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AN EXPERIMENTAL INVESTIGATION ON ENHANCING THE MACHINABILITY OF DIFFICULT TO CUT MATERIALS USING ULTRASONIC ASSISTED MILLING PROCESS

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
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RAMAZAN HAKKI NAMLU

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Approval of the Graduate School of Natural and Applied Sciences, Atilim University

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ABSTRACT

AN EXPERIMENTAL INVESTIGATION ON ENHANCING THE MACHINABILITY OF DIFFICULT TO CUT MATERIALS USING ULTRASONIC ASSISTED MILLING PROCESS

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Ti-6Al-4V has unique material properties such as high strength-to-weight ratio, good corrosion resistance, and excellent fracture toughness. Therefore, it's widely used in aerospace, medical and automotive industries where machining is an essential process. However, machining of Ti-6Al-4V is highly challenging due to its wear resistance and low thermal conductivity. Ultrasonic assisted machining is quite recent a method in metal cutting applications and it has numerous advantages over conventional machining processes such as reduced cutting forces, increased surface quality and lowered tool wear. In addition, minimum quantity lubrication (MQL) is an alternative type of cooling that is being used instead of conventional cooling systems in machining because of its several improvements on process efficiency. Cutting forces are one of the most important outputs that measure cutting performance of a machining process. Another important output for machining is the surface roughness due to its direct impact on the quality of the workpart. However, there is not much work to compare the changes in cutting forces and surface roughness in ultrasonic assisted machining with the use of minimum quantity lubrication. In this study the changes in cutting forces and surface roughness during the machining of Ti-6AL-4V material were investigated by using ultrasonic assisted milling with ultrasonic vibrations applied to cutting tool on Z axis with the use of MQL. This is believed to be the first time done in literature. Experimental work conducted in the thesis showed that the ultrasonic assisted milling with MQL cooling is capable of significantly enhancing the cutting performance in terms of the cutting forces and the surface quality if the cutting conditions are properly selected.

Keywords: Ultrasonic assisted milling, Minimum Quantity Lubrication, Ti-6Al-4V, Cutting Forces, Surface Roughness

ÖZ

ULTRASONİK DESTEKLİ FREZELEME İŞLEMİ KULLANARAK KESİLMESİ ZOR MALZEMELERİN İŞLENEBİLİRLİĞİNİ ARTIRMAYA YÖNELİK DENEYSEL BİR ARAŞTIRMA

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Ti-6Al-4V, yüksek mukavemet/ağırlık oranı, iyi korozyon direnci ve mükemmel kırılma tokluğu gibi eşsiz malzeme özelliklerine sahiptir. Bu nedenle, işlemenin önemli bir süreç olduğu havacılık, tıp ve otomotiv endüstrilerinde yaygın olarak. Bununla birlikte, Ti-6Al-4V'nin işlenmesi aşınma direnci ve düşük ısı iletkenliği nedeniyle oldukça zordur. Ultrasonik destekli işleme, talaşlı imalat uygulamalarında oldukça yeni bir methoddur ve azaltılmış kesme kuvvetleri, arttırılmış yüzey kalitesi ve azaltılmış takım aşınması gibi geleneksel işleme proseslerine göre sayısız avantaja sahiptir. Ek olarak, minimum miktar yağlama (MMY) işlem verimliliğindeki birçok iyileştirme nedeniyle, geleneksel soğutma sistemlerinin yerine kullanılan alternatif bir soğutma türüdür. Kesme kuvvetleri, bir işleme prosesinin kesme performansını ölçen en önemli çıktılardan biridir. İşleme için bir başka önemli çıktı, iş parçasının kalitesi üzerindeki doğrudan etkisi nedeniyle yüzey pürüzlülüğüdür Bununla birlikte, ultrasonik destekli işlemede kesme kuvvetleri ve yüzey pürüzlülüğündeki değişiklikleri minimum miktarda yağlama kullanımı ile karşılaştırmak için çok fazla çalışma yoktur.. Bu çalışmada, Ti-6AL-4V malzemesinin işlenmesi sırasında kesme kuvvetleri ve yüzey pürüzlülüğündeki değişiklikler, MMY kullanılarak Z ekseninde kesici takıma uygulanan ultrasonik titreşimler ile ultrasonik destekli frezeleme kullanılarak araştırılmıştır. Bunun literatürde ilk kez yapıldığı düşünülmektedir. Tezde yapılan deneysel çalışma, MMY soğutmalı ultrasonik destekli frezelemenin, kesme koşulları uygun şekilde seçilirse kesme kuvvetleri ve yüzey kalitesi açısından kesme performansını önemli ölçüde artırabildiğini göstermiştir.

Anahtar Kelimeler: Ultrasonik Destekli Frezeleme, Minimum Miktar Yağlama, Ti-6Al-4V, Kesme Kuvvetleri, Yüzey Pürüzlülüğü

It was dedicated to my grandfather who passed away during my thesis. I will always be proud to bear his name.

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CHAPTER 1

1 Introduction

Materials with unique metallurgical properties such as titanium alloys, tool steels, stainless steels, hardened steels and other super-alloys have been developed to fulfıl the requirements in extreme applications. These advanced engineering materials with superior properties are indispensable in today's industrial world and extreme conditions which demand these materials can be seen in different sectors like, defense industry, medical applications, nuclear reactors and etc. These sectors are high value added high technological sectors and therefore play a very critical role in countries' economic, politic and military strategies and consequently affects their situation in world. Advancements and competition in global market force designers and manufacturer to enhance their products' properties and force the frontiers of engineering and science in development of new products. For example, in aerospace industry engineers intend to improve the dynamics of airplanes but at the same time decrease the fuel consumption. The designer has no choice but to select low density materials which have quite high mechanical properties. Aluminum is a light metal, but its mechanical properties are not sufficient to meet designers' expectations, or steel have good mechanical properties, but it is too dense and heavy material for this purpose. A material capable of satisfying these two conditions can be titanium alloys. Titanium alloys are light materials which have quite satisfying mechanical properties.

Ti-6Al-4V (UNS designation R56400) is the most common titanium alloy in aerospace industry and also is widely being used in the medical sector due to its high corrosion resistance, flexibility and biocompatibility to the human body [1]. The majority of the implants being used in orthopedics and brain surgeries are also made of this material. Titanium is a metal that is lighter and more durable than steel. Aluminum is one of the metals with the highest corrosion resistance. Since vanadium in the composition is a ductile flexible material, it is generally used in high speed steel construction and increases the impact resistance, ductility and provides a flexible structure that does not break easily. Ti-6Al-4V titanium alloy generally exists in alpha state, with HCP lattice crystal structure and beta state, with BCC crystal structure [2]. As a result, the material obtained is lightweight, high strength, resistant to thermal shocks and corrosion, and is an excellent material especially for aviation. Skeleton parts of planes, usually called rings and ribs, are made of this material [3]. Over 50% of the world's titanium products are produced out of this alloy by casting, powder metallurgy or hot forming processes [4]. The properties of the various product forms depend on the chemical composition and thermo-mechanical processing used. One of the features that distinguish Ti-6Al-4V from other titanium alloys is that it can be heat treated, so that its mechanical and physical properties can change according to the desired application conditions. Thanks to this feature, it can be used in various fields ranging from biomedical implants to the aerospace industry by adapting to the desired conditions [5]. The alloy is generally used in the annealed state which gives the best combination of strength, toughness and ductility [6].

In order to meet the demand for high consumption in today's world, the industry supports mass production as well as fast and easy production to meet these needs. Metal cutting operations are essential processes for mass production. With metal cutting operations, the desired shapes can be given to the material under certain conditions. Machining processes started to be used as a manufacturing operations since the 17^{th} century and so many researches and studies have been conducted regarding different machining operations. Over the years, automated machining systems have focused on faster and less defective manufacturing. Like other manufacturing processes, machining also has its disadvantages and shortcomings. Due to changes in materials morphological structures they will have quite different mechanical properties. In machining operations cutting tool which has a better mechanical properties than workpiece material, removes excess material from workpiece. As there is a direct contact between cutting tool and workpiece friction occurs between these two materials and this increases the temperature in contact area. Severe increase in temperature during the operation, increases the wear of the cutting tool, decrease cutting tool life and decreases the surface quality of workpiece. The high power requirement due to the high cutting forces is also one of these problems. Nowadays researchers are working on these issues to improve the cutting conditions and eliminate such problems. Detail explanations are given in Chapter 2.

Ti-6Al-4V alloy has very low machinability and is classified as difficult-to-cut material. The low machinability of this alloy does not result from being a hard material in fact the main reason for this is its low thermal conductivity [7]. Due to its low thermal conductivity, the temperature that occurs between the workpiece and the cutting tool in cutting zone during machining retains at this area and is not scattered on and most of generated heat concentrates on cutting edge of cutting tool. Under normal circumstances, the high percentage of heat should not be deposited in the cutting tool, but should be disposed of with chips [8]. Most cutting tool materials begin to lose strength due to this increased temperature, and as a result, the edge of the cutting tool wears out very quickly. This causes the poor surface quality of the workpiece due to the worn cutting tools and causes high cutting forces. Under traditional machining circumstances it is very difficult to overcome this problem.

Hybrid and non-traditional machining methods are rather new methods developed for eliminating mentioned obstacles. While non-traditional machining methods operate with processes that are almost completely different from the traditional machining methods, hybrid machining methods are emerged by integrating the possibilities of today's technologies to traditional machining methods. Laser-assisted machining, cryogenic-assisted machining and ultrasonic-assisted machining are some of them. The method we focus on in our study is a type of hybrid machining which is ultrasonic assisted machining. Ultrasonic assisted machining method applied to the cutting tool by giving high frequency (17-40 KHz) and low amplitude (5-20 µm) vibrations [9]. The intermittent contact between the cutting tool and workpiece increases the cutting performance efficiency [10]. In addition, coolant systems come into play to reduce the heat accumulated on the cutting tool and not on the chips that make the machining of Ti-6Al-4V material difficult [1]. One of the most important properties of coolants - or cutting fluids - is to eliminate temprature concentration and remove heat from the environment and traditionally used methods in the industry are either unable to cut Ti-6Al-4V or the process costs are too much due to excessive consumption of coolants [11]. In addition, due to their chemical content, they endanger the environment and the health of the user [12]. In order to eliminate these risks and facilitate the machining of materials such as Ti-6A-4V, a relatively new method, Minimum Quantity Lubrication (MQL) technique, has been introduced. The amount of coolant used with MQL technique decreases, the efficiency of the operation increases, and the harmful effects to the environment and the user are minimized [13].

Machining operations are divided to; turning, milling, drilling and grinding operations. Among these operations, Studying milling operations is rather difficult due to the complex nature of different relational movements. Therefore, there are less studies and researches conducted regarding milling comparing to other cutting operations.

In this research, ultrasonic assisted machining, which is one of the recent hybrid machining methods, and MQL technique are used together to improve the machining performance of Ti-6A-4V alloy.

In ultrasonic assisted milling, it is aimed to increase the efficiency of the operation by giving vibrations at ultrasonic level to the cutting tool or workpiece. In this context, it is aimed to achieve this aim by giving vibrations in the Z axis which is the spindle axis. In addition, MQL technique is aimed to increase the operational efficiency by spraying aerosol with the help of an external nozzle.

The main purpose of using the ultrasonic system is to eliminate the problem of low thermal conductivity and high wear resistance of Ti-6Al-4V by preventing the continuous contact of the tool with the workpiece by vibrations occurring in the Z axis and to prevent heat accumulation on the cutting tool. The use of the MQL system also eliminates the build-up of heat on the cutting tool using aerosol spraying and the instant evaporation of the chemical lubricant contained therein. Thus, due to the reduction of wear of the cutting tool, improvement in surface roughness and reduction in cutting forces are expected.

CHAPTER 2

2 Literature Review

2.1 Manufacturing Operations

A manufacturing process is a designed procedure that results in physical and/or chemical changes to a starting work material with the intention of increasing the value of that material. Manufacturing operations can be divided into two main categories: (1) processing operations and (2) assembly operations. A processing operation changes a workpiece from one state of completion to a more advanced state that is closer to the net desired product. It adds value by changing the geometry, properties, or appearance of the starting material. In general, processing operations are performed on discrete workparts, but some processing operations are also usable to assembled items. An assembly operation joins two or more components to create a new piece, called an assembly, subassembly, or some other term that refers to the joining process. A classification of manufacturing processes is shown in Figure 2.1 [14].

2.2 Machining

2.2.1 Introduction to machining operations

Machining is a subtractive manufacturing process in which materials are cut to form their final shape and size by a controlled material removal process. Machining process is realized by implementing sufficient energy enough to separate excess material from workpiece and a controlled relational movement between cutting tool and workpiece which are provided by a power driven machine tool. Based on nature of cutting process, movement control mechanism and also the type of energy which is used for removing material from workpiece machining operations could be divided into several sub categories like, turning, drilling, milling and etc. As machining is a net shape process, most metal components and parts require some form of machining during the manufacturing process. Other materials, such as plastics, rubbers, and paper goods, are also commonly fabricated through machining processes. In the machining process, the excesses are removed in the form of chips using the appropriate tooling and cutting tool to bring the workpiece to the desired geometry, dimensions and surface quality.

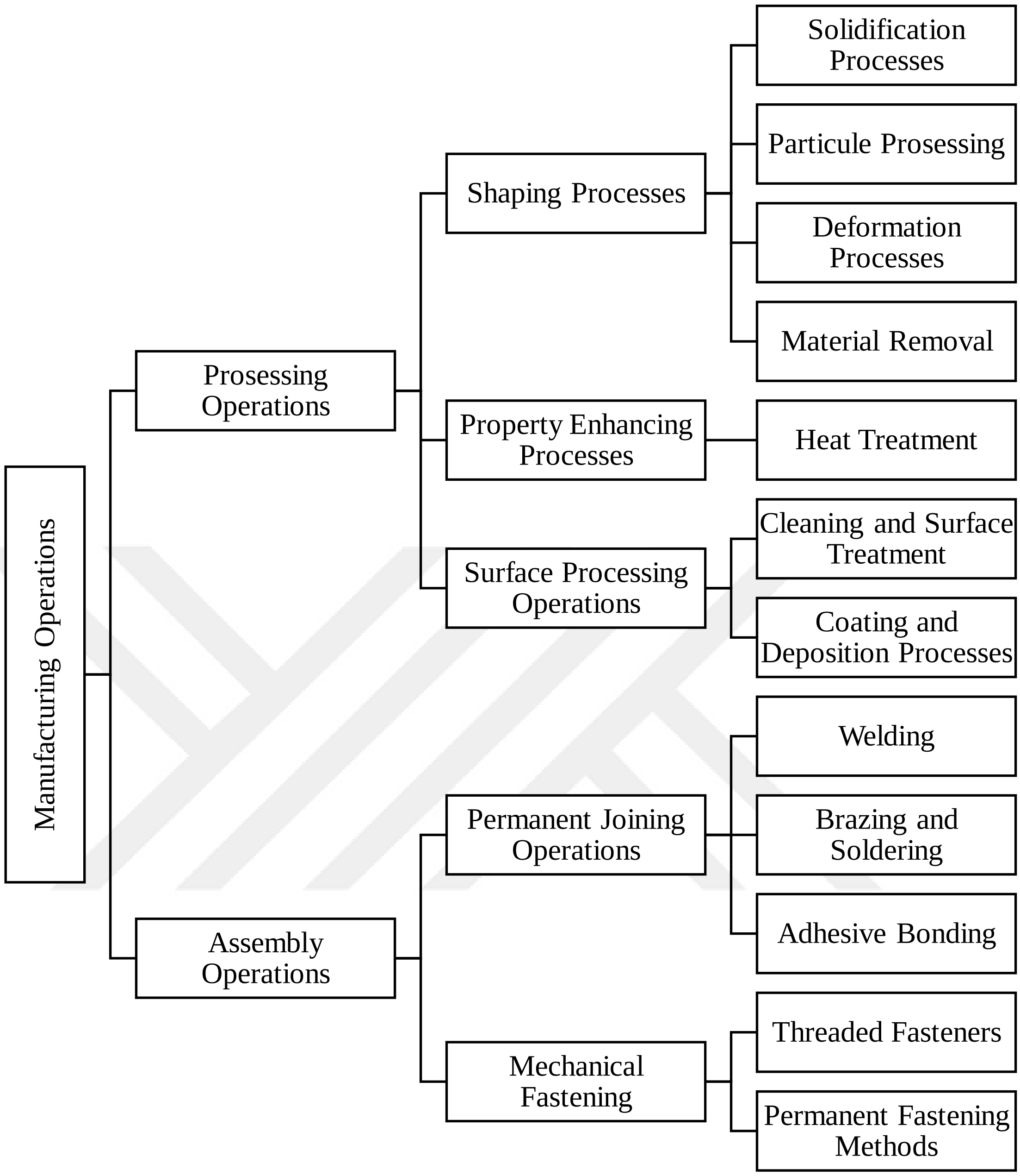

Figure 2.1 Classification of manufacturing processes [14]

Table 2.1 Types of machining processes

Traditional Machining Processes
• Turning Operations • Milling Operations • Drilling Operations • Miscellaneous Machining Operations
Abrasive Machining Processes
• Grinding • Honing • Lapping • Polishing • Other Abrasive Machining Operations
Non-Traditional Machining Processes
• Mechanical Processes • Chemical Processes • Electro-Chemical Processes • Thermoelectric Processes

Machining is a material removal process. The main thing is to remove the chip from the workpiece with the cutting tool. In traditional machining processes, there are two main movements. These movements are effected on the part of the cutting tool, the first movement is the cutting speed and the second movement is the feed. Some factor effect the machining processes directly, for example; cutting tool need to be precise because it effects directly the surface of the workpiece material which is very important factor for the operation's quality, also the processing technique, like movement of the tool/workpiece or manual/automatic control, is very important due to its effect on duration and complexity of the process, depth of cut is another important aspect for the machining quality and it is crucial for the needed desired dimensions of the workpiece and also effect the process rough cutting or finish cutting. The process generally consists of penetrating the surface of the workpiece of the cutting tool at a predetermined depth and removing the progressive chip on the surface. A new surface emerges from under the chip which is lifted from the surface due to this process. The following Figure 2.2 shows the basic chip removal of the machining process [15].

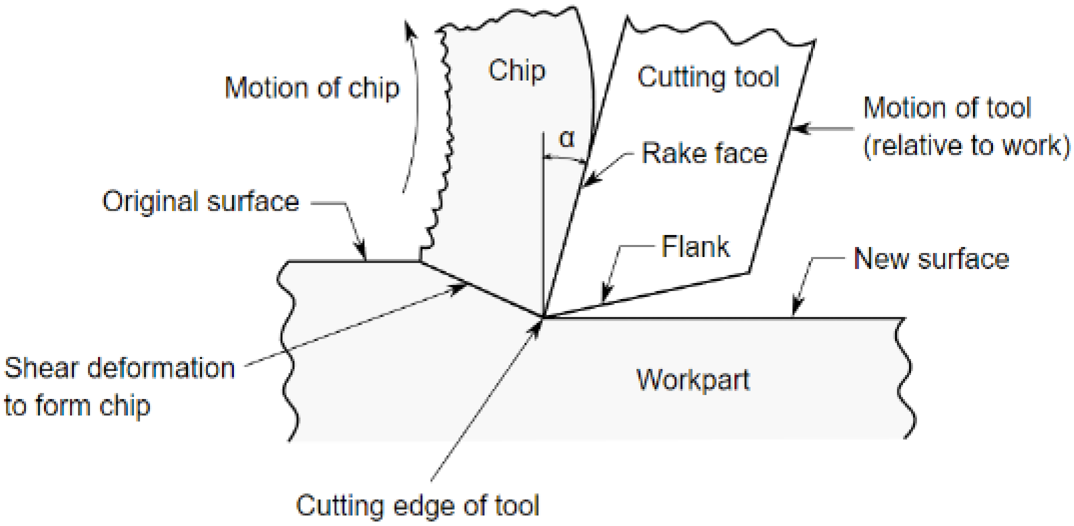

Figure 2.2 Chip removal of the machining process [15]

2.2.2 Advantages of machining operations

Machining operations are net shape forming processes, therefore most of the parts are required to be machined after passing from other manufacturing processes. One of the biggest advantages of machining is the variety of parts that can be machined. Many materials, from steel to composite materials, can be processed in machining conditions [16, 17].

Machining can be used on regular surfaces such as flat surfaces, circular holes and cylinders. Irregular geometries can be created with various tool shapes and paths. Sequential application of different chip removal processes can achieve unlimited complexity and variety of shapes. However some operations are special for some purposes such as turning operations are suitable for the cylindrical parts but milling operations are good for flat surfaces. For an efficient operation, part geometry is very crucial and the suitable process must selected for specific geometry.

Surface roughness in machining operations is another important output. Processing up to 0.4 micron sensitivity can be achieved. This level of precision machining can be carried out by micro-machining, a sub-branch of machining that performs micron-level machining. In engineering processes, it is not possible to obtain a hundred percent desired dimension of a part drawn with technical drawings. The machining process must have a certain tolerance range. Tolerance ranges are standardized for common use all over the world. The most commonly used tolerance standards are ISO and DIN standards. Thanks to these standards, parts manufactured anywhere in the world will always be produced with the same precision [18]. In the case of machining outside the tolerance range, the result is not considered successful and requires a second process. For example, parts that cannot be given the desired tolerance range in the turning process can then be brought to the desired tolerance level by grinding. The rate of residence within the limits of tolerance in machining is very high. Certain workpieces that require high precision can be produced within the desired tolerances in the machining methods [19].

2.2.3 Disadvantages of machining operations

There are some disadvantages in machining as in almost every process. According to the technique of chip removal apply material waste. Chip is the waste material that is the result of chip removal process. However, the chips are often recovered. Machining methods require longer times than other manufacturing techniques such as casting and forging. The removal of the chips requires a lot of labor and energy, which means that the number of necessary staff is also high and these come back to us as cost. The complex shapes are difficult to manufacture. Most machining operations use coolant and most coolants are harmful to human and environmental health. In addition, due to the fact that the internal structure of the material cannot be homogenous in parts produced by machining, it has weaker strength than the parts produced in manufacturing methods such as casting or forming [20].

2.2.4 Traditional Machining Operations

Traditional machining processes started roughly at the 18th century [14]. Wood was the main machining material at that period. The foundations of modern machining have been laid in Europe and America since the early 19th century. Mechanization with the industrial revolution has accelerated the developments in this area. After the industrial revolution started with the discovery of the steam engine, the development of manufacturing methods gained momentum. The machines required to perform the machining operations had to be extremely precise and stable, but with the technology of the 18th century, these features were difficult to achieve. The industrial revolution provided the necessary progress at this point and, as in the whole industry, supported development in machining. More precisely manufactured parts both supported the development of the machines to be used in machining and increased the productivity of the manufactured parts in general [21]. In late 19^{th} and early 20^{th} machine tools became more standardized and cutting tools started to evolve much faster [22].

