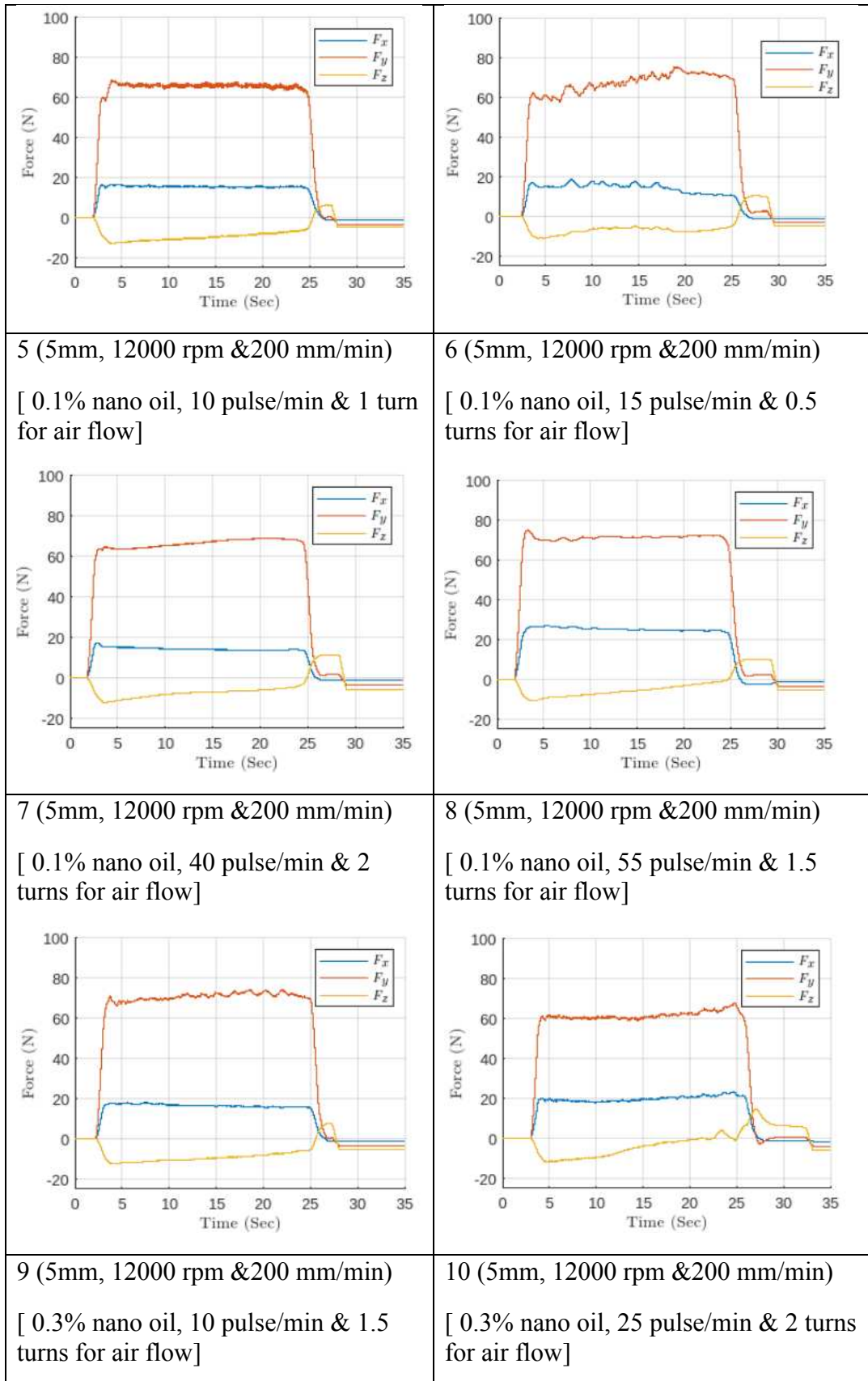
Dry (5mm, 12000 rpm & 200 mm/min) [No Oil] 	0% (5mm, 12000 rpm & 200 mm/min) [0% nano oil, 55 pulse/min & 2 turns for air flow] 
0.1% (5mm, 12000 rpm & 200 mm/min) [0.1% nano oil, 55 pulse/min & 2 turns for air flow] 	0.3% (5mm, 12000 rpm & 200 mm/min) [0.3% nano oil, 55 pulse/min & 2 turns for air flow] 
0.5% (5mm, 12000 rpm & 200 mm/min) [0.5% nano oil, 55 pulse/min & 2 turns for air flow]	0.7% (5mm, 12000 rpm & 200 mm/min) [0.7% nano oil, 55 pulse/min & 2 turns for air flow]