Traditional machining uses tools for example lathes, milling machines, boring machines, drilling machines etc. with a tool to remove material from the workpiece to achieve the desired geometry. There is a direct contact between the tool and workpiece material. In the traditional machining methods, it is based on the principle of shaping the workpiece with the plastic deformation with the cutting tool. Cutting tool generally harder than the workpiece and it must be withstanding the heat generation during the process [14].

2.2.4.1 Types of Traditional Machining Processes

There are many different methods in machining. These methods are selected depending on variables such as the geometric properties of the workpiece to be created. In the basic sense, the three most commonly used machining processes are turning, milling and drilling.

2.2.4.1.1 Turning

Turning contains rotation of the workpiece while the cutting tool moves in a linear motion as shown in Figure 2.3. This gives as a cylindrical shape. The speed motion in turning is provided by the rotating work-part, and the feed motion is achieved by the cutting tool moving slowly in a direction parallel to the axis of rotation of the workpiece [14]. Machine of choice for all turning operations is the lathe. It has three main parts of a headstock, tailstock and a tool post. Headstock is used to hold the workpiece and it can be rotated at different speeds. Tailstock is used to hold the workpiece to align with the center of chuck if the workpiece is too long. It is also used to hold attachments for various operations. Tool post is present at the between the middle of headstock and tailstock and can slide on X and Y axis. The tool required to perform required operation is fixed in tool post. Main components and other parts can be seen in Figure 2.4 [23].

Like most machining operations, turning can be done manually or automatically. Manual lathe is shown in Figure 2.4. The manual turning needs to be controlled continuously however automatic turning does not. With Computer Numerical Control (CNC), all the movements, speeds, and tooling changes are adjusted by a program. These commands then get sent to the lathe and run by controller of machine. CNC allows for reliability and efficiency of high production runs. CNC lathe can be seen in Figure 2.5 [24].

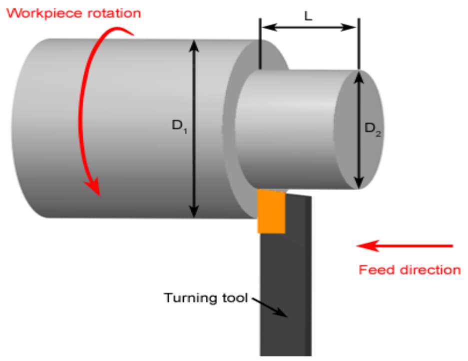

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Figure 2.3 Turning process

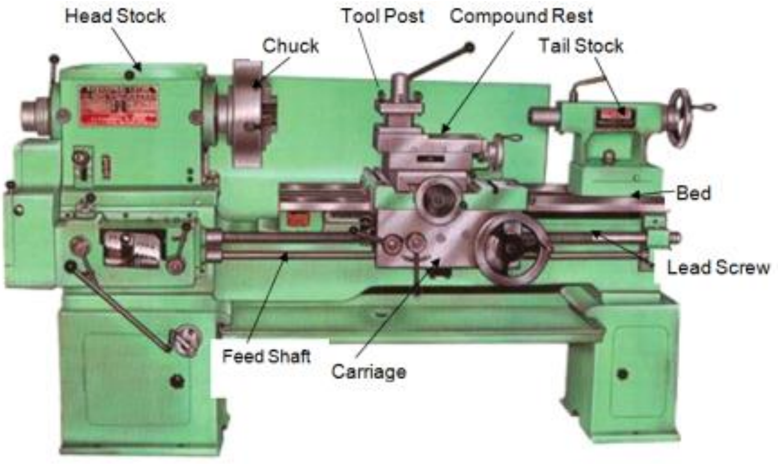


Figure 2.4 Manual lathe machine [23]

Figure 2.5 CNC Lathe Machine [24]

2.2.4.1.2 Drilling

Drilling creates a round hole in a workpiece. Chips are the bits of waste metal produced when machining a workpiece. The shape of the drill bit helps chips fall away from the workpiece, keeping the workpiece free of wreckage. Its mechanism can be seen in Figure 2.6.

Placing the drill perpendicular to the workpiece reduces drifting. For better precision, a center drill operation is frequently added before drilling. Some drilling operations need angular drilling. Angular drilling needs special work-holding tooling. Other options include: rotation of the head on a manual machine or use of multiple axis’ on a CNC machine [25]. Drilling machine can be seen in Figure 2.7 [26].

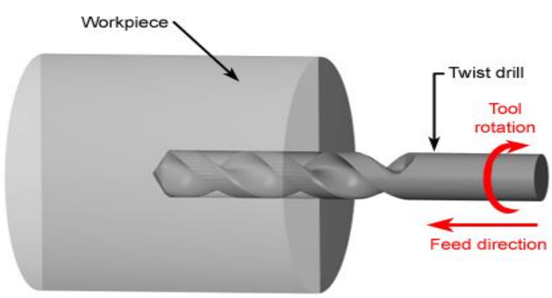


Figure 2.6 Drilling Process

Figure 2.7 Drilling Machine [26]

2.2.4.1.3 Milling

In milling process in order to realizing the cutting process, a rotating cutting tool is feed into workpiece. The tool may contain a single or multiple cutting edges. The machines that are used for milling are called milling machines.

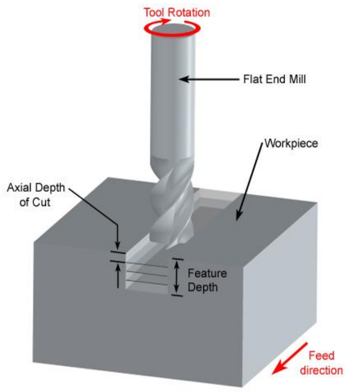


Figure 2.8 Milling Process

Milling is one of the most common form of machining, a material removal process, which can create a variety of features on a part by cutting away the undesirable material. The milling process requires a milling machine, work-piece, fixture, and cutter. The work-piece is a piece of pre-shaped material that is secured to the fixture, which itself is attached to a platform inside the milling machine. The cutter is a cutting tool with sharp teeth that is also secured in the milling machine and rotates at high speeds. By feeding the work-piece into the rotating cutter, material is cut away from this work-piece in the form of small chips to create the desired shape [27]. A more detailed review of the milling is available in the following sections.

Since these processes have been used for centuries, it has given many advantages to the traditional machining processes. Years of experience in the industry have resulted in continuous development and transfer. In this way, solutions to many problems that may be encountered were obtained through experience. In addition, thanks to the constantly developing technology, the process of transition from manual machines to automation has been made more efficiently with the experiences gained from the past. It is aimed to eliminate the problems in manual use during the transition to automation and innovations have been made in this direction. For example, in manual milling, the speed and feed rate of the cutting tool can be set by the manually but in the CNC milling centers it adjusts automatically.

Some common limitations and weaknesses of traditional machining processes include:

1. Tool wear is unavoidable.
2. The prediction of tool wear is very difficult.
3. The tooling material must be of a harder and higher quality than the workpiece material. It the situation limits the variety of work materials.
4. High shear forces are required for high strength materials. It creates significant constraints and technological problems in the design of the machining centers.
5. Processing speed is inversely proportional to material strength. Processing of super-alloys, such as Ti-6Al-4V, Inconel 718 which they meet the needs of today's industry, has been difficult and costly because of that.
6. Heat in the cutting zone affects and limits the processing speed.
7. Chip lifting can only be linear and circular.

8. Team vibration creates problem.
9. Cutting tools can't be produced in small sizes. This limits the working dimensions [27].

With the new developments in material technology, new materials have been put into use. Examples of such materials include composites, polymers and super-alloys. These materials have different mechanical properties than previously used steels and alloys. Examples of these different properties include good strength to weight ratio, high resistance to wear and high corrosion resistance. However, some disadvantages arise that are difficult to overcome, such as poor process stability and cutting tool wear during machining. The knowledge and experience of traditional machining methods from the past is unfortunately not sufficient for the processing of these materials. Because for these reasons, traditional machining processes have begun to give its place to non-traditional and hybrid machining processes.

2.2.5 Non-Traditional and Hybrid Machining Processes

Hybrid manufacturing methods have historically emerged after World War II [21]. Progressive industrial activities and differentiated human needs such as faster transportation, more comfortable life have inevitably made this development. With the help of the developing technology, new processes have been produced and presented to the use of the industry.

There are so many limitations of traditional machining for example tool wear, difficult to machining complex surfaces efficiently, insufficient surface finish after operations etc. Traditional machining processes are limited due to hardness of workpiece. For machining of hard surface with conventional machining, we need a harder tool material than the workpiece which is most of the time not economical or unavailable. These limitations of traditional machining can be tide over by non-traditional and hybrid machining process.

With rapid increasing in recent years we have now number of 70-80 hybrid manufacturing methods. But just 50-55 of them now are used in industry, the others are still developing in laboratory conditions or using for very special purposes [28].

Unlike traditional processes, these methods are using various types of energy without applying mechanical force, physical contact and relative motion. Generally, low intensity energy is used by focusing on a narrow area and an appropriate tool or focus assembly is used to perform the machining event [29].

There are three main issues that lead to the development of hybrid manufacturing methods

1. Extraordinary materials were produced as a result of improvements in metallurgical engineering and materials science. The materials cannot be processed by traditional methods because they are very high-resistant. Also, since these materials are very expensive, the workpiece dimensions have to be reduced. This situation has brought problems that cannot be solved with conventional manufacturing methods.
2. With the invention of transistors a new series of products such as integrated circuits have been introduced with this new development, the computer power required to control a machine has been reduced to very small dimensions. In addition, thanks to this technological advancement, many parameters such as repeatability and standardization, which previously could not be controlled automatically, became controllable. Thus, many disadvantages of conventional machining methods have been eliminated [30].

The fact that newly developed materials can be used more efficiently in smaller sizes has provided design engineers with ease of use. In this way, the use of these new materials in new designs has increased interest in those materials. This paved the way for future innovations for the machining of these materials. In this way, the spread and development of non-traditional machining processes, which are emerging new methods, have accelerated [31].

The main target with hybrid manufacturing methods; to produce products with increased accuracy and flexibility with improved processing and applicability methods. Hybrid methods are used in cases where traditional machining methods are insufficient in some subjects. Weaknesses of traditional methods are difficulties in processing and bonding of very hard and brittle materials, inefficiency and cost burden caused by tool wear, limiting the direction of chip removal by only circular and linear tools, requiring high cutting forces for high strength materials and this has a negative effect on precision, problems due to the very thin and flexible structure of the material and machining of the complex part geometry.

Hybrid manufacturing methods have advantages over certain materials and geometries compared to the method involved. It provides the processing of materials with high strength and hardness, easier production of geometries which are difficult to produce due to the constraints caused by tool movement in machining and enables the machining of workpieces that go down to small dimensions, it is suitable for production with thin sheets, it allows for drilling, grooving in µm dimensions. [32]. Hybrid Machining Processes are often categorized by the type of energy they are using for machining the workpiece

2.2.5.1 Mechanical Processes

Mechanical processes produce material removing by mechanical abrasion and shearing. Usually they use kinetic energy coming from accelerated abrasion particles hit. Common cutting medium is water or air. This property is an important advantage of mechanical energy methods over electrical processing methods. Among the mechanical energetic methods, Ultrasonic Assisted Machining (UAM), Water Jet Machining (WJM), Abrasive Water Jet Machining (AWJM) methods have found the widest industrial application field. One of the most commonly used mechanical process is Abrasive Water-Jet Machining. In abrasive water-jet machining (AWJM), the water jet contains abrasive particles such as aluminum oxide, which increase the material-removal rate above that of water-jet machining. Metallic-non-metallic, and advanced composite materials of different thicknesses can be cut in single or multilayers. AWJM is suitable especially for heat-sensitive materials that difficult to machine by processes in which heat is produced. Consequently, the process may not be acceptable for situations requiring high production rates because of its complexity. Basic scheme of the abrasive water jet machining can be seen in Figure 2.9. [33].

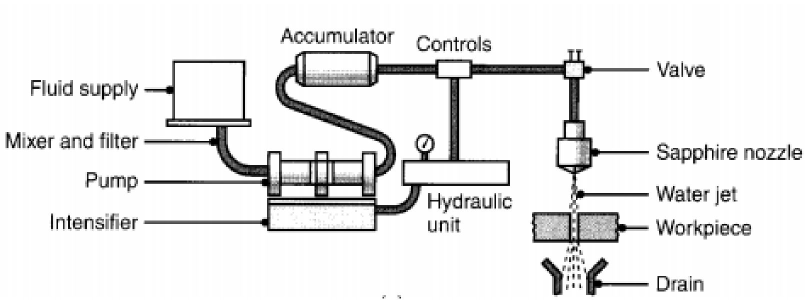


Figure 2.9 Basic scheme of the abrasive water jet machining[33]

2.2.5.2 Chemical Processes

In chemical processes, material removal done by chemical reaction. The material is treated with controlled chemical abrasion. Generally, the abrasion unwanted surfaces are covered with a suitable preservative (mask). Exposed surfaces are sprayed with abrasive chemical liquid or the workpiece is immersed in this liquid. The amount of processing dependent on the workpiece in contact with the liquid and / or depth. The chemical machining process is carried out by chemical dissolution using reagents or etchants, such as acids and alkaline solutions. Chemical machining is the oldest of the advanced machining processes and has been used in engraving metals and hard stones, in deburring, and in the production of printed-circuit boards and microelectronic devices. Processing speed is generally dependent on fluid properties, the density is typically set to give linear processing speeds of 0.025 mm / min [34]. There are four main processing methods that fall into group manufacturing methods are Chemical Processing (Milling) (ChM), Photochemical Processing (PCM), Chemical Polishing (ELP), Thermal Chemical Processing (TCM).For an example, chemical milling can be seen in Figure 2.10. In chemical milling, shallow cavities are produced on plates, sheets, forgings, and extrusions, generally for the overall reduction of weight. The process has been used on a wide variety of metals, with depths of removal as large as 12 mm. Selective attack by the chemical reagent on different areas of the workpiece surfaces is controlled by removable layers of material [33].

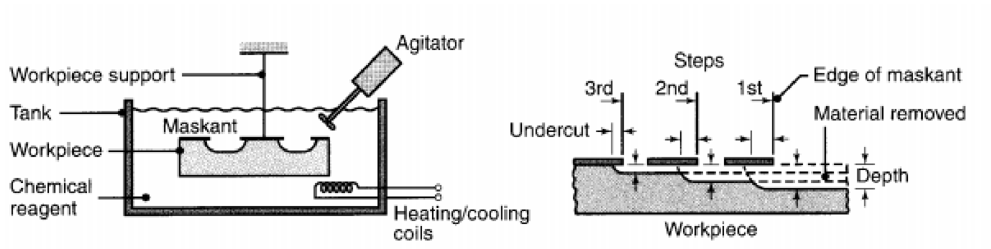


Figure 2.10 Chemical machining [33]

2.2.5.3 Electrochemical Processes

Material removal by electrochemical reaction. It uses the technique called ‘Reverse Electroplating’ means it removes metal instead of adding it. This technique is based on the principle that two conductive electrodes in an electrolytic liquid are eroded according to different electromagnetic field properties. Low voltage (6, 12-24 V) and high current (1000, 3000 and higher) conditions apply. Usually used for mass production for hard materials which are difficult to cut using conventional processes. Both outer and inner parts of the workpiece can be machined. [35] A basic type of electrochemical machining can be seen in Figure 2.11[33].

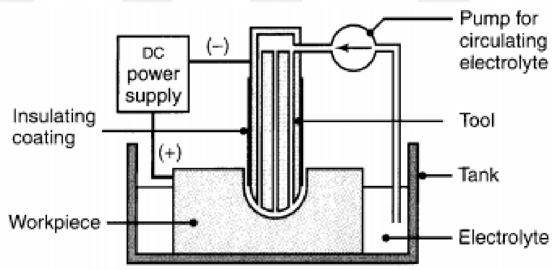


Figure 2.11 Electrochemical machining[33]

2.2.5.4 Thermoelectric Processes

Methods that use condensed thermal energy to remove material from the workpiece. As a thermal energy source, various methods such as electric discharge, electron beam (laser) and laser beam are used. In all methods, the temperatures reached at the focal point at the surface of the material are well above the melting and evaporation temperatures of all known materials. For this reason, it is possible to process the materials using methods using thermal energy. The methods that enter this group are more varied in terms of the machining mechanism than the other groups. Especially

Electro Discharge Machining (EDM) and Laser Beam Machining (LBM) have taken a very important place in contemporary technology within the group. For example, in laser-beam machining (LBM), the source of energy is a laser, focuses optical energy on the surface of the workpiece as shown in Figure 2.12 [33]. The highly focused, high-density energy source melts and evaporates parts of the workpiece in a controlled way. This process is used to machine different kinds of metallic and nonmetallic materials. Other methods', such as Electron Beam Machining, industrial practices are too much. [36]

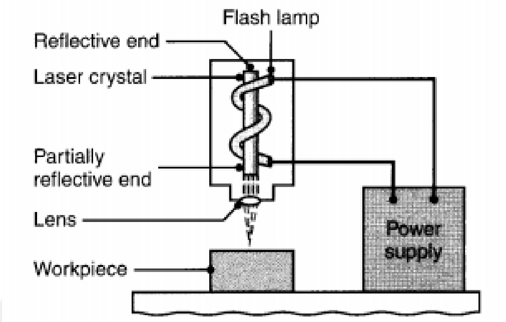


Figure 2.12 Laser-beam machining [33]

These four main hybrid machining processes have different advantages and disadvantages. All of these advantages and disadvantages are based used materials, required properties, type and intensity of applications after manufacturing. According to the outcomes of experiments in the literature, the most widely used and reliable method for machining of hard to cut materials are mechanical non-traditional machining operations. Most used techniques in industry are Water Jet Machining (WJM), Electric Discharge Machining (EDM) and Ultrasonic Assisted Machining (UAM). The most widely used and cost effective ones out of these methods are WJM and EDM which are used both in small and large companies. Apart from the other two of them, UAM still a developing process. Researches and industrial applications are still going on. In this perspective, for research of UAM is very appropriate both for industrial benefit and academically investigation.

2.3 Ultrasonic

Ultrasonic sounds are sound waves above the human auditory range. The audible sound for human is in the range of 20 Hz to 20000 Hz. Sound is a mechanical wave composed of vibration movement and Table 2.2 shows the classification of sounds according to their frequencies [37].

Although ultrasonic sound production is a very mechanical method similar to audible sound production methods, such as vibrating a membrane, piezoelectric events are used in ultrasound production. Ultrasound were firstly found by Piere and Jacques Curies in 1880, with piezoelectric properties. In the production of ultrasound, quartz, lithium sulphate, cadmium sulfate, zinc oxide, tourmaline, barium, titanate, lead titanate, are used because of their piezoelectric properties. The piezoelectric event simply means the occurrence of an electrical voltage in some crystal and ceramic materials that are subjected to mechanical pressure. A crystal material with piezoelectric properties is cut as disc or prism and its surfaces covered with a thin conductive metal (gold, silver, aluminum). If mechanical pressure is applied to the lower and upper surfaces of the crystal, polarization is obtained on these surfaces, and consequently, a series of elongation and shortening is obtained depending on the frequency of the continuously changing voltage.

Table 2.2 Classification of sounds[37]

Sound Type	**Frequency Range**
Infrasound	<20 Hz
Audible Sound	20 Hz- 20000 Hz
Ultrasound	20000 Hz- 1 GHz
Hypersound	>1 GHz

This mechanical extension and shortening (vibrations) also gives us ultrasound. The piezoelectric event is bi-directional. The ultrasound is obtained by inverse piezoelectric event, the system is used as a transmitter. Normal piezoelectric event detects ultrasound and uses it as receiver [38].

2.3.1 Mechanical Application of Ultrasound

Magnetostrictive vibrators are used as electroacoustic transducers to generate or to receive ultrasonic waves. In ultrasonic depth sounders pulsed electrical energy excites the transducer to transmit an ultrasonic wave train into the water towards the bottom from where an echo is reflected to the transducer and converted back into electrical energy. The total travel time of the sound transmission determines the distance (depth). The same principle is applied in ultrasonic fish-finders where the echoes are obtained from schools of fish. In ultrasonic sonar apparatus the direction of ultrasonic transmission and reception is usually horizontal and targets can be detected and measured by their distance and azimuthal direction. Sonic energy produced by ultrasonic transducers is also directly used in various industrial applications. Ultrasonic shakers or ultrasonic cleaners of various functions and sizes are now commercially available. The mechanical vibration of ultrasonic frequency is also industrially utilized in such applications as impact grinding [39] of hard materials, ultrasonic impact welding [40] of metal pieces, and ultrasonic acceleration of thin-wire drawing. In these applications, a solid horn is generally used to mechanically amplify the vibrational amplitude of the electromechanical transducer. The frequency of the ultrasonic waves in these applications is usually between 5 and 100 kHz; magnetostrictive transducers are widely used as substitutes for electrostrictive or piezoelectric transducers. The basic shapes of magnetostrictive transducers are shown in Figure 2.13; the physical dimensions of a transducer are designed so that the whole body (the core of the electrical winding) will be mechanically resonant at the ultrasonic operating frequency [41].

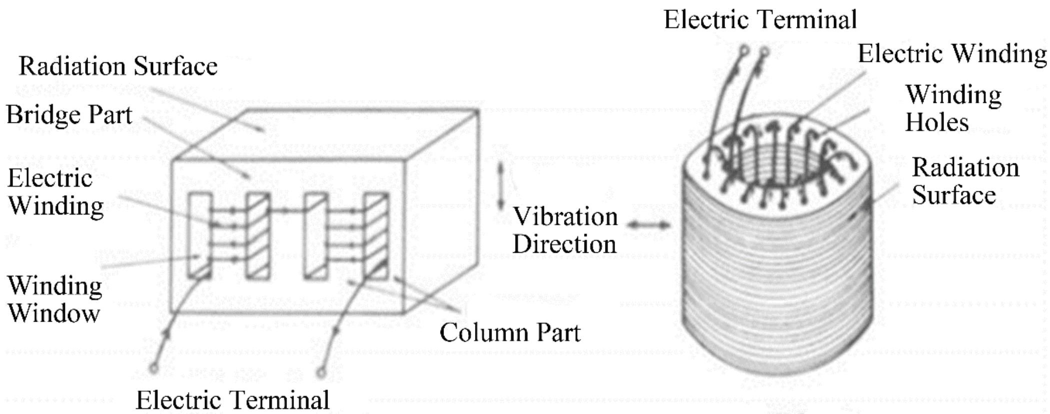


Figure 2.13 Basic shapes of magnetostrictive transducers [41]

2.3.2 Ultrasonic Assisted Machining

Ultrasonic assisted machining (UAM) is a hybrid machining process in which the ultrasonic sound waves generally generated in high frequency and low amplitudes are converted into a mechanical movement by means of a transducer, or directly applied to the tool or workpiece [42]. Hybrid production methods and technologies can be defined as the application of at least two different energy sources for the part to be processed [43]. Some of the traditional machining processes with ultrasonic vibration studies explained as follows; first one is ultrasonic assisted turning, which is highly effective in machining high-strength alloys such as titanium and nickel. It is also used for the processing of iron and brittle materials which are difficult to machine. Vibration prevents temperature rise during machining and reduces tool wear. In ultrasonic assisted turning, the periodic intervals reduce the effective stress and cutting forces. Residual stresses decrease and surface quality increases [44]. Ultrasonic assisted milling is widely used in high strength, low thermal conductivity and high work hardening materials such as Ti6Al4V. Ultrasonic vibrations are applied to the cutting tool or the workpiece itself. In this method, the chip thins, cutting forces and temperature drops. Also; tool life, machining efficiency and material removal speed are increased [45]. Ultrasonic assisted milling is discussed in more detail in the following sections. Another ultrasonic assisted machining operation is drilling. Drilling is performed with the vibrations given to the cutting tool. This method is used to drill deep holes in hard-to-work materials such as hard alloys, composites and brittle materials. The method reduces cutting force and tool wear. Delamination of layered composite materials are prevented by low cutting force. Chip size decreases and chip build up decreases. During this process, generally discontinues chip is produced [46]. Lastly, the grinding process can be done with ultrasonic vibrations. Cracks quickly lead to abrasion of the grinding stone. Ultrasonic assisted grinding can be applied as one dimensional axial, horizontal and two dimensional elliptical. Compared to the conventional grinding method, the cutting forces are reduced and the surface quality improves due to the polishing effect. Vibration allows abrasives to cut the part from multiple cutting edges. The load per particle is reduced. Thus the wear of the grinding stone is reduced [47].

2.3.2.1 Ultrasonic Assisted Milling

Ultrasonic processing is commonly applied in the processing of very hard and brittle materials (eg. glass, diamonds, ceramics, carbide etc.) which are often very difficult to cut by conventional methods. Ultrasonic vibrations application to hard and brittle materials is based on the ability to rapidly abrade when the treated material comes into contact with the vibration set. To ensure proper contact, only the vibration unit needs to lightly press on the workpiece, the more pressure on the workpiece extinguishes the vibration and reduces the cutting speed [43].

Materials with low machinability such as titanium alloys, nickel based alloys, tool steels and supper-alloys have properties like high hardness and toughness, low heat sensitivity, high corrosion resistance and metal fatigue. These properties are desirable for industrial applications but when it comes to the manufacturing processes these properties make difficulties. This kind of materials' application areas are very critical; aerospace and aviation industries, nuclear applications, medical applications and so on. Inconel 718 is a super-alloy which includes nickel-chrome and molybdenum and because of these ingredients it has extreme corrosion resistance, creep resistance and high tensile and fracture strength. Because of these specifications it can be applicable for space, nuclear and marina applications. But it create also numerous problems when it comes to metal cutting [48].

Ti6Al4V is one of these materials and it is the most commonly used one among titanium alloys. It can work with fluctuating forces, has low thermal conductivity and low modulus of elasticity. These properties makes this material very suitable for aircraft and rocketry applications but titanium and vanadium ingredients limit the cutting of the material [49].

The other example is tool steels which poses high toughness, high creep resistance and high tensile strength. In addition to these materials, composite materials have resistant to heat and moisture, lightweight, high strength and high abrasion resistance are also used in areas such as high space technology, medicine, robotics and defence industry but the anisotropy, inhomogeneity and abrasive properties found in most composite materials have many disadvantages, such as high shear forces, high torque and high tool wear [50]. The widespread of these materials these materials force manufacturers to find a way to cut these materials and form them using machining processes.

In line with these needs, it is necessary to make use of non-traditional machining methods and also improve traditional machining methods performance (turning, milling, etc.). In this respect, ultrasonic assisted machining has a very advantageous position in processing such materials. Ultrasonic assisted machining integrates the ultrasonic vibrations technology with traditional machining operations. The first ultrasonic processing, which was first made by Pierre Curie in 1880 with the help of this method which started with the investigation of the piezoelectric bases, has been used for drilling and abrasion works, usually in the 1940's [51].

However, ultrasonic assisted machining method is separated by some aspects of ultrasonic machining. In the ultrasonic machining method, a liquid containing abrasive particles is used, and by this ultrasonic vibration of the tool, the surface of the workpiece of the abrasive particles is processed with the help of this liquid. However, in the ultrasonic assisted machining process, there is no need for a liquid containing abrasive particles it can be use of course but it is not a necessity. This makes ultrasonic assisted machining more economical and more productive in terms of speed and productivity.

In ultrasonic assisted machining there are number of researches. They mostly focus on enhancing the machinability of the materials with using ultrasonic assisted machining.

In a study on AISI316L, a material widely used in the petrochemical, marine and chemical industries due to its high quality stainless steel grade and high corrosion resistance, tool wear has been reduced compared to the conventional method, however residual stresses and surface integrity remains the same as conventional methods [42]. Also in 2016 according to Tsai et al. in milling operation Modified AISI 420 stainless steel material, they observed that ultrasonic assisted machining gives better results in surface roughness, reduced tool wear and increased tool life [52]. Suarez et al. on Ni-Alloy 718, a super-alloy with high corrosion resistance and high strength, has been observed increase on the fatigue lifetime by 14.74% according to the conventional method of ultrasonically assisted chip manufacturing [53]. In 2012, it was revealed that the average cutting forces decreased considerably in the ultrasonic-assisted machining of aluminum alloys, and also the surface errors after machining in the same work decreased and the geometrical uniformity in the width of the drilled holes increased [54]. Same researchers conducted another study on 2012 which was the continuation of this work, with the same material, and they have reported that the surface roughness of the ultrasonic vibration applied part in the direction of feed decrease to a very high level of 265% [55]. According to the results of ultrasonic machining on glass-ceramic, which is a material with thermal expansion coefficient close to zero and therefore it compensate for rapid temperature changes without dimension changes, tool wear decreased between 3% and 20%, and the edge indentations in the production line decreased from 9% to 15% when using ultrasonic assisted machining [56]. In another study on glass material, it was observed that in micro-milling process ultrasonic-assisted machining reduced surface damage and surface roughness to 45% [57]. Ultrasonic assisted drilling on aluminum 6061-T6 material with high durability, good machinability and high corrosion resistance results in cutting forces dropping compared to conventional methods, 22% improvement in tool wear and 30% decrease in surface roughness of holes, have been observed to improve their centralization [13]. Another study on 5250-4 BMI type of resin (CFRP) reported that cutting forces in UAM were 10% lower compared to conventional machining and also surface roughness was between 5% to 25% smoother compared to conventional machining and this research revealed out that cutting temperature was also 15% lower than conventional machining [59]. Chenbing Ni et al. made a study about Ti-6Al-4V on ultrasonic assisted machining, the authors found out that F_x and F_y respectively reduced by 21.5%-37.24 % and 31.02%-46.30% compared to conventional machining, results also shows that increasing the amplitude of vibration results, decreases the F_x and F_y, enhance surface roughness and extends tool life compared to conventional machining [60].

Ming et al. investigated on the effects of minimum quantity lubrication (MQL) with vibration assisted machining in SKD 61 steel (AISI H13) using Bluebe LB-1 a vegetable oil. This study is the very first use of MQL in that kind of applications. Researchers reported that surface roughness improved, as the cutting length increases and surface roughness is greatly deteriorated due to lower tool flank wear in ultrasonic assisted machining. Also 18% reduction in down-milling burrs in ultrasonic assisted machining compared to conventional machining, extend tool life at 3.39 m/min. Their MQL result is; MQL in vibration assisted machining shows much better cutting performance compared to conventional micro milling. MQL reduced tool wear so improved the surface roughness and burr formation. Burr height reduced up to 80% compared to conventional one [61]. There is another study was done by Rafzar et al., about AISI 1020, they found out ultrasonic assisted machining in comparison with conventional one improves surface roughness by 12.39% on average. Curves of surface roughness were similar (increase with the increasing of feed rate and spindle speed) but the value in ultrasonic assisted machining is smaller under same conditions. Their other finding is the average percentage of surface roughness improvement decreases with increasing feed and cutting speed, for lower feed and cutting speed, the tool and the workpiece are separated from each other; thus, the average cutting forces decrease and the significance of the surface roughness improvement increases[62]. In 2013 H. Lian et al. made a research about Al 6061 for ultrasonic assisted micro milling. It was found out that surface roughness increase with the increasing with the amplitude and their amplitude parameters were a: 0 (no vibration) 11 µm, 15 µm and 19 µm [63]. Abootorabi et al. made experiments on up and down milling with ultrasonic assistance on AISI 420 stainless steel. Study results shows that ultrasonic assisted milling has smaller cutting forces on average and surface roughness can be improved in ultrasonic assisted milling with adjusting the right parameter selection [64]. Same research group made another research with the another stainless steel which is X20Cr13, experimental results indicate that the amount of cutting forces in ultrasonic assisted milling is less than in conventional milling as with cutting speed increases, the tool-workpiece contact increases as well therefore the cutting forces become closer to the conventional milling. Since vibration amplitude increases, tool–workpiece separation zones increases then cutting force in ultrasonic assisted milling to conventional milling decreases [65]. Al 5083, is known for exceptional performance in extreme environments and it is highly resistant to attack by both seawater and industrial chemical environments and Marcel et al. made experiments on this material with ultrasonic assisted machining and revealed unexpected result such as surface roughness almost did not depend on feed rate, and they reveal that the best cutting speed parameter for machined surface was 6000 rpm [66]. Tao et al. made research about Ti-6Al-4V and they used cutting fluid PRO-CUT CCF-10 μ-emulsified cutting fluid. Cutting fluid and water ratio was1/3. According to their work results, whatever vibration amplitudes are, smaller feed rates ultrasonic assisted machining effects are negligible, however as feed rate increases horizontal cutting force increases at first then decrease [67].

There are several studies on ultrasonic assisted milling in the literature. Ultrasonic assisted milling of many different materials have been studied. However, there are few studies on Ti-6Al-4V alloy. In addition, these few studies have insufficient knowledge about the machining of Ti-6Al-4V. Further research is needed to improve the machining performance of Ti-6Al-4V material. It is necessary to fill the lack of work in this field and contribute to the literature.

2.4 Cutting Fluids in Machining

Machining operations often cause high temperatures due to the friction between the workpiece and the cutting tool. Since the thermal conductivity of air under normal conditions is low, there is no chance of eliminating this high temperature. Therefore it is a needed to use coolants and / or lubricants, to disperse high temperature generated during cutting operation from cutting zone. Ideal cutting fluids are expected to produce both a cooling effect and a lubricating effect [68].

In addition, there are some basic properties of cutting fluids. These features include:

- The cutting fluids should not harm the environment and operator health;
- It should not be fire hazard and no risk for flammable;
- Not to cause any damage to the machinery or equipment used;
- It must contain corrosion resistance and should not cause any oxidation on the workpiece.
- It must be as cheap as possible [68]

There are generally four types of coolants. The first is liquids. This group is divided into four subgroups as follows;

1) Straight or neat oils: Typically, undiluted mineral oils. Frequently include fats, vegetable oils, esters together with high-pressure compounds based on chlorine, sulphur, phosphorus

2) Soluble oils: Oil with emulsifiers to allow oil to disperse in water. 3-15% in water. Least expensive and widely used

3) Synthetic fluids: Oil-free solutions formulated from alkaline inorganic and organic compounds with corrosion inhibitors 3-10% in water. Provide best cooling performance.

4) Semi-synthetic fluids: Combination of synthetic and soluble oil fluids. [27]

The other group is gels; it is generally used in manual operations such as drilling and tapping. Substances with high viscosity and less fluid are used instead of liquid. The main purpose of this application is to keep the lubrication effect high. [68]

The last group is known as mist or aerosol; in this group, gas and oil mixtures cover the cutting zone by spraying in aerosol form. The advantage of this application is that it can penetrate all over the cutting point. Inaccessible areas in liquid or gel form become very easily accessible due to the physical state of the aerosol. However, a disadvantage of this application is that it can have a direct effect on the worker if substances harmful to human health are used. This event has been solved with minimum quantity lubrication (MQL) technique [69].

2.4.1 Minimum Quantity Lubrication

Friction occurs during machining. This friction is between the tool and the workpiece, leading to many problems such as high temperature, poor surface quality and tool wear. Coolant / cutting fluid is used to eliminate these unwanted situations.

Traditionally, the machining of parts uses flood cooling in which coolant is directed on the way to the cutting zone. The coolant is flooded in large amounts. There are numerous disadvantages to using this technique. This method is cost inefficient. Coolant and its disposal is nearly fifteen percent of total cost in machining [70]. The second disadvantage is safety problem for the operators. When operators stay in interaction with the coolant for a long time, it may cause health problems. The third one is environmental effect of coolants. As the mix of oil and chips are mostly hazardous to the environment they cannot be disposed normally and directly and they should be processed first and then disposed or reused. The alternative solution is minimum quantity of lubrication (MQL). MQL is also known as near dry machining. [71]

MQL technique uses a minor quantity of oil or lubricant. It is mixed with compressed air to generate a mist or an aerosol and these particles provide lubrication also compressed air helps to reduce the heat during machining [72]. Oil consumption of MQL is varies between 2–500 mL/H [12]. This amount is very small compared to conventional coolants where the typical consumption rate is nearly 1200 l/h [73]. The air pressure varies from 2 bar to 8 bar and the selection of the parameters be determined by the type of tool material, the workpiece material and the machining processes itself [74]. The selection of the parameters be determined by the type of tool material, the workpiece material and the processes itself.

MQL can be applied internal way or external way. In the internal way of applying MQL, mist is passed through the spindle, tool holder and tool. There are two basic methods for applying MQL internally. In one method, oil and compressed air are mixed in an external unit and passed through the spindle and tool holder. In the other approach, the oil and the compressed air are mixed inside the spindle and passed through the tool holder. In the external way of applying MQL, the oil is mixed with the compressed air in one external unit and is positioned through an external jet. This system is simple, less expensive and effective for milling. [75]

The benefits of MQL over flood coolant system [69]:

- Gives longer tool life by reducing friction
- Increases productivity in terms of reducing machining time by allowing machining with higher feed rates.
- Chips are clean and dry.
- No need to recirculate the old or smelling coolant
- Minimum disposal cost as mostly mist evaporates during machining.
- Machine as well as machining area remains clean and hence a much safer working area.

- No coolant tank for coolant and no significant filtering system is required.
- The entire process is environmentally friendly, as the fluid does not need to be treated, recycled or disposed of

Okonkwo et al. expressed that MQL coolant machining gives %20 better result than the dry condition of surface roughness of end milling of Al6061[76]. Furthermore, Li et al observed that MQL significantly reduces the surface roughness, improves tool life and burr formation in near micro milling [77]. Kishawy et al. examined the effect of MQL technique and observed that MQL showed results similar with that of wet machining in terms of surface roughness, tool wear and cutting force [78]. Heinemann et al. explored that enhanced cutting tool life could be succeeded by continuous application of MQL in drilling [79]. Furthermore, Li et al noticed a noteworthy decrease in surface roughness as well as notable improvement in tool life with MQL in micro grinding [80]. Consequently, MQL can reduce the environmental hazards and manufacturing cost significantly. Kang et al. found that MQL milling presented an outstanding cutting performance under high speed end milling and noted the lowest flank wear between all wet, dry, and MQL cooling conditions [81]. Silva et al opposed the previously argued research work and found that the MQL technique did not show good performance during milling of medium carbon steel in terms of material removal rate (MRR) [82]. In their research, the MQL technique reported the lowest MRR value. Namlu et al. examined the cutting performance of the MQL technique on Al 6061 in milling, the results proposed that cutting forces and surface roughness are lower than dry and wet cutting in all feed rates and cutting speeds [83]. According to Li et al. the use of MQL enhanced the tool life and reduced flank wear by about 60% compared to dry milling and also improved the burr formation [77]. MQL generated a surface roughness less than 0.2 mm and did not change much with the variation of feeds and cutting speed. Tosun et al. studied the milling of AA 7075-T6 alloy and found that MQL milling created better surface finish in comparison to the traditional cooling using HSS and WCeCo tool and comparable results with that of TiCN cutting tool [84].

CHAPTER 3

3 Research Methodology

3.1 Research Motivation

Our research motivation is to investigate the effects of ultrasonic assisted milling and minimum quantity lubrication methods together with different cutting conditions on the cutting force and surface roughness results of Ti-6Al-4V material.

3.2 Workpiece Material

The workpiece used in the experiments of this research is Ti-6Al-4V Grade 5. It is an alpha beta titanium alloy with aluminum stabilizing the alpha phase and vanadium stabilizing the beta phase. Chemical, physical and mechanical properties are given in Table 3.1, 3.2 and 3.3 respectively [85]. Three samples of $90mm \times 55mm \times 15mm$ and one sample of $80mm \times 60mm \times 70mm$ were prepared for testing under different conditions. In order to measure the forces during the milling operations a dynamometer has been used. Dynamometer specifications are given in Section 3.7. Each workpiece was placed on dynamometer with fixtures and milling experiments were performed under different conditions. Workpieces fixed with fixtures and before each set of tests workpieces were reset to accept the point of origin.

Table 3.1 Chemical composition of Ti-6Al-4V [85]

Component	Wt. %
Al	6
Fe (Max)	0.25
O	Max 0.2
Ti	90
V	4

Table 3.2 Physical properties of Ti-6Al-4V [85]

Property	Typical Value
Density g/cm^3 (lb/ cu in)	4.42 (0.159)
Melting Range °C±15°C (°F)	1649 (3000)
Specific Heat J/kg.°C (BTU/lb/°F)	560 (0.134)
Volume Electrical Resistivity ohm.cm (ohm.in)	170 (67)
Thermal Conductivity W/m.K (BTU/ft.h.°F)	7.2 (67)

Table 3.3 Mechanical properties of Ti-6Al-4V [85]

Property	Minimum Value	Typical Value
Tensile Strength MPa (ksi)	897 (130)	1000 (145)
0.2% Proof Stress MPa (ksi)	828 (120)	910 (132)
Elongation Over 2 Inches %	10	18
Reduction in Area %	20	
Elastic Modulus GPa (Msi)		114 (17)
Hardness Rockwell C		36

3.3 Cutting Tool

Cutting tools are STOCK brand 64551 end mills as shown in Figure 3.1. The tool is made of solid carbide TiAlN coating, has four cutting edges and tool diameter is 10 mm. Carbide end mills are the most commonly used end mills for cutting titanium alloys [3]. TiAlN coating is also applied to increase abrasion resistance. It has a helix angle of 35^0 degrees. Other specifications given in Table 3.4 [86].

The cutting tools were used for the first time during these experiments and for each of 9 experiments a dedicated cutting tool has been used. Since the ultrasonic vibration and coolant conditions change in every 9 experiments, it is aimed to make a correct comparison in order to prevent tool wear. A total of 9 cutting tools were used.

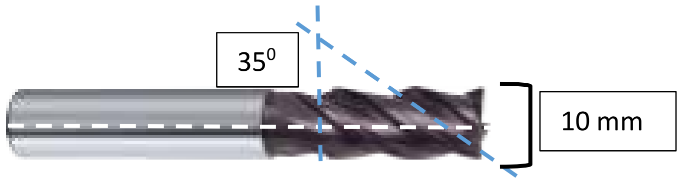


Figure 3.1 The cutting tool used in experiments [86]

Table 3.4 Specification of the cutting tool [86]

Brand-Model	**STOCK-64551**
Base Material	Carbide
Coating	TiAlN
Number of cutting edge	4
Diameter (mm)	10
Helix Angle	35^0

3.4 CNC Milling Machine

The experiments were carried out on a 4-axis VTEC brand CNC milling machine. The properties of the machine are given below [87].

Table 3.5 Technical Details of CNC machine used in experiments [87]

Technical Spec	**Value**
Number of Axis	4
Dimensions	2400 × 1300 × 1000 mm
Power	55 kVA
Maximum Speed	6000 RPM
Net Weight	33400 kg

VTEC CNC milling machine (shown in Figure 3.2.) is used to adjust feed, cutting speed, depth of cut and use of cutting fluid through manual monitor not with any CAM software. In order to prepare the wet cutting conditions in experiments the coolant has been guided to the cutting zone using VTEC CNC machine cooling system. This system could be switched off or on manually. In the wet conditions, 3 bar pressure was applied. Used oil in wet cutting is Generax 327 LF [86]. The oil used is a vegetable based, easily mixable with water and used in general machining operations. Mixing ratio with water is 5.5%.

Figure 3.2 VTEC CNC milling machine [87]

3.5 Ultrasonic System

Ultrasonic vibrations during milling process are given by Altrasonic brand Ultrasonic Tool Holder and Ultrasonic Vibration Generator. Ultrasonic milling equipment consists of an ultrasonic milling head and digital ultrasonic vibration generator. Ultrasonic milling head includes standard interface handle, high power ultrasonic transducer, fixture and milling tool, used to produce ultrasonic vibration to cut the workpiece. The transducer converts the input electric pulses into mechanical vibrations. Its working principle is the transducer in the longitudinal back and forth telescopic movements, the amplitude is a few microns. The power is not sufficient to get used directly in machining operation and needs to be amplified. Therefore milling head is followed by the amplifier part. Milling drive power supply includes rectifier, oscillation, amplifier, feedback, tracking, protection, matching circuits and, finally the display instrument. It used to generate high- frequency high-power current, driving the ultrasonic vibration components work. The power of the drilling generator is adjustable to accommodate different operating conditions. Milling generator chassis can also be integrated according to the needs of timing controller, set the control of ultrasonic vibration time and intermittent time.

The ultrasonic tool holder is mounted directly on the VTEC CNC milling machine spindle. It was used both in the experiments without giving the ultrasonic vibration and without any vibrations. The ultrasonic tool holder is connected to the ultrasonic generator by a standard connecting cable. The frequency values can be set via the generator. The frequency of vibration in experiments was 19 KHz. Technical specifications of ultrasonic tool holder are given below in Table 3.6.

Table 3.6 Technical parameters of ultrasonic tool holder

Technical Parameters	**Values**
Tool Holder Type	BT50
Working Frequency	15-21 KHz
Amplitude	10 µm or more
Matching Tool	2-13 mm

Figure 3.3 Ultrasonic tool holder used in experiments

Ultrasonic milling generator can transfer 220V 50Hz electricity to high-frequency, high-power strong current, and then drive the transducer.

Table 3.7 Technical Parameters of ultrasonic generator

Technical Parameters	Values
Max Power	500 W
Input Power	220±10% V
Dimensions	330mm×360mm×170 mm

Figure 3.4 The ultrasonic generator used in experiments

3.6 Minimum Quantity Lubrication System

In order to use minimum quantity lubrication (MQL) technique, Bielomatik brand, B1-210 model, MQL device was used. Technical details regarding this system are given in Table 3.8.

Table 3.8 Technical details of MQL device

Property	Value
Tank Capacity	1,8 lt
Air Pressure	5-10 bar
Calibration	Manuel
Exit Options	Two piece with pressure regulator
Operating	Selanoid Valve
Pressure Display	Pressure Manometer
Size	460x290x170mm

The operation diagram of the MQL system is shown in Figure 3.5. This system makes it possible to spray a combination of high pressure air and coolant from oil tank to cutting zone.