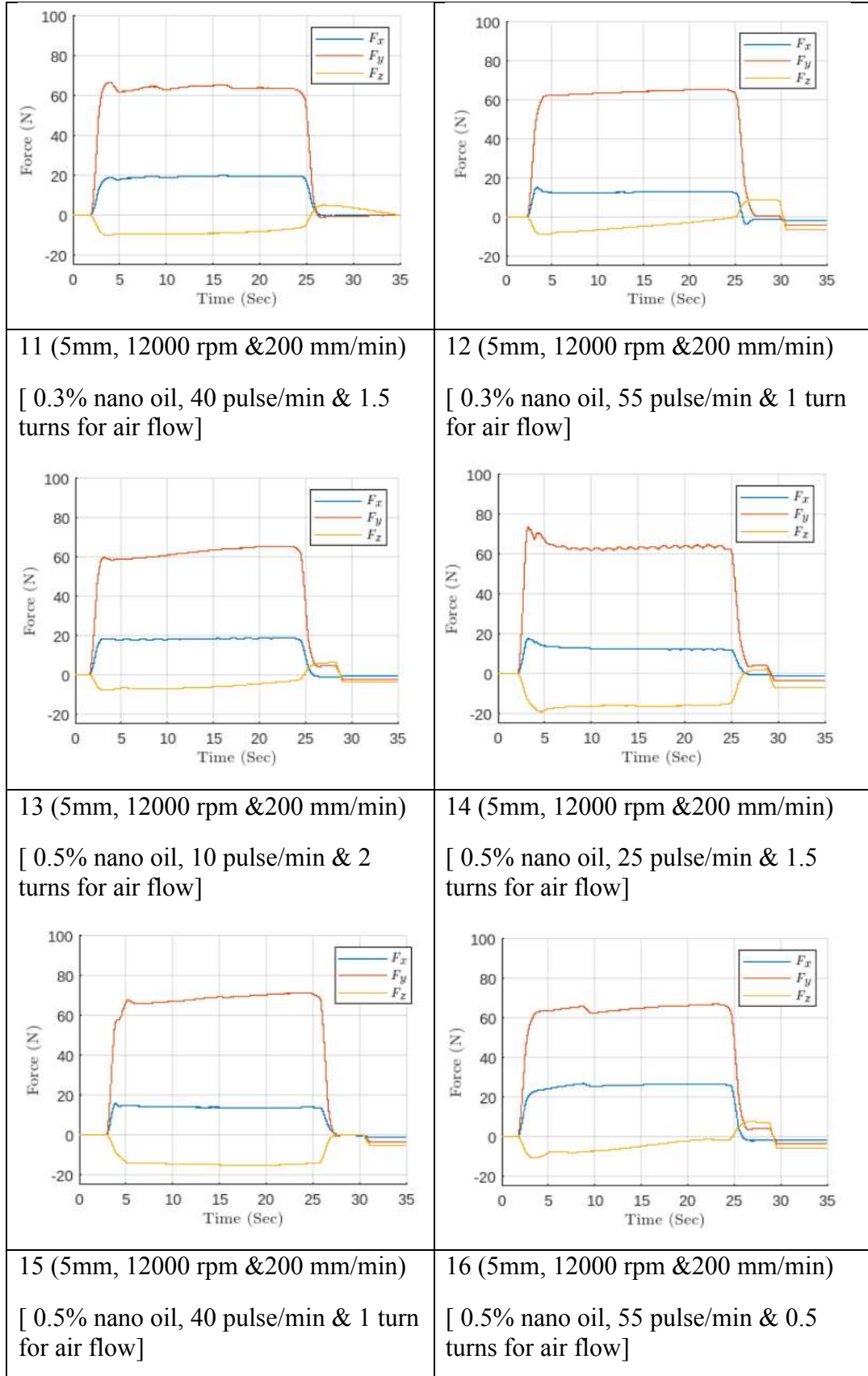


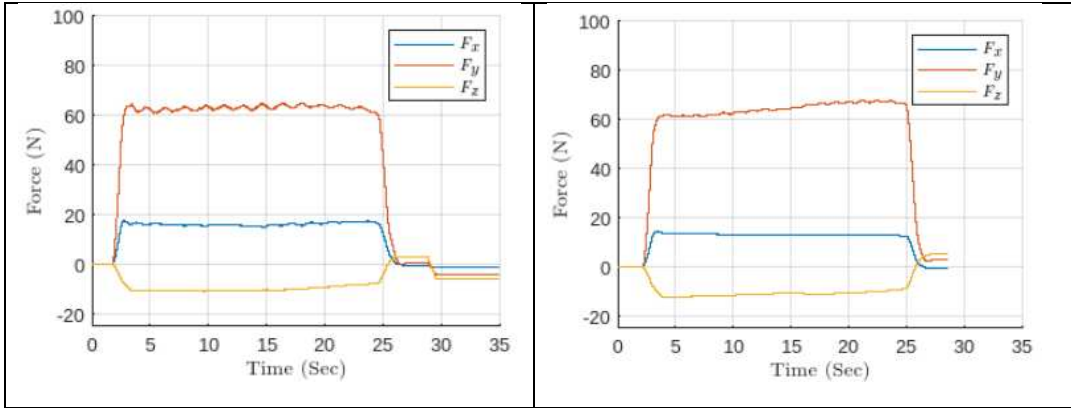
- Results of Experiment (2)

Table A.3 The Mean Cutting Force Signals for Experiment (2).

1 (5mm, 12000 rpm & 200 mm/min) [0% nano oil, 10 pulse/min & 0.5 turns for air flow]	2 (5mm, 12000 rpm & 200 mm/min) [0% nano oil, 25 pulse/min & 1 turn for air flow]
3 (5mm, 12000 rpm & 200 mm/min) [0% nano oil, 40 pulse/min & 1.5 turns for air flow]	4 (5mm, 12000 rpm & 200 mm/min) [0% nano oil, 55 pulse/min & 2 turns for air flow]



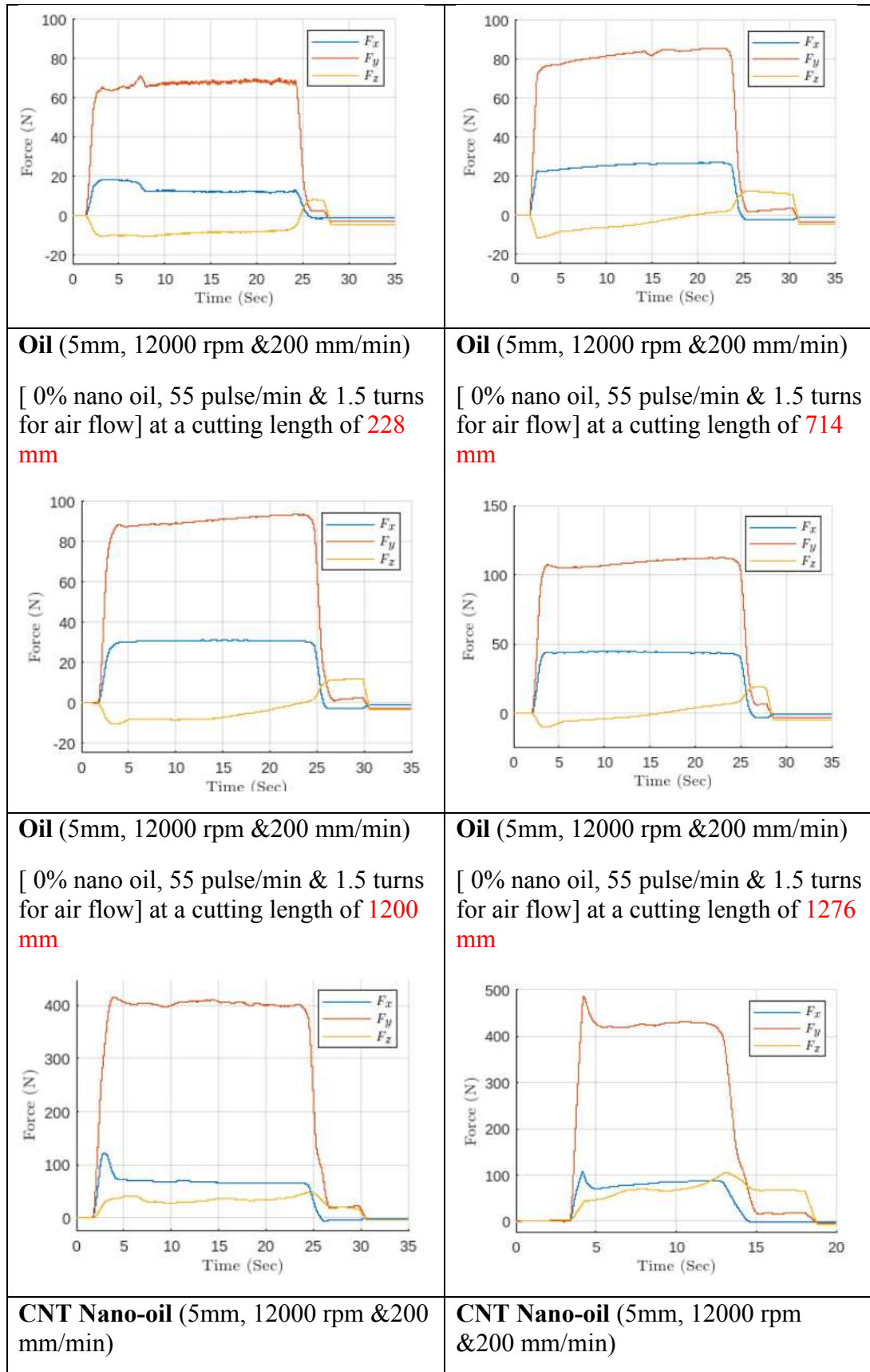


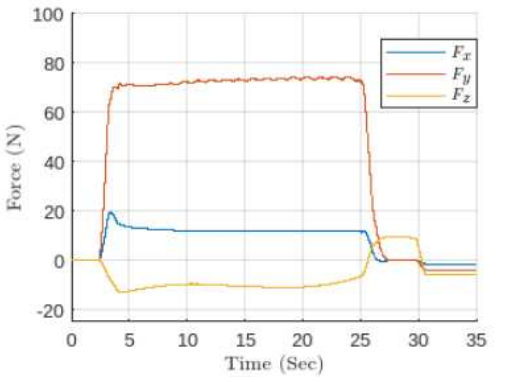