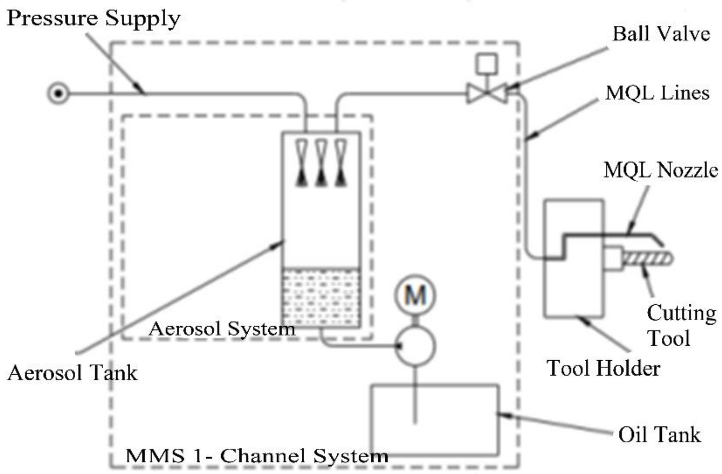


Figure 3.5 Operation diagram of MQL system

The main component is aerosol tank as shown in Figure 3.6. Aerosol generation takes place in the aerosol tank, which is divided into an aerosol chamber and an oil reservoir. The aerosol chamber contains 3 aerosol generating nozzles those use the Venturi principle to draw oil from the reservoir and atomize it and form aerosol. The system is very dependent on the internal pressure differential and the attainable aerosol speed. The lower the pressure differential, the smaller the amount of generated aerosol. The higher aerosol speed, the greater lubricant quantity that can be delivered. In turn, the aerosol speed is determined to a large extent by the cooling channel diameter and air supply. The lubricant is pumped into the aerosol tank through the oil filter by a hydraulic pump. The fill level of the aerosol unit can be monitored separately.

The other main component is ball valve in Figure 3.7. The pneumatically actuated ball valve is controlled electrically and is used to shut off the aerosol line. It serves as the on/off switch of aerosol unit. Similarly, the ball valve assures faster response times after brief interruptions in machining, e.g. when changing the tool. The valve can be connected to and controlled directly by the machine tool's control system.

Figure 3.6 Oil tank of the MQL system

Figure 3.7 Valve of the MQL system

MQL cutting fluid is Samnos ZM-22W and its formation consisting of hydrous polyalkylene-glycol-solution [88]. Nozzle of the MQL system has 5 mm diameter inside and it also has a 30 degrees from horizontal axis as shown in Figure 3.3. Since ester-based cutting fluids are very useful with their high lubricity and good hydrolytic stability[13], in this study this type of coolants has been chosen.

The Bielomatik MQL system integrated to VTEC CNC milling machine. The MQL system directly connected to the 8 bar compressed air source and could be opened and closed manually via the valve. Since the MQL system can be opened and closed manually, it is fixed on the test setup. In the experiments using MQL, the system was opened and aerosol was sprayed from a distance of approximately 10 mm at an angle of 30 degrees. In MQL free experiments the system has been closed and its nozzle was kept in a safe distance from cutting tool.

3.7 Dynamometer

Dynamometer, which measure all of the components of the mechanical forces, are invaluable in research, tool manufacture and production technology. They are used in analyzing, comparing and selecting materials, tools and machines [89]. Additional areas of application result from defining optimum cutting conditions, analyzing the breakage behavior of tools and the chip formation process and their influence on mechanical forces. Piezoelectric force measuring systems are considerably different from other methods of measurement. The forces acting on the quartz crystal element are converted to a proportional electric charge [90]. The measuring range of such an element is very large. In this study Kistler Brand 9265B model 3 axis cutting force dynamometer has been used. Dynamometer system consists of 3 main parts in total [91].

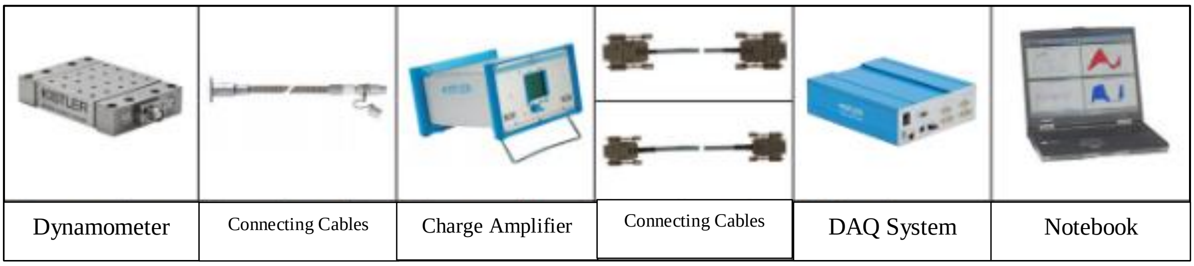


Figure 3.8 Parts of the Kistler dynamometer system

- The first part is the dynamometer with the piezoelectric sensors, where the workpiece is connected. The four 3-component force sensors inside the dynamometer are switched as appropriate to make this force measurement possible. Forces F_x, F_y and F_z are measured directly, whereas moments M_x, M_y

and M_z are calculated with the help of the individual force components and sensor distances. Sensor placements and F_x, F_y, F_z directions can be seen in Figure 3.9.

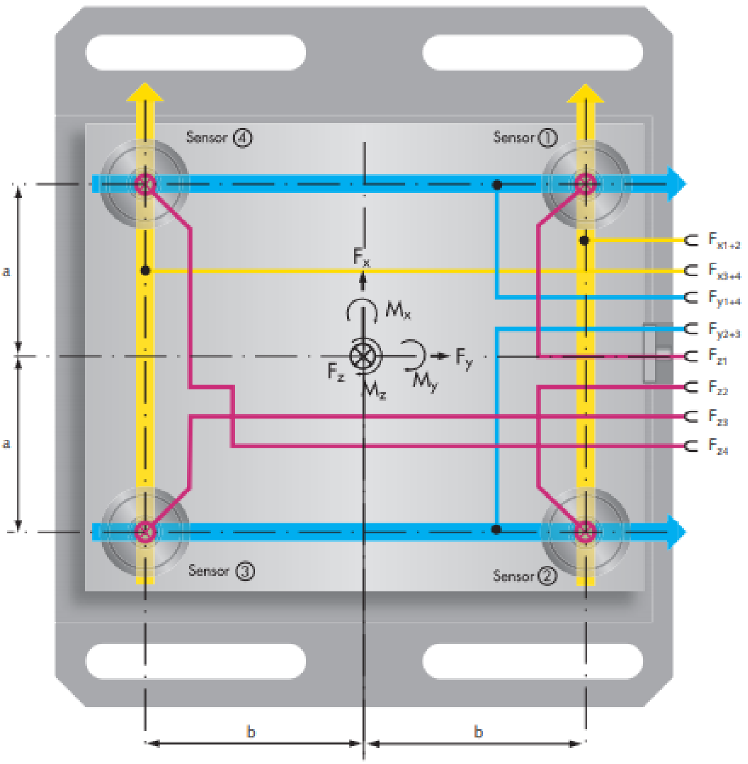


Figure 3.9 Sensor Placement of the Kistler dynamometer [91]

Calculation of the three forces F_x, F_y, F_z and three moments M_x, M_y, M_z

$$F_x = F_{x_{1+2}} + F_{x_{3+4}}$$

$$F_y = F_{y_{1+4}} + F_{y_{2+3}}$$

$$F_z = F_{z_1} + F_{z_2} + F_{z_3} + F_{z_4}$$

$$M_x = b(F_{z_1} + F_{z_2} - F_{z_3} - F_{z_4})$$

$$M_x = b(F_{z_1} + F_{z_2} - F_{z_3} - F_{z_4})$$

$$M_y = a(-F_{z_1} + F_{z_2} + F_{z_3} - F_{z_4})$$

$$M_z = b\left(-F_{x_1} + 2 + F_{x_3} + 4\right) + a(F_{y_1} + 4 - F_{y_2} + 3)$$

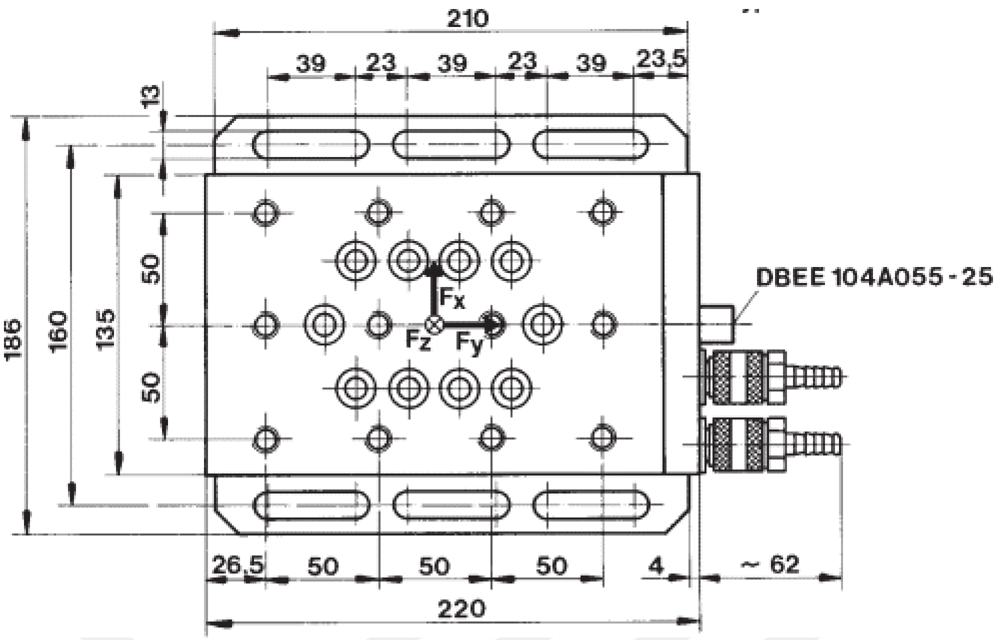


Figure 3.10 Technical drawing of the Kistler dynamometer [92]

The dynamometers consist of multi-component force sensors mounted under high preload between two base plates and a cover plate. Preloading is needed to transmit frictional forces. Ground-isolated installation of the force sensors largely eliminates ground loop problems and the sensors receive the first data [92].

- The second part is the Kistler Type 5070 Charge Amplifier. The purpose of this component is generally to amplify the current signals coming from the sensors and make them usable.
- The last part is the Data Acquisition System (DAQ) connected to the Charge Amplifier. With DAQ, the incoming and amplified signals from amplifier are set to be digitally transmitted to the computer. In this way, the data can now be used over the computer. DynoWare software, which is the interface of Kistler dynamometers, also helps to change raw data to meaningful knowledge on the computer. Kistler’s DynoWare software calculates the three forces (F_x, F_y and F_z) and the three moments (M_x, M_y and M_z); the 6-component summing processor in the charge amplifier can also perform the calculation in the same way.

The Kistler dynamometer was fixed on VTEC CNC milling machine table. The fixture mounted on dynamometer and workpieces were fixed on fixture. The data from the dynamometer was first transferred to the charge amplifier, then to the data acquisition and finally transferred to the laptop computer. DynoWare application installed on the computer and data were obtained simultaneously with the experiments. The data flow can be controlled via DynoWare, allowing data to be received and stopped at any time. Using this feature of the DynoWare application, the data flow was started a certain time before cutting operation, and the data flow stopped a certain time after ending the cutting operation. Obtained data saved after each experiment.

Table 3.9 Technical parameters of Kistler dynamometer system [91]

Measuring Range	-15…15 KN
Overload	-20/20 KN
Threshold	<0,01
Sensitivity	8 Pc/N
Natural Frequency (Mounted)	1,5 kHz
Operating Temperature Range	0….70 ℃
Temperature Coefficient of Sensitivity	-0,02 %/°C
Weight	20 Kg

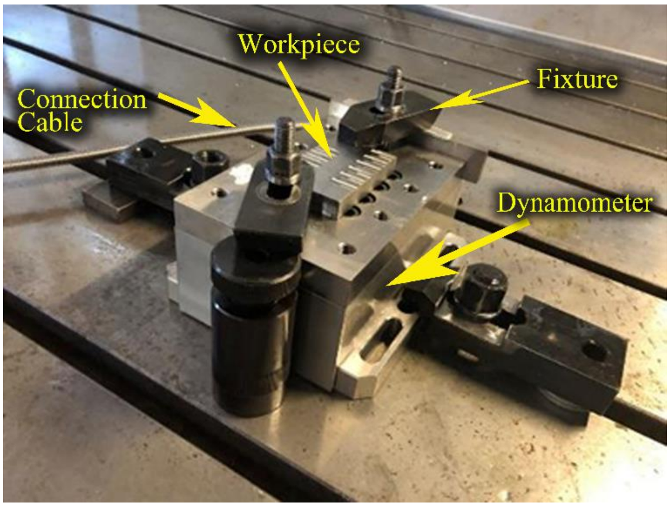


Figure 3.11 Placement of the workpieces on the Kistler dynamometer

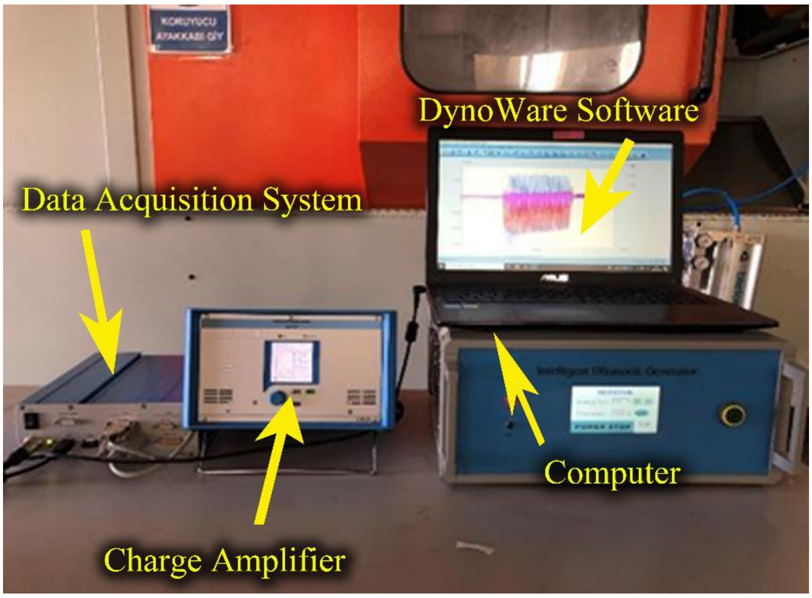


Figure 3.12 Experimental setup of the Kistler dynamometer system

3.8 Experimental Setup

Experiments setup is illustrated in Figure 3.13.

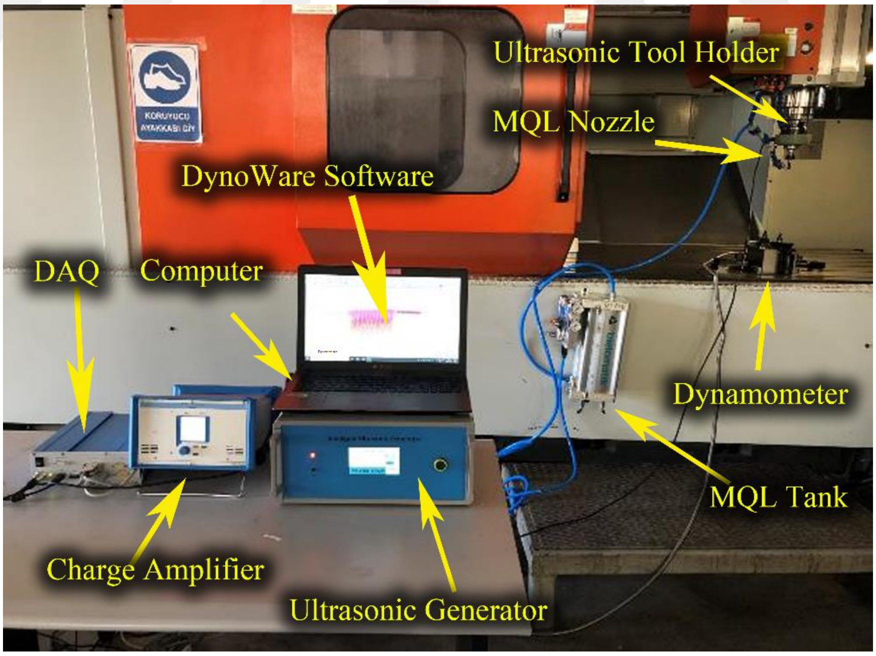


Figure 3.13 The experimental setup

General scheme of experimental setup given in Figure 3.14 below.

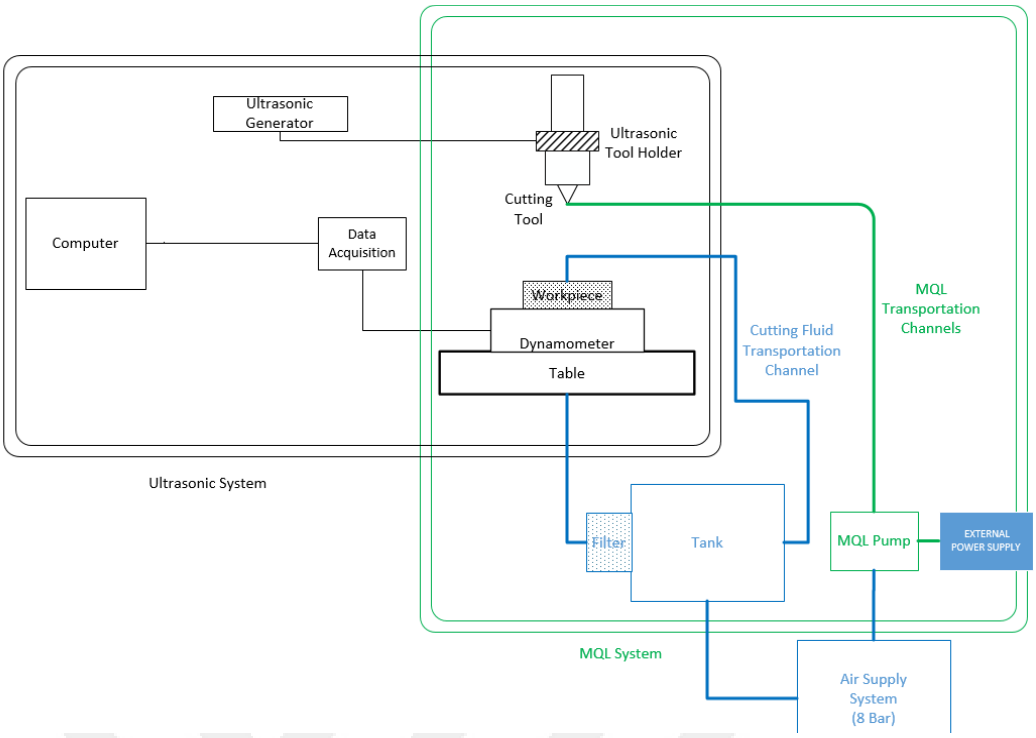


Figure 3.14 Scheme of the experimental setup

Black lines and objects represents ultrasonic system while green lines and objects shows the MQL system and finally blue lines and objects stands for conventional cutting fluid system.

3.9 Design of Experiments

In order to investigate the effect of cutting parameters and different environmental conditions in ultrasonic assisted machining of Ti-6-Al-4V two set of experiments for finishing and rough cutting conditions have been designed. The experiments were performed at 0.3 mm and 3 mm depth of cuts for resampling finishing and rough cutting conditions respectively. To study the effect of other parameters following combinations have been studied in 0.3 mm depth of cut;

- -With and without Ultrasonic Vibration
- -Different coolant conditions: Dry - Wet - MQL
- -Different cutting speeds: 47-62-78 m / min
- -Different feeds: 0.03-0.04-0.05 mm / tooth

And the conditions at 3 mm depth of cut were;

- -With and without Ultrasonic Vibration
- -Different coolant conditions: Dry - MQL
- -Different cutting speeds: 47-78 m / min
- -Different feeds: 0.03-0.04-0.05 mm / tooth

Design of experiments for 0.3 mm depth of cut are given Table 3.10 below;

Table 3.10 Design of experiments of the finish cut

Experiment Number	**Machining Conditions**		**Ultrasonic Vibration: ON**		
	Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed mm/tooth**	**Coolant Condition**		
1	1500 | 47,12	0,03	Dry	Wet	MQL
2		0,04	Dry	Wet	MQL
3		0,05	Dry	Wet	MQL
4	2000 | 62,8	0,03	Dry	Wet	MQL
5		0,04	Dry	Wet	MQL
6		0,05	Dry	Wet	MQL
7	2500 | 78,5	0,03	Dry	Wet	MQL
8		0,04	Dry	Wet	MQL
9		0,05	Dry	Wet	MQL
Experiment Number	**Machining Conditions**		**Ultrasonic Vibration: OFF**		
	Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed mm/tooth**	**Coolant Condition**		
1	1500 | 47,12	0,03	Dry	Wet	MQL
2		0,04	Dry	Wet	MQL
3		0,05	Dry	Wet	MQL
4	2000 | 62,8	0,03	Dry	Wet	MQL
5		0,04	Dry	Wet	MQL
6		0,05	Dry	Wet	MQL
7	2500 | 78,5	0,03	Dry	Wet	MQL
8		0,04	Dry	Wet	MQL
9		0,05	Dry	Wet	MQL

Design of experiments for 3 mm depth of cut are given Table 3.11 below;

Table 3.11 Design of experiments of the rough cut

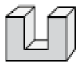
Experiment Number	**Machining Conditions**		**Ultrasonic Vibration: ON**	
	Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed (mm/tooth)**	**Coolant Condition**	
1	1500 | 47,12	0,03	Dry	MQL
2		0,04	Dry	MQL
3		0,05	Dry	MQL
4	2500 | 78,5	0,03	Dry	MQL
5		0,04	Dry	MQL
6		0,05	Dry	MQL
Experiment Number	**Machining Conditions**		**Ultrasonic Vibration: OFF**	
	Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed (mm/tooth)**	**Coolant Condition**	
1	1500 | 47,12	0,03	Dry	MQL
2		0,04	Dry	MQL
3		0,05	Dry	MQL
4	2500 | 78,5	0,03	Dry	MQL
5		0,04	Dry	MQL
6		0,05	Dry	MQL

Total of 81 experiments were performed. Experiments were calculated as full factorial design and intention was to see the interaction of all variables with each other. The selected cutting speeds and feed rates were the recommended values given by cutting tool manufacturer for milling the titanium alloy material. Figure 3.15 shows the 64551 HB cutting tool catalogue. As shown in Figure 3.15 the recommended feed code for slot milling in titanium alloys for the 64551 HB cutting tool is shown as "N". For code "N" 0.044 mm/tooth feed is recommended for cutting tools with 10 mm diameter. 0.04 mm/tooth was taken as an average and other feed values were given as +/- 0.01 mm/tooth. 60 m/min is also recommended for the cutting speed. Similarly, the average cutting speed of 62.8 m/min was taken. This is because the rotational frequency (spindle speed) value is fixed to 2000 rpm. It is given for the spindle speed (rotational frequency) values at +/- 500 RPM. With these selected values, it is aimed to observe the effects of changes in feed and cutting speed.