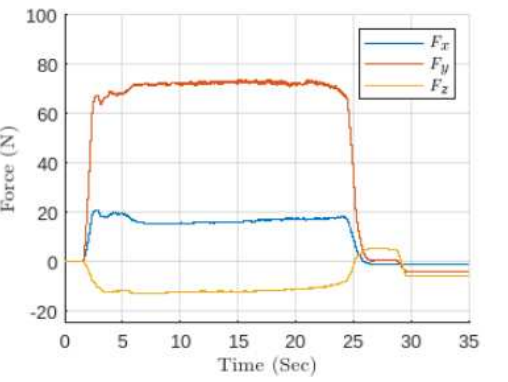
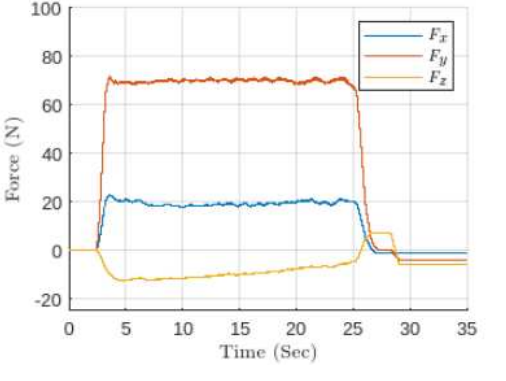
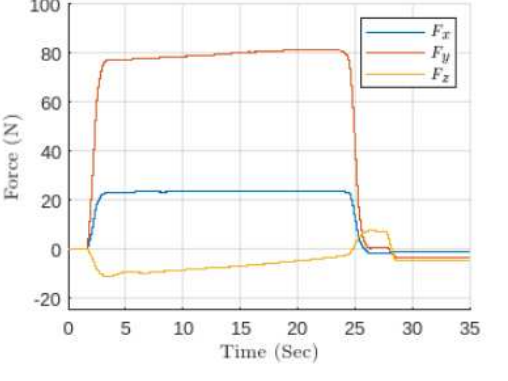