F-UT N	
HA	HB
54551	64551
54562	54563
54552	64550

Slot drilling

$a_p = \leq 1 \times D$
$a_e = 1 \times D$



$a_p = 1 - 2 \times D$
$f_z = 70\%$

Material group	Tensile strength MPa (N/mm²)	Hardness	v_c (HA)	f_z (HA)	v_c (HB)	f_z (HB)
Steel	< 850 N/mm²		180	Q	180	Q
Steel	850-1200 N/mm²		160	Q	160	Q
Steel	> 1200 N/mm²		135	P	135	P
Hardened steel		< 54 HRc	70	M	70	M
Hardened steel		54-60 HRc				
Acid and stainless resistant steel	< 750 N/mm²		120	O		
Acid and stainless resistant steel	700-900 N/mm²		80	N		
Acid and stainless resistant steel	< 900 N/mm²		70	L		
Nickel-base alloys	< 1300 N/mm²		30	K	30	K
Ti-alloys	< 1300 N/mm²		60	N	60	N

Feed column

Code-letter (tool-Ø mm)	K	L	M	N	O	P	Q	R	S
4.00	0.011	0.015	0.015	0.016	0.020	0.021	0.020	0.024	0.026
6.00	0.017	0.024	0.025	0.027	0.031	0.029	0.033	0.039	0.039
8.00	0.024	0.032	0.032	0.035	0.042	0.042	0.047	0.053	0.052
10.00	0.030	0.038	0.039	0.044	0.050	0.053	0.059	0.065	0.066
12.00	0.036	0.046	0.048	0.052	0.059	0.063	0.072	0.079	0.085
16.00	0.045	0.054	0.058	0.063	0.071	0.079	0.088	0.095	0.100
20.00	0.057	0.066	0.073	0.080	0.090	0.097	0.100	0.110	0.120

Feed f (mm/tooth)

Figure 3.15 Optimum cutting parameters according to the cutting tool producer [86]

CHAPTER 4

4 Results and Discussion

4.1 Investigation on Cutting Forces Results

4.1.1 Cutting Force Measurement

Acquired cutting force data from dynamometer have been measured by DynoWare program. Figures 4.1 and 4.1, show the raw form of incoming data from dynamometer to DynoWare. As mentioned in previous chapter in this study Dynamometer has been set up to measure forces in three X, Y and Z directions. Here in this Figure 4.1 and 4.2 blue, red and pink colors indicates the forces on X, Y and Z axes respectively. Both of the experiments in the images are under the MQL condition, at the cutting speed of 48.12 m/min and at a feed of 0.03 mm/tooth. The only difference between these two experiments is absence or presense of ultrasonic vibrations, where Figures 4.1, 4.3 and 4.5 show the experiment without ultrasonic vibration, while Figures 4.2, 4.4 and 4.6 show the experiment with ultrasonic vibration. As can be seen, the movement of the graph showing the forces in the Z axis in the experiments applied ultrasonic vibration shows us the presence of ultrasonic vibration

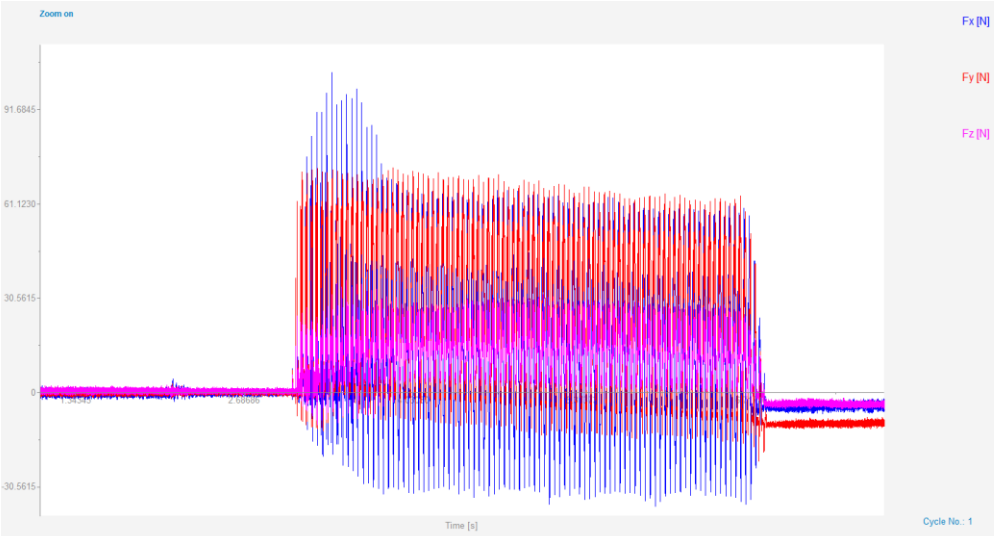


Figure 4.1 Raw data from dynamometer (MQL Condition, Without Ultrasonic Vibration, 48.12 m/min, 0.03 mm/tooth)

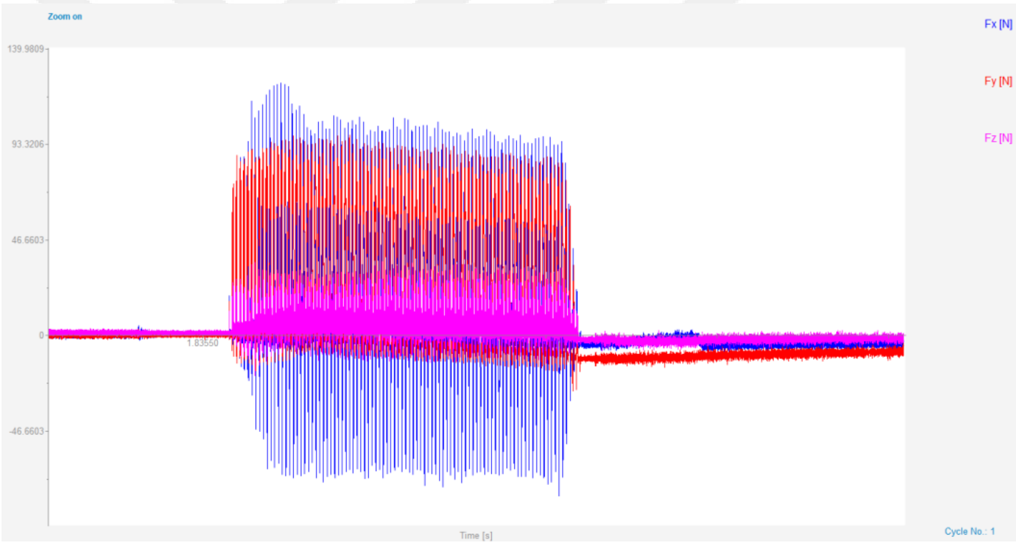


Figure 4.2 Raw data from dynamometer (MQL Condition, With Ultrasonic Vibration, 48.12 m/min, 0.03 mm/tooth)

The interval at which the dynamometer should receive data is an important choice. The input entered in the DynoWare program as sample rate refers to the data received by the dynamometer within one second. In this context, a value equal to or higher than the frequency of the ultrasonic tool holder 19 KHz must be selected so that all the data of the vibrations 19000 times per second can be obtained. Therefore, 20000 Hz sample rate was entered. Thus, all the effects of ultrasonic vibrations on the Z-axis can be observed.

In the Figure 4.3 and Figure 4.4, there are fluctuation as seen in the cutting forces in the X and Y axis. The reason for this change is due to the cutting mechanism of the milling process. the shape and form of cutting tool, cutting parameters, number of cutting edges affects the fluctuation of forces in milling processes[46]. When more than one tooth cuts simultaneously, the contribution of each tooth to total feed and normal forces must be considered. It must also be noted that, because each tooth will be away from its neighboring tooth by the amount of pitch angle (φ_p), the uncut chip thickness removed by each cutting edge will be different at an instantaneous position of the cutter [15]. Also the chip is very thin at the beginning where the tooth first contacts the work, and increases in thickness as the cutter rotates. It reaches the maximum when the tooth leaves the workpiece. This can be clarified by causing these fluctuations in the cutting forces in a rotation of the cutting tool. The chip thickness fluctuations over a revolution result in periodical changes of the cutting forces with the entry/exit of the cutting tooth. The chip thickness fluctuations over a revolution result in periodical changes of the cutting forces with the entry/exit of the cutting tooth [93].

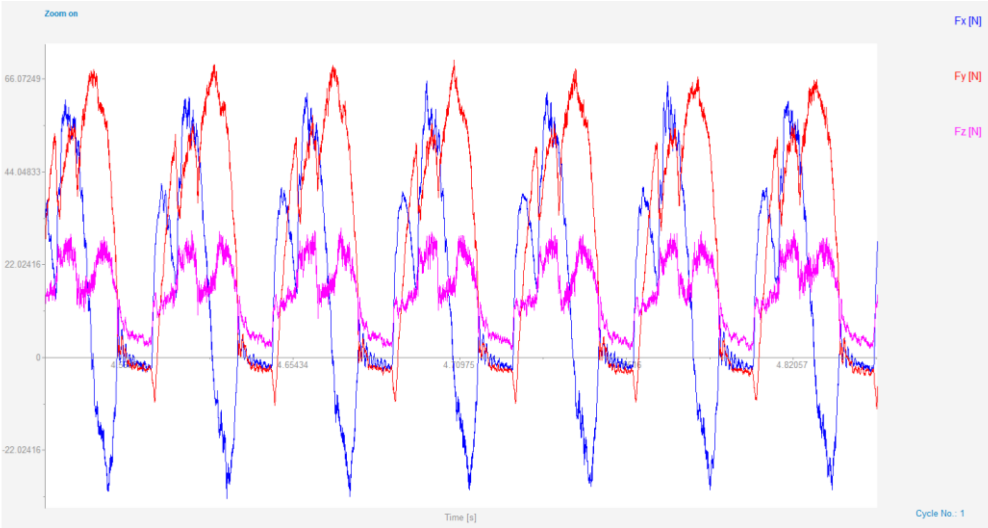


Figure 4.3 More detail view of raw data from Dynamometer (MQL Condition, Without Ultrasonic Vibration, 48.12 m/min, 0.03 mm/tooth)

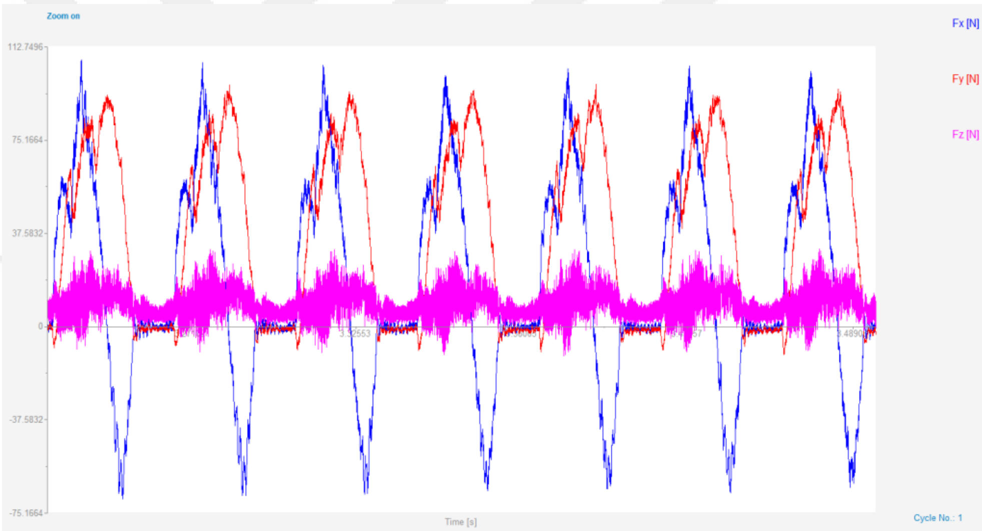


Figure 4.4 More detail view of raw data from Dynamometer (MQL Condition, With Ultrasonic Vibration, 48.12 m/min, 0.03 mm/tooth)

In Figures 4.5 and Figures 4.6, the presence of ultrasonic vibrations on the Z-axis can be clearly seen. In Figure 4.5, the forces on the Z-axis flactuate normally during cutting according to the cutting tool tips and cutting degree, while the cutting forces on the Z-axis in Figure 4.6 flactuate more often. At the same time, the peak and bottom points of the forces in the Z axis in Figure 4.6 are quite symmetrical. The main reason for these images is the ultrasonic vibrations applied to the cutting tool. These vibrations on the Z axis with a frequency of 19 KHz cause the F_Z to flactuate very often. Furthermore, the difference between peak and bottom points gives us the amplitude of the ultrasonic vibration. It is also possible to see some vibration in the graphs of the cutting forces on the X and Y axis, as seen in Figure 4.6. Although not as frequent as on the Z-axis, these images indicate that the vibrations are also effective on the X and Y axis. The reason why the peak values of the cutting force graphs on the X and Y axis are sharper in ultrasonic vibrated images can be attributed to ultrasonic vibrations.

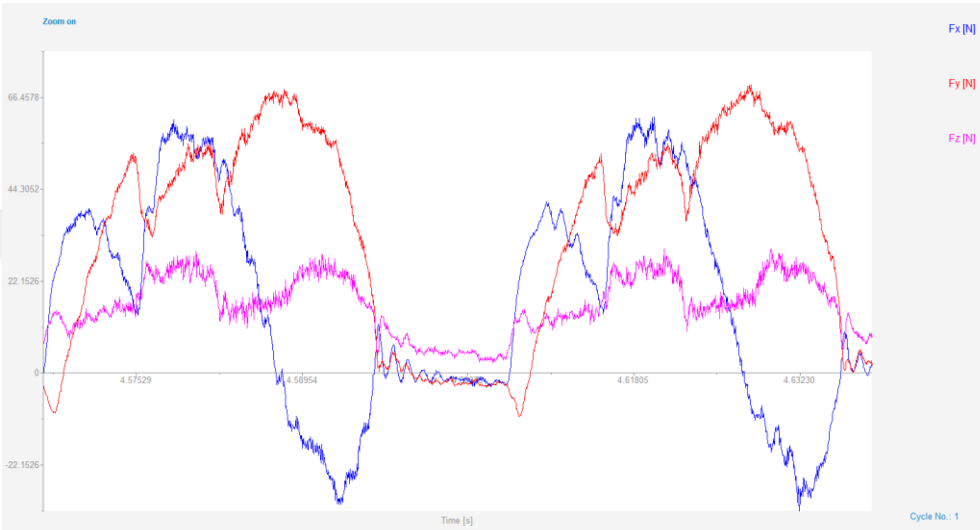


Figure 4.5 Two cutting rotation cycle data from Dynamometer (MQL Condition, Without Ultrasonic Vibration, 48.12 m/min, 0.03 mm/tooth)

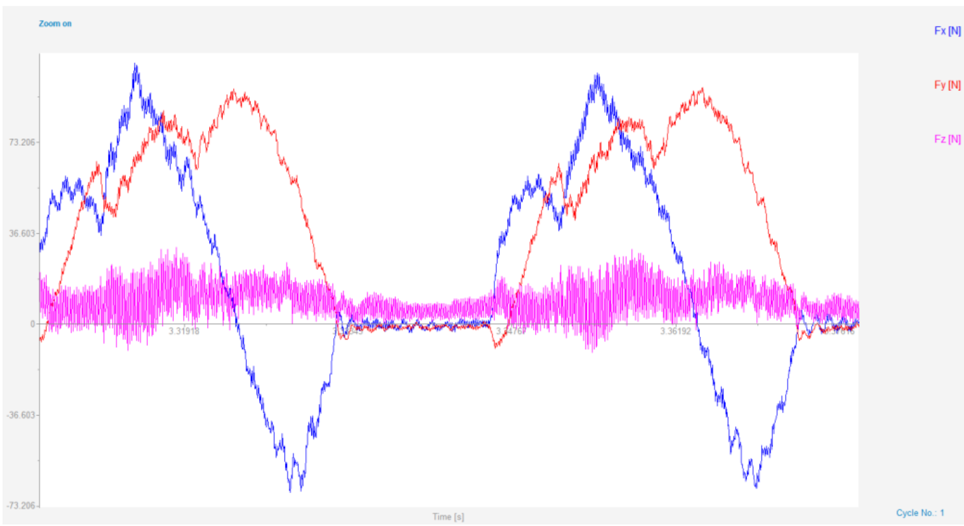


Figure 4.6 Two cutting rotation cycle data from Dynamometer (MQL Condition, With Ultrasonic Vibration, 48.12 m/min, 0.03 mm/tooth)

It is very important to select the cutting depth during milling. The cost and precision of the process depend particularly on the depth of cut. While the cutting depth is kept low in the parts where sensitivity is required, work is performed in low tolerance ranges, but when cutting process time and cost are desired, high cutting depths are used. Low cutting depths are called "finish cut" and high cutting depths are called "rough cut". In this context, 0.3 mm cutting depth was selected to see the effect of ultrasonic vibrations and MQL on the finish cut when selecting the cutting depth for our experiments, while the cutting depth was increased by 10 times and 3 mm was selected to see these effects in rough cut.

4.1.2 Finish Cutting Experiments

4.1.2.1 Investigation of Ultrasonic Vibration Effect on Finish Cutting Experiments

Experimental results for the 0.3 mm resultant cutting forces is shown in Tables 4.1, 4.2 and 4.3. As seen in tables, the forces in the X and Y directions are the most important components affecting the resultant forces. The forces in the Z direction are very low and they could be negligible therefore it can be concluded that the main cutting operation is carried out on the X-Y plane. However after applying ultrasonic vibrations on Z direction the amount of forces in this direction increases drastically and it can not be ignored anymore.

In the first three experiments, they were carried out at speeds of 47.12 m / min and 0.03-0.04 and 0.05 mm / tooth feeds, respectively. In the next three experiments, 62.8 m / min speed was used and the same feeds were used respectively. In the last three experiments, a speed of 78.5 m / min and the same feeds were used.

In Tables 4.1, 4.2 and 4.3 below, the cutting forces on the X, Y and Z axis of the experiments are given. Variations of cutting force components under different conditions can be examined.

Table 4.1 Cutting Force Components of Dry Coolant Condition in Finish Cutting Experiments

			Dry-With Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1		0,03	98	98	53
2	1500 | 47,12	0,04	89	98	45
3		0,05	110	62	26
4		0,03	85	73	37
5	2000 | 62,8	0,04	96	74	40
6		0,05	111	81	46
7		0,03	92	76	36
8	2500 | 78,5	0,04	103	83	44
9		0,05	123	88	41

			Dry-With Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1		0,03	121	94	72
2	1500 | 47,12	0,04	154	106	48
3		0,05	175	124	59
4		0,03	126	113	63
5	2000 | 62,8	0,04	168	121	63
6		0,05	182	132	59
7		0,03	127	109	54
8	2500 | 78,5	0,04	142	113	48
9		0,05	169	122	49

Table 4.2 Cutting Force Components of Wet Coolant Condition in Finish Cutting Experiments

			Wet- Without Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1		0,03	74	54	18
2	1500 | 47,12	0,04	91	76	23
3		0,05	94	76	18
4		0,03	90	68	27
5	2000 | 62,8	0,04	92	83	9
6		0,05	98	91	15
7		0,03	84	63	23
8	2500 | 78,5	0,04	98	88	28
9		0,05	122	112	28

			Wet- With Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1	1500 | 47,12	0,03	81	61	31
2		0,04	100	88	34
3		0,05	114	104	30
4	2000 | 62,8	0,03	99	71	23
5		0,04	101	88	28
6		0,05	125	108	39
7	2500 | 78,5	0,03	97	72	28
8		0,04	106	94	34
9		0,05	126	112	40

Table 4.3 Cutting Force Components of MQL Coolant Condition in Finish Cutting Experiments

			MQL- Without Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1	1500 | 47,12	0,03	79	56	18
2		0,04	91	73	20
3		0,05	93	77	23
4	2000 | 62,8	0,03	78	65	17
5		0,04	91	81	15
6		0,05	95	79	29
7	2500 | 78,5	0,03	80	68	18
8		0,04	98	85	16
9		0,05	106	89	28

			MQL- With Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1	1500 | 47,12	0,03	98	76	30
2		0,04	130	91	35
3		0,05	175	115	46
4	2000 | 62,8	0,03	147	96	42
5		0,04	174	113	38
6		0,05	194	132	33
7	2500 | 78,5	0,03	145	107	42
8		0,04	176	113	90
9		0,05	208	126	96

After finding the components of the resultant cutting force on the X, Y and Z axis, resultant cutting forces is calculated using Equation 4.1

$$F_R = \sqrt{Fx^2 + Fy^2 + Fz^2} \quad (4.1)$$

The variation of the resultant cutting force according to the cutting conditions can be seen in Table 4.4 below.

Table 4.4 Resultant Cutting Forces of Finish Cutting Experiments with different cutting conditions

Resultant Cutting Force (N) 0.3 mm							
Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed (mm/tooth)**	**DRY-NU**	**DRY-U**	**WET-NU**	**WET-U**	**MQL-NU**	**MQL-U**
1500 | 47,12	0,03	148,37	169,13	93,36	106,03	91,16	127,59
	0,04	139,82	193,02	120,87	137,48	118,60	162,50
	0,05	128,21	222,45	122,00	157,20	118,15	214,40
2000 | 62,8	0,03	117,47	180,59	115,99	123,98	98,47	180,52
	0,04	127,64	216,41	124,20	136,85	122,99	210,92
	0,05	144,91	232,44	134,94	169,74	126,91	236,96
2500 | 78,5	0,03	124,64	175,86	107,49	124,00	104,85	185,04
	0,04	139,41	187,72	135,09	145,70	124,73	229,94
	0,05	156,70	214,12	143,33	173,26	138,69	262,13

In finishing operations the effect of ultrasonic vibrations on cutting forces was the same under all three different cooling conditions and cutting forces increased after applying ultrasonic vibrations.

The reason for this situation can be explained as follows; As this is a finishing operation, cutting tool is exposed to small forces in all X, Y and Z directions. Immediately after applying ultrasonic vibrations on z axis due to impacts between work piece and cutter 19000 times per second. . These very frequent and rapid impacts cause frequent loads on the cutting tool. this incident increase the amount of cutting forces in Z direction severly. As a result of this phenomenon, which can be called hammer effect, ultrasonic vibrations increase resultant cutting forces significantly. This result is consistent with El-Taybany’s [94] experimental results at a 0.03 mm depth of cut with soda glass and Uhlmann’s [95] research about ultrasonic assisted milling of reinforced plastics.

4.1.2.2 Investigation of Coolant Effect on Finish Cutting Experiments

As it described in previous chapter this study includes 54 experiments for 0.3 mm depth of cut in different machining conditions. These conditions are:

1. Dry machining
2. Dry machining with ultrasonic vibrations on Z axis
3. Wet machining
4. Wet machining with ultrasonic vibration on Z axis
5. MQL machining
6. MQL machining with ultrasonic vibration on Z axis

The intention of these experiments is to find out what are the effects of ultrasonic vibrations and MQL method on cutting forces and surface roughness in rough and finihs cuttings in milling operations. Beside that different lubrication methods also have been investigated in this research to find out the best combination in cutting Ti-6Al-4V alloys.

In order to investigate the effects of coolants on cutting forces in ultrasonic assisted milling, three different conditions are provided. The first condition is the dry cutting condition, there is no coolant on the process. Dry condition with ultrasonic vibration effect can be seen in Figure 4.7.

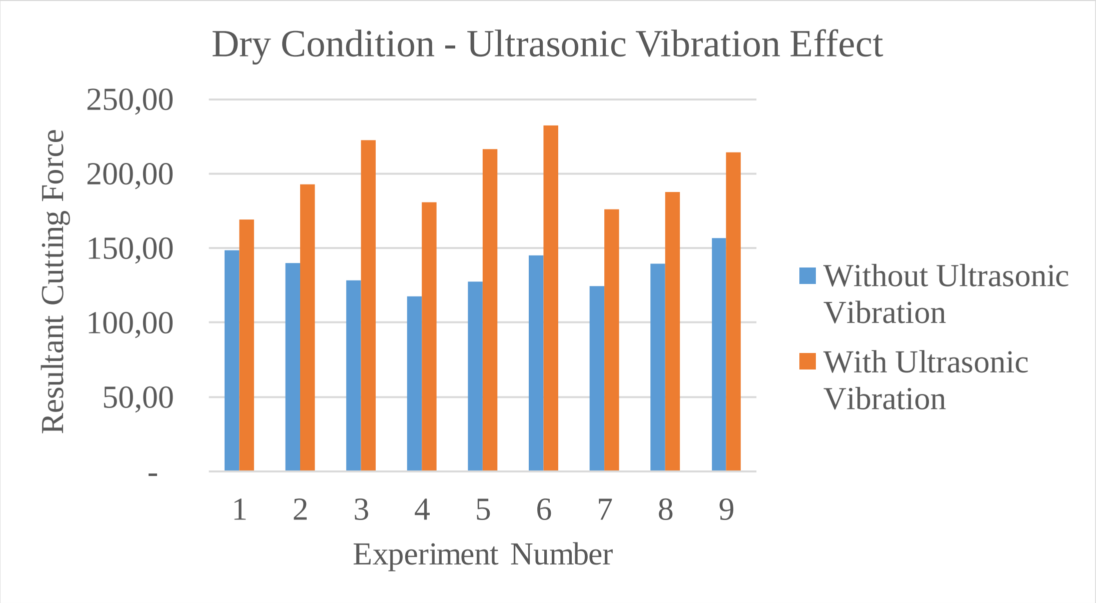


Figure 4.7 Dry condition with ultrasonic vibration effect on finish cut

The second condition is the wet cutting condition. In this method boron oil is supplied through conventional CNC coolant system to the cutting zone. This condition is normally the most commonly used cooling method in processing Ti-6Al-4V alloys. Wet condition with ultrasonic vibration effect can be seen in Figure 4.8.

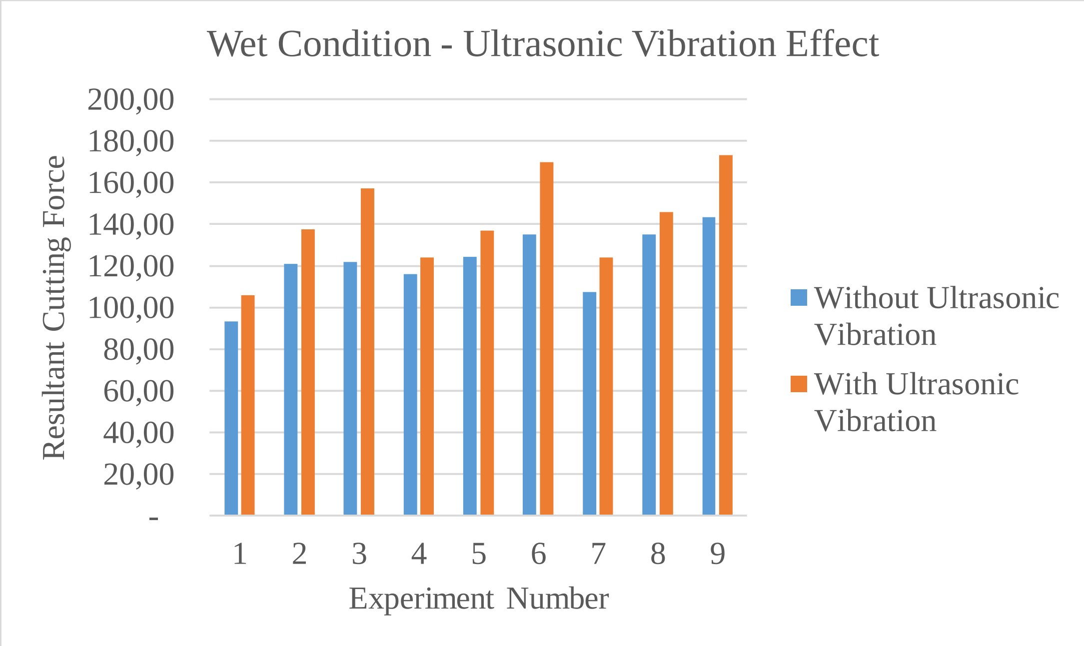


Figure 4.8 Wet condition with ultrasonic vibration effect on finish cut

Third and last coolant condition is MQL. In MQL method, ester based aerosol was sprayed to the cutting point via multiple nozzles exactly to the cutting zone. MQL condition with ultrasonic vibration effect can be seen in Figure 4.9.

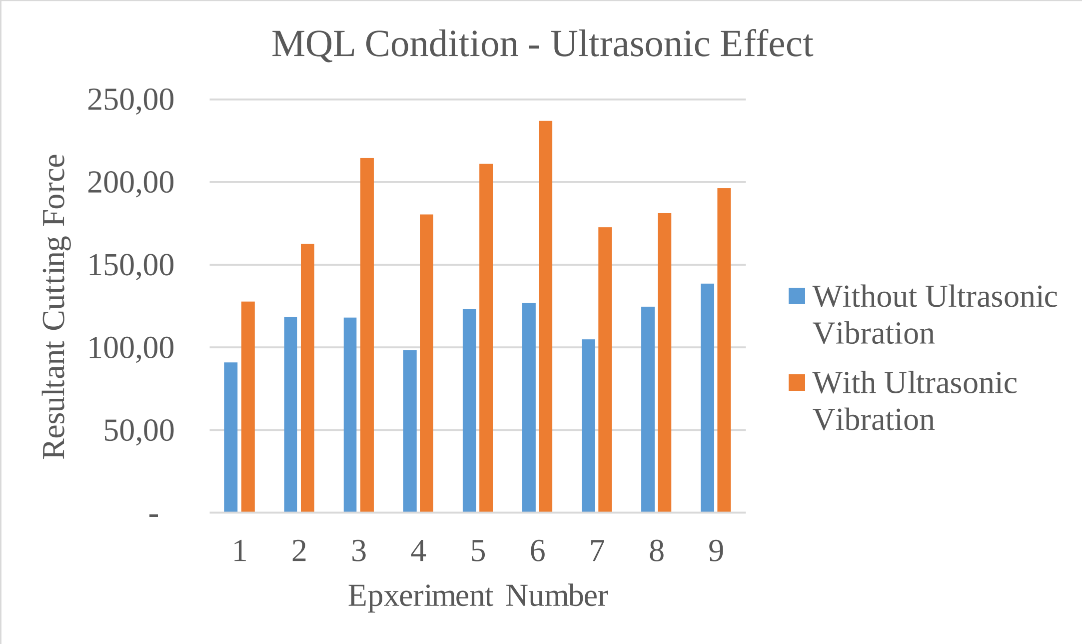


Figure 4.9 MQL condition with ultrasonic vibration effect on finish cut

In all experiments, it was found that the highest resultant cutting forces were obtained from dry cutting conditions. The second highest resultant cutting force was the conventional wet cutting condition. The cooling condition giving the lowest cutting forces was MQL. Experiments using MQL showed a reduction of up to 38.55% compared to dry cutting conditions. Maximum difference occurred at a cutting speed of 47.12 m / min and 0.03 mm / tooth feed. Compared to conventional wet cutting condition, up to 15.1% less resultant cutting forces were observed in the experiments using MQL. The test with the highest difference is observed with a cutting speed of 62.8 m / min and 0.03 mm / tooth feed.

When removing chips from the workpiece, a friction occurs between the chip and the cutting tool, and heat is released due to this friction. Ti-6Al-4V material has very low thermal conductivity as discussed in the previous chapters. This low thermal conductivity, on the other hand, causes the heat generated at the cutting point to be removed by chips. In addition, because of this feature, except for the heat at the cutting point, the heat cannot be transmitted by conductive heat transfer to the rest of the workpiece and all heat accumulates at cutting zone. This accumulated heat sink causes wear the cutting tool, making the tip duller. Therefore, the contact area between the cutting tool and the workpiece is increased even further, which leads to higher friction

and higher friction increases the cutting forces. Since liquid has a cooling effect in conventional wet cutting, this liquid penetrates into the cutting zone, reduces the accumulated heat in the area and decrease the temperature at the cutting zone. The temperature drop at the cutting zone also reduces tool wear, reduces friction between the cutting tool and the workpiece and consequently reduces tool wear, and this results in lower cutting forces. In MQL method, the mechanism is quite different. MQL is sprayed as aerosol form to the cutting zone. It is also sprayed at a high pressure (8 bar) which is much higher than conventional cooling method. In addition, the ester-based oils have a relatively low evaporation point and therefore evaporate immediately after reaching a sufficient temperature. In MQL method the sprayed aerosol under high pressure can penetrate to the space between cutter and workpiece. In this way, it maximize the lubricant effect in the contact area between the cutting tool and the workpiece. MQL aerosol, which reaches all over the cutting zone, evaporates suddenly from the environment with low evaporation temperature and removes the accumulated heat from cutter surface. In this way, the friction between cutting tool and workpiece, the temperature in the cutting zone, and consequently the tool wear is reduced with the reduced temperature, and finally the cutting forces are reduced with the reduced friction. This conclusions in fact MQL condition gives lower cutting forces than dry cutting and wet cutting is consistent with most studies in the literature [13],[77],[83].
These three different coolant condition experiments are made separately both with and without ultrasonic vibrations. In this way, it was aimed to investigate which cutting conditions give better results with ultrasonic vibrations. The resultant cutting forces in the experiments using ultrasonic vibration under different coolant conditions are given in Figure 4.10.

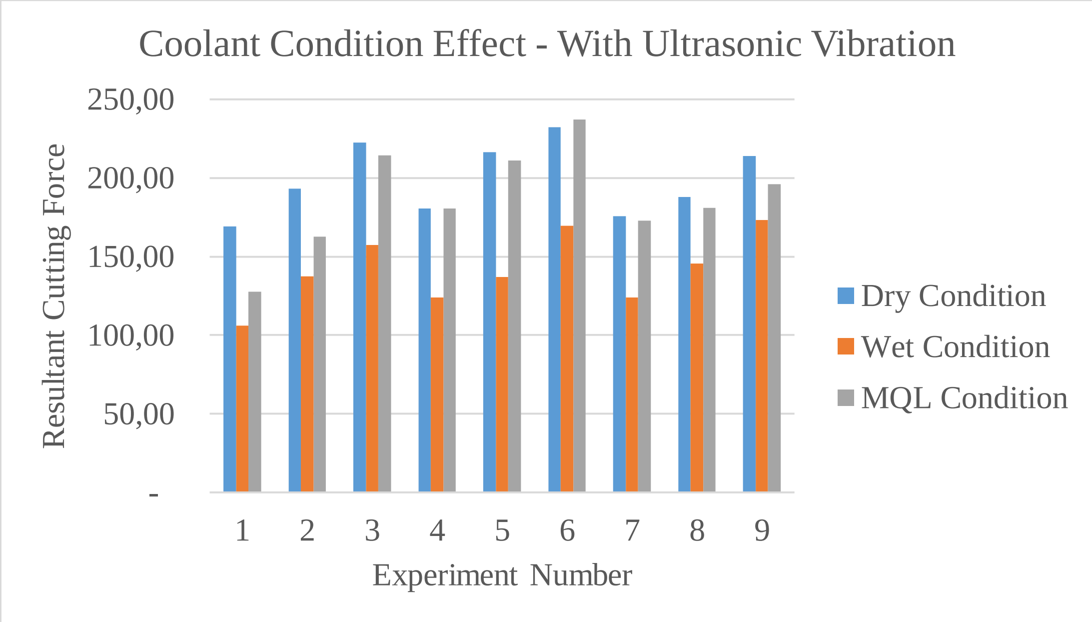


Figure 4.10 Coolant Condition Effect with Ultrasonic Vibration on finish cut

The results obtained are quite different compared to the results in experiments without ultrasonic vibration. The resultant cutting forces in the experiments without using ultrasonic vibration under different coolant conditions are given in Figure 4.11.

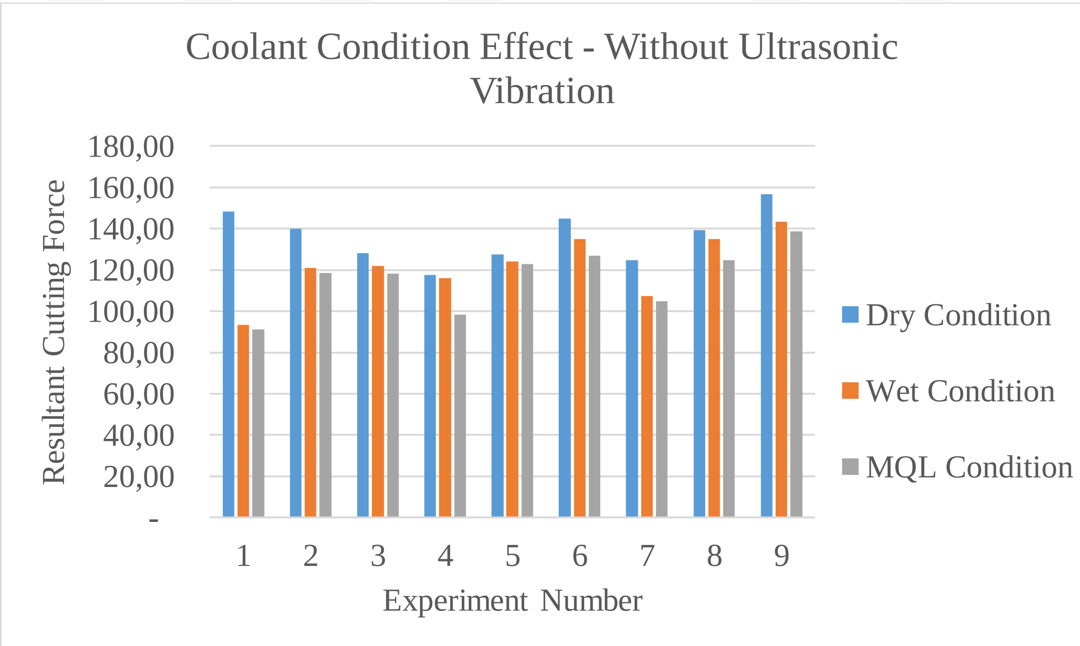


Figure 4.11 Coolant Condition Effect without Ultrasonic Vibration of finish cut

In the experiments with ultrasonic vibrations, the highest resultant cutting forces were obtained under dry cutting conditions. The second highest value according to the resultant cutting forces is the MQL condition. The condition that gives the lowest resultant cutting force is the wet cutting condition. For the experiments, friction in the cutting zone resulting high temperature and this cause tool wear. Because of tool wear cutting forces getting higher. This time, however, the MQL condition gives a higher cutting force than the wet condition. This can be explained as follows; ultrasonic vibrations are applied to the cutting tool, when the cutting tool interacts with the workpiece, it vibrates on the Z-axis at a frequency of 19 kHz, causing a discontinuous contact between workpiece and cutting tool. When the MQL aerosol is sprayed into the cutting zone, it also fills the gap between the cutting tool and the workpiece in the cutting zone due to these vibrations and evaporates due to the high temperature in the environment. Therefore it does not cool down the tool surface as it may not reach the tool surface adequately and the major portion of heat still remains on tool surface although the sudden evaporation reduces the ambient temperature slightly, as a result its efficiency is reduced compared to the condition where no ultrasonic vibration is given. However, the wet cutting condition fills even the gap created in the cutting zone due to vibrations and reduces the heat and lowers the temperature due to the abundance of the environment. This result is a new finding that has not been studied in the literature yet.

4.1.2.3 Investigation of Feed and Cutting Speed on Finish Cutting Experiments

Exepct from ultrasonic vibrations and cooling conditionsi the other important conditions in the milling process are feed and cutting speed. It is also important to examine the variation of these conditions with ultrasonic vibrations and cooling conditions. Variations in three different cutting speeds and three different feeds are described as follows. The results at a cutting speed of 47.12 m / min, 62.8 m/min and 78.5 m/min are given in Figures 4.12, 4.13 and 4.14 respectivly, The highest cutting forces were obtained in experiments using ultrasonic vibrations for dry cutting. The lowest cutting forces were observed in experiments without ultrasonic vibration under MQL condition. In addition, it has been observed that the cutting forces increase in all coolant conditions as feed increases. This is due to the increased amount of chip size as the feed increases. With the increased amount of chip, the area of the cutting tool in contact with the chip increases, which increases the friction between the chip and the cutting tool, and the increase in friction leads to increases the cutting forces.

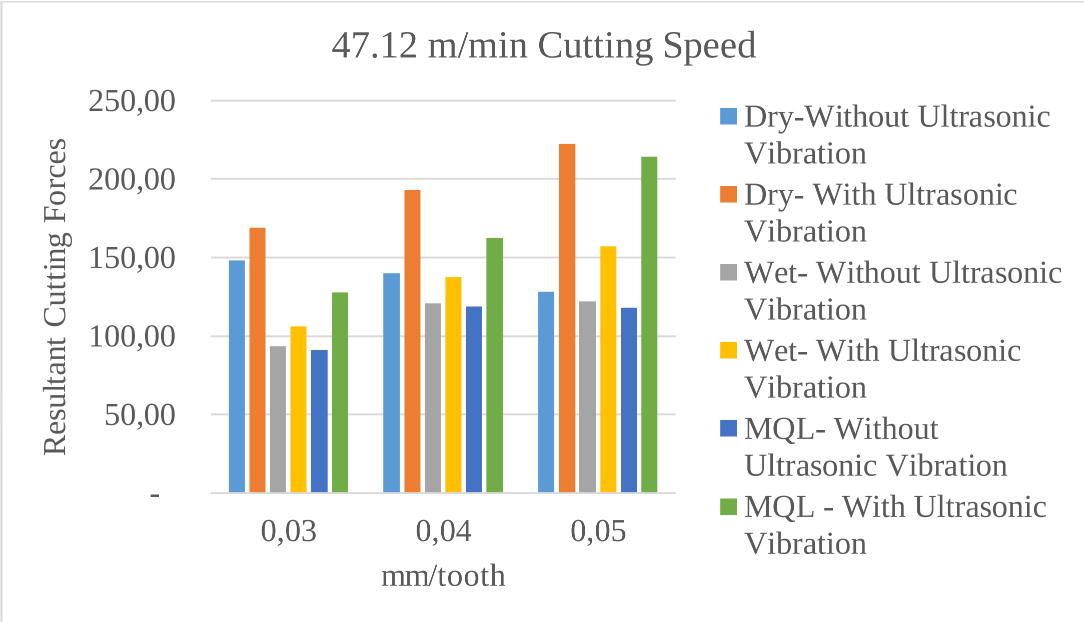


Figure 4.12 Resultant cutting forces of 47.12 m/min cutting speed experiments

The condition that does not conform to the trend of increasing cutting force with feed is only the dry cutting condition without ultrasonic vibration. The phenomenon which causes such anomality could be thermal softening, in these experiments which took place at the 47.12 m/min, the cutting forces decreased due to the low cutting speed and thermal softening occurs due to the absence of any factors to cool the cutting zone.
As the cutting force data in the experiments gathered at cutting speeds of 62.8 m / min and 78.5 m / min consists with each other, so they can be evaluated together.

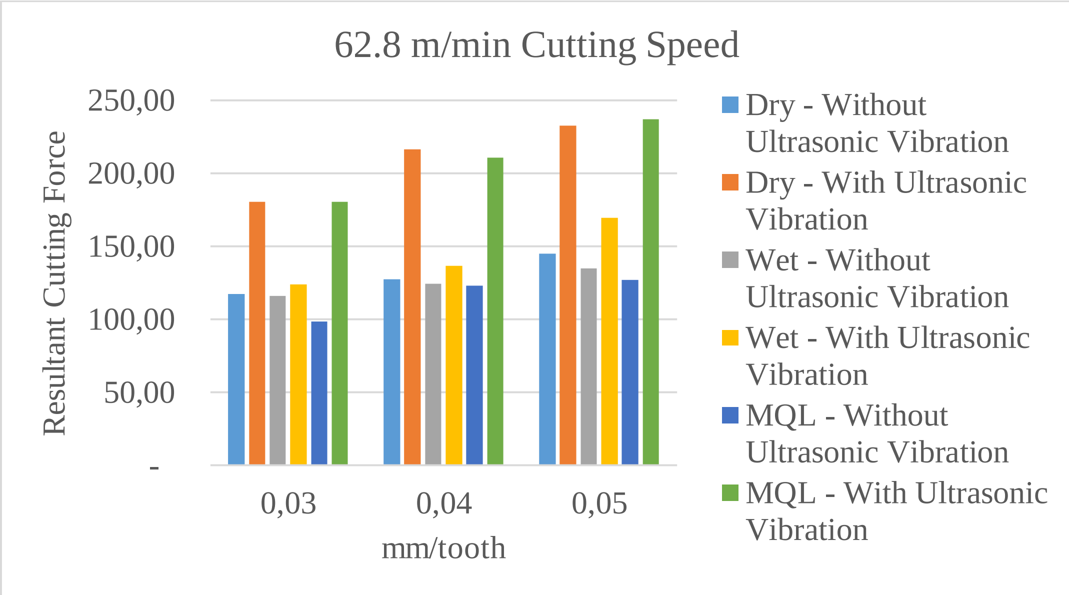


Figure 4.13 Resultant cutting forces of 62.8 m/min cutting speed experiments

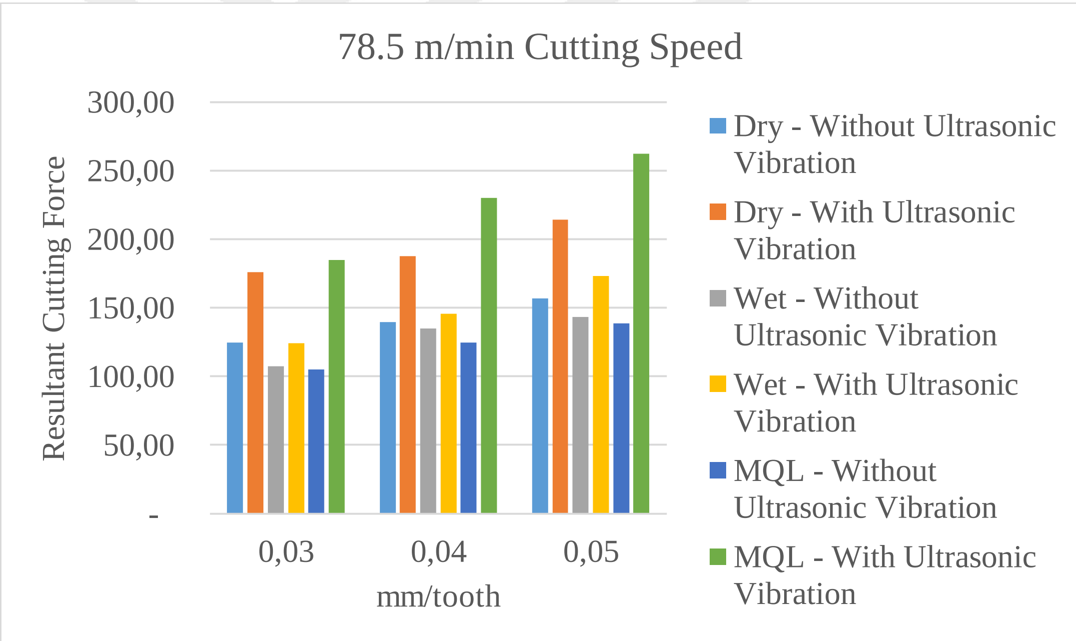


Figure 4.14 Resultant cutting forces of 78.5 m/min cutting speed experiments

Figures 4.12 , 4.13 and 4.14 show that as the feed per tooth increases, the cutting forces increase with it. This is related to higher chip removal as described previously. The higher the amount of chip removed, the greater the contact area between the cutting tool and the workpiece, the higher the friction and the higher the resultant cutting forces. In addition, the highest cutting forces were generally observed in dry and ultrasonic vibration experiments, while the lowest cutting forces were found in the experiments where no ultrasonic vibration was applied with MQL. This showed that the lowest cutting forces were obtained in a combination of MQL/ without ultrasonic vibration conditions in experiments with a cutting depth of 0.3 mm.