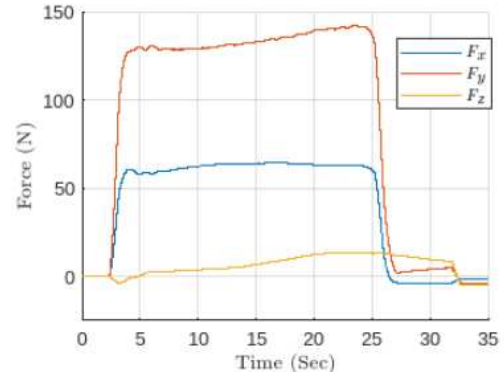
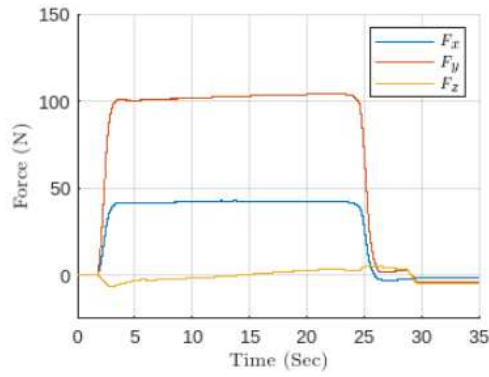
3- Cutting Force Signals of Experiment (3):

Table A.4 The mean cutting force signals for the long run test.

Dry (5mm, 12000 rpm &200 mm/min) [No Oil] at a cutting length of 76 mm	Dry (5mm, 12000 rpm &200 mm/min) [No Oil] at a cutting length of 398 mm
Oil (5mm, 12000 rpm &200 mm/min) [0% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 76 mm	Oil (5mm, 12000 rpm &200 mm/min) [0% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 152 mm



[0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 76 mm 	[0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 152 mm 
CNT Nano-oil (5mm, 12000 rpm &200 mm/min) [0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 228 mm 	CNT Nano-oil (5mm, 12000 rpm &200 mm/min) [0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 304 mm 
CNT Nano-oil (5mm, 12000 rpm &200 mm/min) [0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 790 mm	CNT Nano-oil (5mm, 12000 rpm &200 mm/min) [0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of 1276 mm

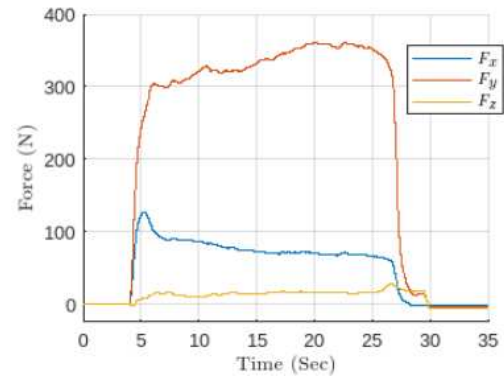
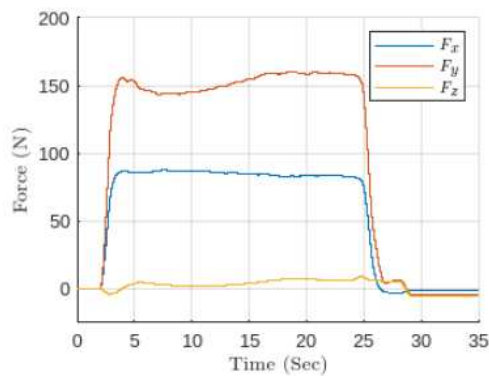


CNT Nano-oil (5mm, 12000 rpm & 200 mm/min)

[0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of **1487 mm**

CNT Nano-oil (5mm, 12000 rpm & 200 mm/min)

[0.3% nano oil, 55 pulse/min & 1.5 turns for air flow] at a cutting length of **1863 mm**



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