When the effects of three different cutting speeds on cutting forces are compared, it can be seen that only the cutting speeds do not have much effect under the same conditions. However, especially in MQL experiments, it was observed that the cutting forces decreased as the cutting speeds increased regardless of the presence of ultrasonic vibration. This indicates thermal softening. As the cutting speeds increase, the increased temperature in the cutting zone causes a decrease in the yield strain of the material. This drop makes plastic deformation easier and facilitates chip removal from the material. In this way, the forces used for chip removal will be reduced and the resultant cutting forces will be reduced in the same way. This finding is compatible with many studies in the literature [96], [97].

4.1.3 Rough Cutting Experiments

In order to investigate the effect of rough cutting on cutting forces with MQL condition and ultrasonic vibrations, experiments with 3 mm depth of cut were performed. As seen in finish cut experiments, it was observed that feed had more effect on cutting forces than cutting speeds. For this reason, the lowest and highest cutting speeds 47.12 m / min and 78.5 m / min cutting speeds were chosen for the experiments in order to reduce the experiment cost, but it was again selected in three stage feed to examine the effect of feeds. In order to see the effect of the MQL condition, which is one of the main subjects of the research, on the cutting forces, a comparison was made with the dry cutting condition. All experiments were subjected to two separate condition, both with ultrasonic vibrations and with conventional milling method without ultrasonic vibrations. As a result of the experiments, cutting speed effect, feed effect, ultrasonic vibration effect and effect of MQL condition were investigated.

4.1.3.1 Investigation of Ultrasonic Vibration Effect on Rough Cutting Experiments

As discussed before, for finding the resultant cutting forces first of all cutting force components must be find out. X, Y and Z cutting force components calculated from DynoWare software. Table 4.5 shows the dry cutting condition cutting force components and Table 4.6 shows the MQL condition cutting force components.

Table 4.5 Cutting Force Components of Dry Coolant Condition in Rough Cutting Experiments

			Dry- Without Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1	1500 | 47,12	0,03	432	482	173
2		0,04	497	536	203
3		0,05	515	590	210
4	2500 | 78,5	0,03	560	619	333
5		0,04	625	692	386
6		0,05	671	822	541
			Dry- With Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1	1500 | 47,12	0,03	434	479	284
2		0,04	454	528	338
3		0,05	501	625	417
4	2500 | 78,5	0,03	482	489	239
5		0,04	483	562	299
6		0,05	520	571	273

Table 4.6 Cutting Force Components of MQL Coolant Condition in Rough Cutting Experiments

			MQL- Without Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1	1500 | 47,12	0,03	448	425	172
2		0,04	457	440	200
3		0,05	479	504	216
4	2500 | 78,5	0,03	414	459	300
5		0,04	459	465	278
6		0,05	566	632	354
			MQL- With Ultrasonic Vibration		
Exp. #	**Spindle Speed (rpm) | Cutting Speed (m/min)**	**Feed (mm/tooth)**	**F_x**	**F_y**	**F_z**
1	1500 | 47,12	0,03	422	469	276
2		0,04	442	532	312
3		0,05	459	665	329
4	2500 | 78,5	0,03	410	393	307
5		0,04	428	367	336
6		0,05	440	538	432

After finding the components of the resultant cutting force on the X, Y and Z axis, resultant cutting forces is calculated using Equation 4.1. The changes of the resultant cutting force according to the cutting conditions can be seen in Table 4.7 below.

Table 4.7 Resultant Cutting Forces of Rough Cutting Experiments with different cutting conditions

Resultant Cutting Force (N) 3mm					
Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed (mm/tooth)**	**DRY-NU**	**DRY-U**	**MQL-NU**	**MQL-U**
1500 | 47.12	0.03	184,66	168,21	165,31	157,48
	0.04	253,96	244,99	238,38	232,54
	0.05	337,30	333,61	315,42	234,85
2500 | 78.5	0.03	280,02	266,87	235,04	195,54
	0.04	343,41	339,73	293,48	243,40
	0.05	431,19	376,68	352,75	301,94

As it described in previous chapter this study includes 24 experiments for 3 mm depth of cut in different machining conditions. These conditions are:

1. Dry machining
2. Dry machining with ultrasonic vibrations on Z axis
3. MQL machining
4. MQL machining with ultrasonic vibration on Z axis

Figure 4.15 shows the effect of ultrasonic vibration under dry cutting conditions, Figure 4.16 shows the effect of ultrasonic vibration under MQL conditions.

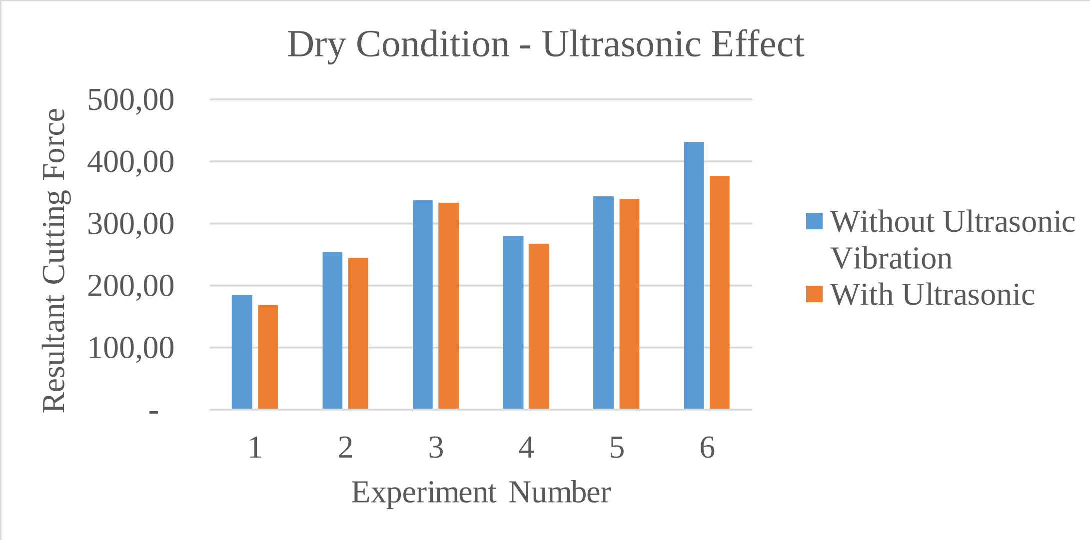


Figure 4.15 Dry condition with ultrasonic vibration effect on rough cut

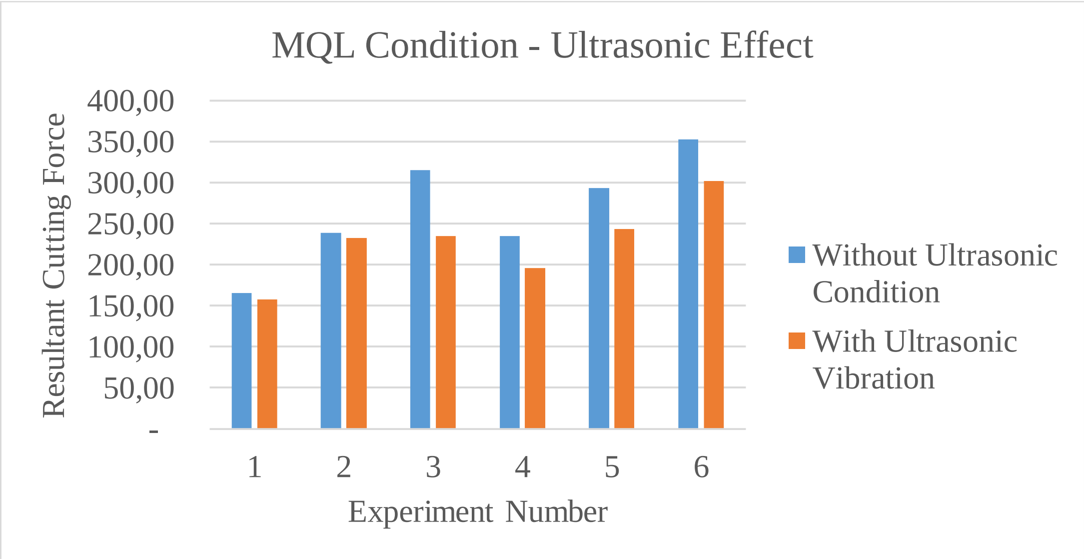


Figure 4.16 MQL condition with ultrasonic vibration effect on rough cut

In all experiments using ultrasonic vibrations, it has been observed that it reduces the resultant cutting forces regardless of the cooling medium. In dry cutting experiments, the highest improvement was found to be 78.5 m / min cutting speed and 0.05 mm / tooth feed with 14.62% cutting force decrease. In the experiments carried out under MQL condition, the highest improvement in cutting forces was observed in the experiment using a cutting speed of 47.12 m / min and 0.05 mm / tooth feed with a decrease of 25.71%. The experiments with the highest effect of ultrasonic vibrations were also observed under the highest feed conditions.

According to the experimental results, when the ultrasonic vibration is applied to the cutting tool, it is seen that the cutting forces always decrease. This can be explained by the following: Almost rough cuts are made at a cutting depth of 3 mm, so that the workpiece surface and cutting tool contact is very large. In this case, relatively high cutting forces are obtained. However, the ultrasonic vibrations applied to the cutting tool on the Z axis prevent this continuous contact. In each vibration cycle, cutting can only be performed at certain times, that is, theoretically, when the cutting tool and the workpiece are separated from each other, the cutting forces are reduced to zero, and with the reassembly, the cutting forces are re-emerged. The high friction caused by the wear resistance of the Ti-6Al-4V material previously mentioned is thus avoided. Since there is no continuous contact, friction is also interrupted and its effect is reduced. This reduced friction causes low cutting forces. When these two conditions are combined, the ultrasonic vibrations applied to the cutting tool on the Z axis reduce the cutting forces. This results consist with many studies in the literature [46],[54],[59],[60].

4.1.3.2 Investigation of Coolant Effect on Rough Cutting Experiments

In order to investigate the effect of coolant usage on cutting forces for the rough cutting, expmeriments were conducted under dry and MQL conditions. These experiments were performed with and without ultrasonic vibration to find the most suitable combination. In Figure 4.17 and Figure 4.18, the comparison of cooling medium is given both in the experiments where ultrasonic vibrations are applied and not, respectively.

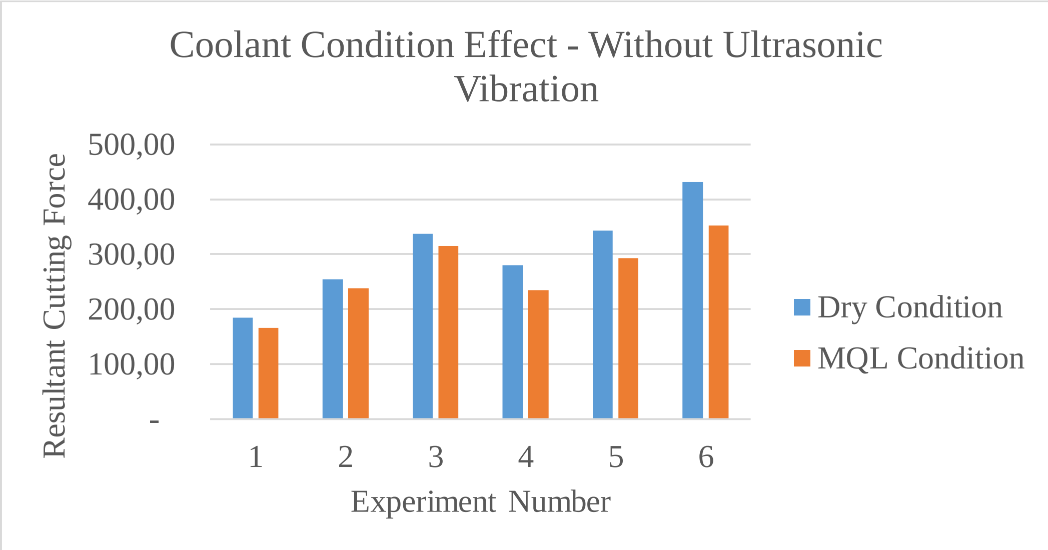


Figure 4.17 Coolant Condition Effect without Ultrasonic Vibration on rough cut

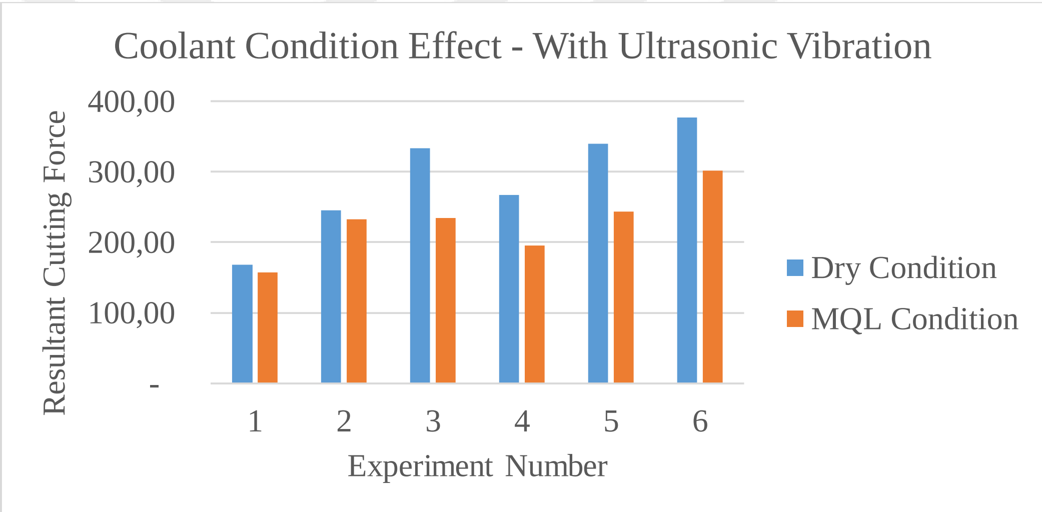


Figure 4.18 Coolant Condition Effect with Ultrasonic Vibration on rough cut

Regardless of the ultrasonic vibrations, the cutting forces were reduced in all experiments using MQL. In the experiments where ultrasonic vibrations were not applied, the cutting forces at 78.5 m / min and the cutting forces at 0.05 mm / tooth feed were the biggest differences with 18.19% drop. In the experiments where ultrasonic vibrations were applied, the highest reduction in cutting forces was observed at 48.12 m / min cutting speed and 0.05 mm / tooth feed and a 29.6% decrease was observed due to MQL usage. In both conditions with and without ultrasonic vibrations, the highest differences in the reduction of cutting forces due to the use of MQL were commonly the highest feed of 0.05 mm / tooth.

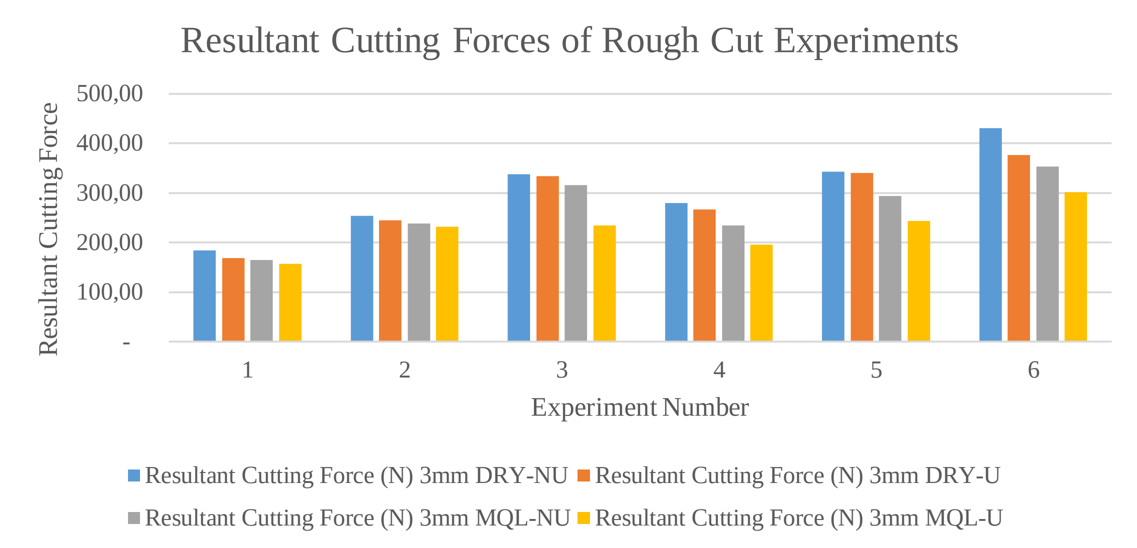


Figure 4.19 Resultant Cutting Forces of Rough Cut Experiments

When all experiments performed at a cutting depth of 3 mm were compared, both ultrasonic vibration and MQL usage were taken into consideration, as shown in Figure 4.19, the highest reduction in cutting forces was observed in experiements which these two conditions together. According to the dry cutting condition and the experiments without ultrasonic vibration, the highest difference of cutting forces in the MQL and ultrasonic vibration experiments was found in the experiment performed at 48.12 m / min cutting speed and 0.05 mm / teeth feed and this difference was seen as 30.37% and also %29.97 reduction observed at 78.5 m/min and 0.05 mm/tooth experiments.

The results obtained can be explained as follows: When MQL is used, the sprayed aerosol can penetrate anywhere in the cutting zone. In addition, it reduces the friction between the cutting tool and the workpiece due to its lubrication feature. On the other hand, when applied to the cutting zone with low evaporation temperature, it can remove the accumulated heat from the medium by sudden evaporation. Due to the low thermal conductivity characteristic of Ti-6Al-4V, the heat accumulated on the tool, not on the workpiece, is thus removed from the environment and prevents damage to the cutting tool.

The reasons for the improvement using ultrasonic vibration and MQL together can be explained as follows, when the ultrasonic vibrations are applied, the cutting tool is separated from the workpiece on a regular basis, but this is at the cutting tip. Apart from the cutting tip, the area where the tool and the workpiece touch is also high due to the height of the cutting depth. The application of ultrasonic vibration improves where the cutting tool is in contact with the bottom surface, where the cutting tool contacts the workpiece, but does not have such effective effect on the surfaces that come into contact with the lateral surfaces because even if the vibrations are applied, intermittent contact is not possible in those areas. This is where MQL comes in and can penetrate both the bottom surface and any side where the lateral surfaces come into contact with the cutting tool. In this way, it reduces friction where the effect of ultrasonic vibrations is low. With this combination, the cutting efficiency is greatly increased and optimally reduces the cutting forces. This combination was made for the first time in this study and this finding is not available in the literature yet.

4.1.3.3 Investigation of Feed and Cutting Speed on Rough Cutting Experiments

Another result that can be deduced from the experiment results is the increase of cutting forces with increasing feed regardless of ultrasonic vibrations, cooling medium and cutting speed. Increased feed amount with increasing feed increases the amount of material that the cutting tool needs to remove. This increase also increases the contact area between the cutting tool and the workpiece, resulting in higher friction and the resulting high friction increases the cutting forces.

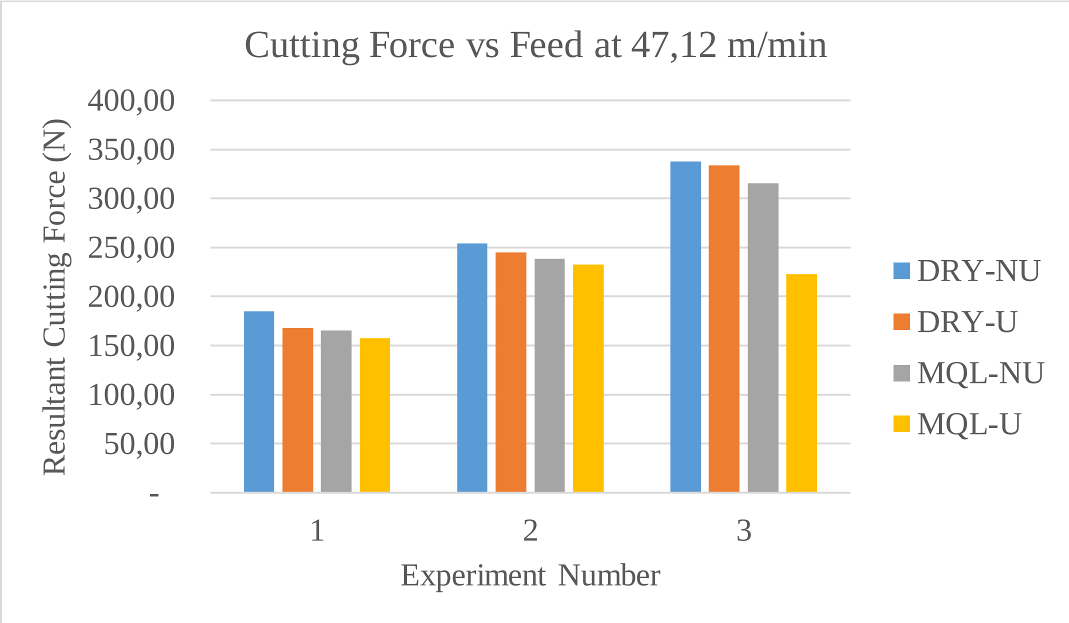


Figure 4.20 Resultant cutting forces of 47.12 m/min cutting speed experiments

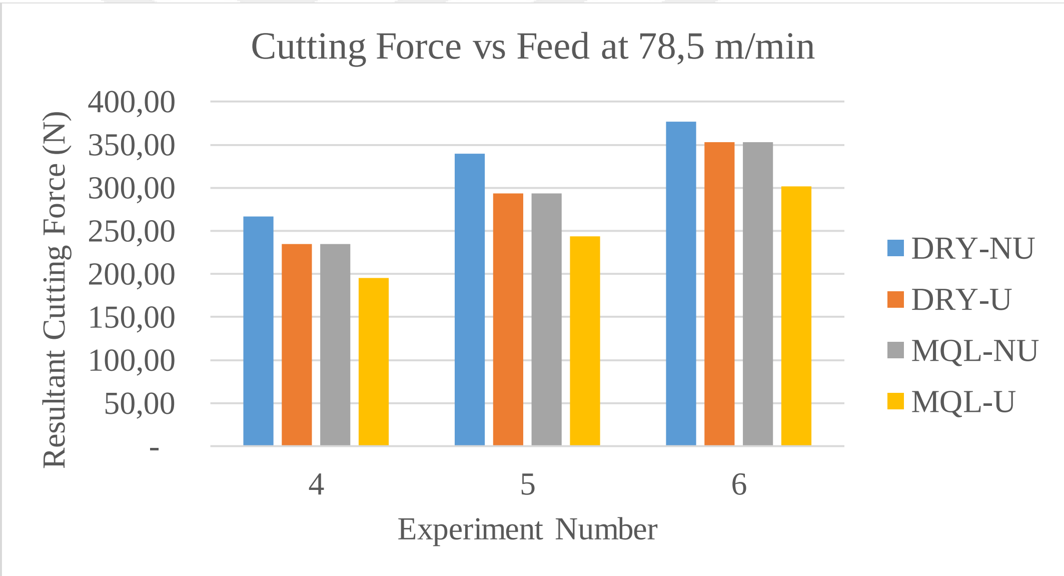


Figure 4.21 Resultant cutting forces of 78.5 m/min cutting speed experiments

It has been observed that the cutting force increases independently of the other variables with the increase of the cutting speeds. It is known that as the cutting speed increases, the temperature in the cutting zone increases due to friction. Low thermal conductivity of the Ti-6Al-4V material makes it difficult to cut. Since the heat accumulated in the cutting zone cannot be removed with the chip, this heat sink accumulates on the uncut surface of the tool and workpiece. Due to the heat accumulated on the uncut surface of the workpiece, the material undergoes strain hardening, which increases the cutting forces by making it difficult to remove chips from the surface of the material. These results supported by several studies in the literature. [98], [99], [100].

4.1.4 Comparison on Cutting Forces of Finish Cut and Rough Cut Experiments

As seen in the experiments, ultrasonic vibrations on the cutting tool caused an increase in the cutting forces in the experiments carried out at the cutting depth of 0.3 mm which is finish cut, while the ultrasonic vibrations applied to the cutting tool decreased the cutting forces in the experiments performed at the cutting depth of 3 mm which is rough cut. According to these results finish cut is not suitable for ultrasonic assisted milling. However, it is concluded that rough cut can be machined more efficiently with ultrasonic assisted milling. The different results of uItrasonic vibrations at different cutting depths can be explained as follows: Ultrasonic vibrations in the Z-axis direction, which are referred to as the hammer effect at a cutting depth of 0.3 mm and increase the cutting forces, have increased the cutting forces to a negligible level when the cutting depth is reached. However, thanks to the intermittent contact caused by ultrasonic vibrations, the advantage was achieved and reduced cutting forces at a cutting depth of 3 mm. At the cutting depth of 0.3 mm, the effect of this intermittent contact was lower than the hammer effect and therefore no positive results were obtained. In addition, the feeds where the ultrasonic vibrations obtained the most effective results in the experiments were often the highest feeds of 0.05 mm / tooth. High feed is also a feature of rough cut like high depth of cut. This data is supported by the fact that ultrasonic vibration applied to the cutting tool causes improvement in rough cut operations. In the light of this information, it is clearly seen that high cutting forces occur and ultrasonic vibrations decrease the cutting forces and result in less energy consumption in rough cut processes. It was also found that ultrasonic vibrations with MQL were more efficient for higher cutting force reduction as seen in rough cut experiments. The same cannot be said for the 0.3 mm cutting depth. The use of MQL combined with ultrasonic vibrations at a cutting depth of 0.3 mm has been found to increase cutting forces, but without ultrasonic vibration, MQL alone reduces cutting forces. This information also demonstrates the benefit of using MQL and ultrasonic vibrations together at high cutting depths.

4.2 Investigation on Surface Roughness Results

4.2.1 Finish Cutting Experiments

In order to study the effects of cutting parameters, coolant conditions and ultrasonic vibrations on surface roughness, for each experiment machined surfaces roughness measured. Surface roughness measurement was done with Mahr PS1 Pocket Surf 6910214. In order to ensure consistency of the measured values, three measurements were made from the surface formed after each experiment and averaged. The mesurement results from the bottom surface for finish cutting experiments are given in Table 4.8 below.

Table 4.8 Ra Value of Finish Cut Experiments

Finish Cut Experiments Ra Value							
Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed (mm/tooth)**	**Dry-NU**	**DRY-U**	**Wet-NU**	**Wet-U**	**MQL-NU**	**MQL-U**
1500/47,12	0,03	0,940	0,803	0,898	0,745	0,855	0,606
	0,04	1,232	0,864	1,072	0,816	0,922	0,744
	0,05	1,509	1,212	1,367	1,105	1,272	0,989
2000/62,8	0,03	1,121	0,855	0,997	0,752	0,925	0,532
	0,04	1,171	0,945	1,133	0,836	1,008	0,734
	0,05	1,596	1,114	1,475	0,956	1,366	0,776
2500/78,5	0,03	1,254	0,986	1,100	0,882	1,045	0,648
	0,04	1,507	1,102	1,425	1,051	1,375	0,941
	0,05	1,653	1,180	1,602	1,154	1,501	1,072

4.2.1.1 Effect of Ultrasonic Vibrations on Surface Roughness in finishing operations

Effects of ultrasonic vibrations on surface roughness with in different lubrication conditions (dry, wet and MQL) is investigated and the graphs for all cooling media are given below. The ultrasonic vibration effect in dry cutting is shown in Figure 4.22.

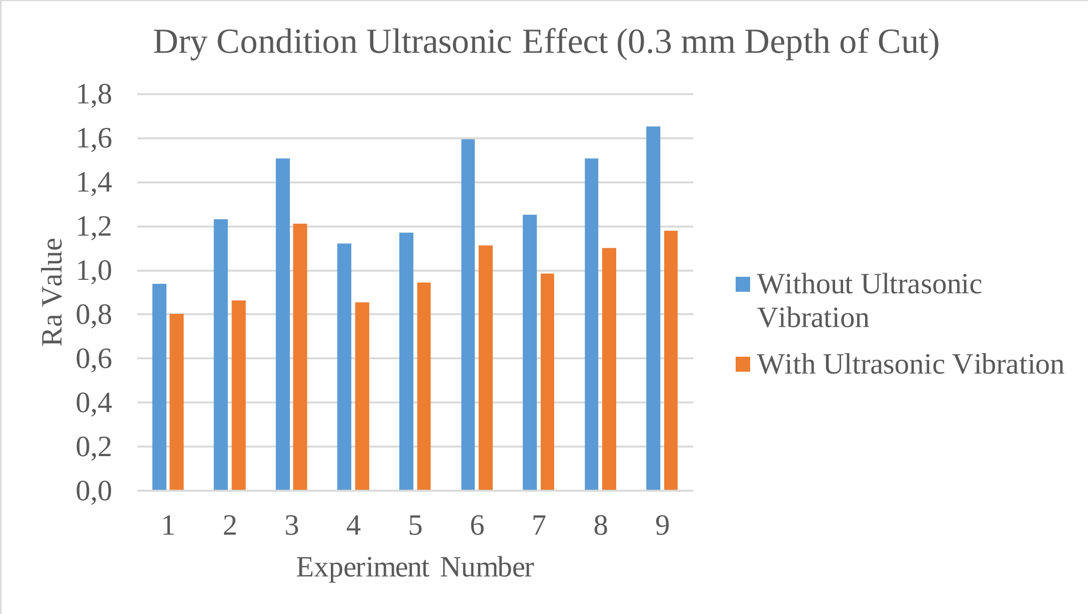


Figure 4.22 Dry condition with ultrasonic vibration effect on Ra value of finish cut

When ultrasonic vibrations were applied in the dry cutting condition, the highest rate of improvement was observed in the experiments at a cutting speed of 62.8 m / min and 0.05 mm / tooth feed and reduced surface roughness by 30.2%. Minimum reduction was observed at cutting speed 47.12 m/min and 0.03 mm/tooth feed with 14.5%. Average reduction is 23.8% in dry cutting condition when ultrasonic vibrations were applied.

The ultrasonic vibration effect in wet cutting is shown in Figure 4.23.

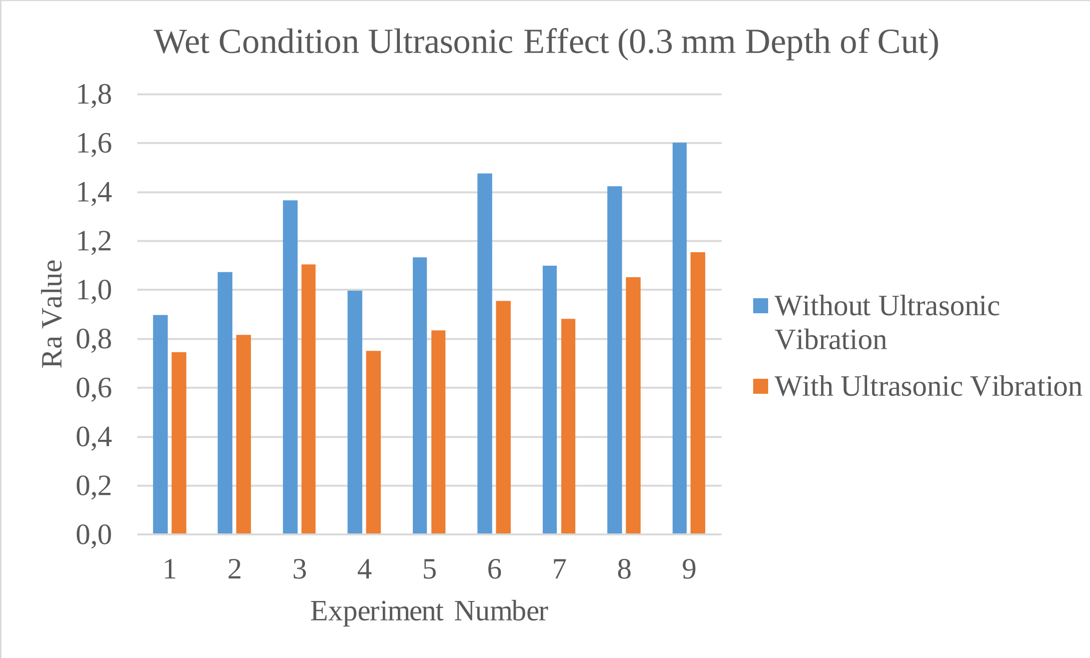


Figure 4.23 Wet condition with ultrasonic vibration effect on Ra value of finish cut

In wet cutting conditions, the highest improvement was achieved with a decrease of 35.16% and again with a cutting speed of 62.8 m / min at 0.05 mm / tooth feed. The lowest reduction was observed in experiments at cutting speed 47.12 m/min and 0.03 mm/tooth feed with 17%. The average value of reduction of surface roughness was 24.4% when considering all wet cutting conditions with ultrasonic vibration applied. The ultrasonic vibration effect in MQL cutting is shown in Figure 4.24.

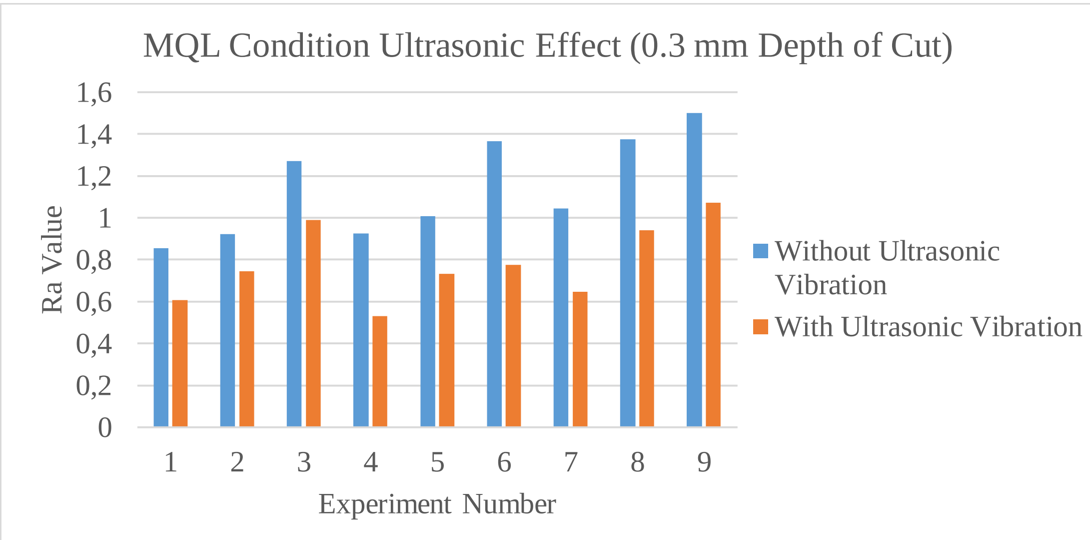


Figure 4.24 MQL condition with ultrasonic vibration effect on Ra value of finish cut

In the MQL condition, the highest improvement rate was obtained in 62.8 m / min and 0.05 mm / tooth feed and this decrease rate was calculated as 43.13%. The lowest decrease in the results obtained in the experiment with a cutting speed of 47.12 m / min and 0.03 mm / tooth feed was 19.3%. On average, a reduction of 31.3% was observed when ultrasonic vibration was used in MQL experiments.

In all experiments, it was observed that surface roughness decreased when ultrasonic vibration was applied on the cutting tool. This reduction occurs independently of the cooling medium, cutting speed and feed. According to the results, the highest improvement rates were always the same cutting speed and feed parameters which is 62.8 m/min cutting speed and 0.05 mm/tooth feed, regardless of the cooling medium. The lowest reduction rates in dry and wet cutting experiments were also in the same tests and these test parameters were 47.12 m / min cutting speed and 0.03 mm / tooth tests, but in MQL experiments this condition changed and the lowest reduction rate was 47.12 m / min cutting speed and 0.03 mm/tooth feed experiments. As can be seen, the cutting speed with the lowest reduction is 47.12 m / min for all coolant conditions but a common value of the three coolant conditions could not be determined for the feed parameter.

When ultrasonic vibration is applied, it is seen that the highest reduction rate of surface roughness is obtained when using MQL with 31.3% according to cooling conditions. The surface roughness of MQL was 6.9% lower than wet cutting and 7.5% lower than dry cutting. The difference between dry cutting conditions and wet cutting conditions was observed to be only 0.6%.

The graph showing the effect of ultrasonic vibrations together with the coolant conditions is given in Figure 4.25.

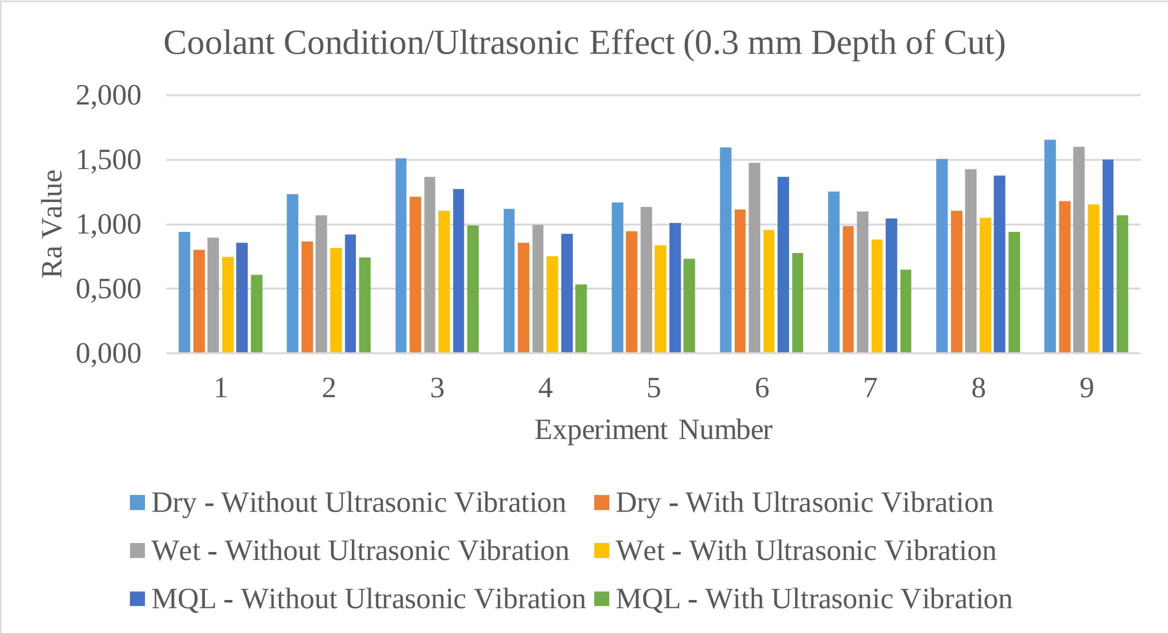


Figure 4.25 Coolant condition with ultrasonic vibration effect on Ra value of finish cut

As shown in Figure 4.25, the lowest surface roughness values were obtained by combining the MQL condition with ultrasonic vibrations. It is followed by a combination of ultrasonic vibration and wet cutting condition. The third is the surface roughness values of ultrasonic vibrations and dry cutting conditions. This shows that when ultrasonic vibrations are used, better surface roughness values are obtained independent from cooling medium.

4.2.1.2 Effect of Coolant Condition on Surface Roughness of Finish Cutting Experiments

The effect of ultrasonic vibrations on surface roughness in different cooling conditions, is given in Figure 4.26.

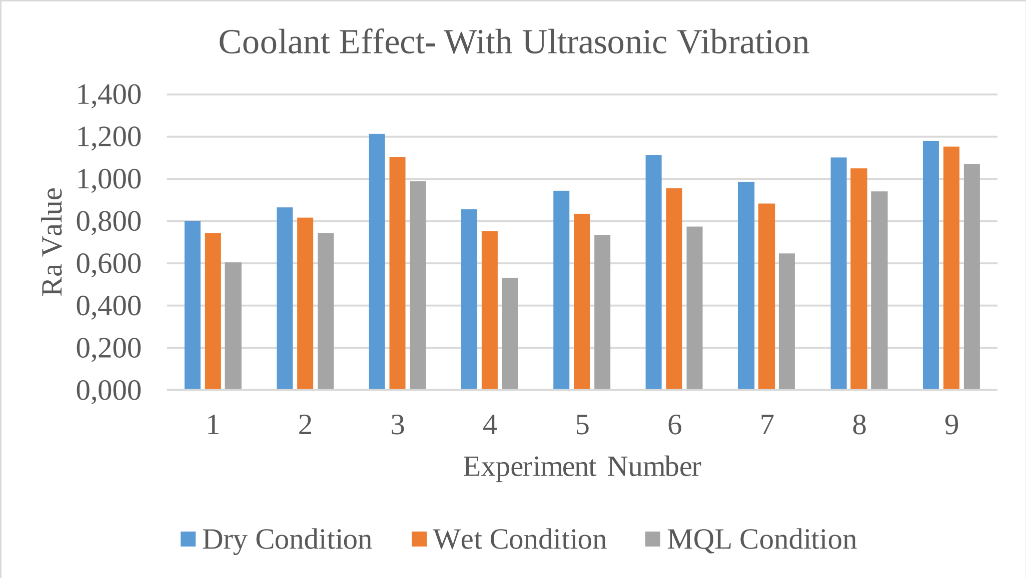


Figure 4.26 Effect of coolant condition with ultrasonic vibration on Ra value of finish cut

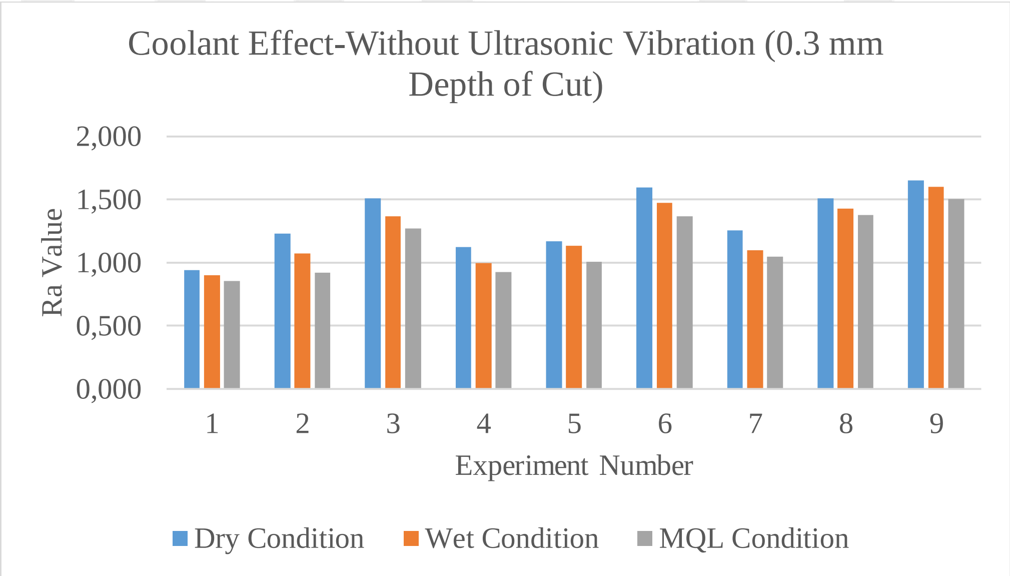


Figure 4.27 Effect of coolant condition without ultrasonic vibration on Ra value of finish cut

When the difference between dry cutting condition and wet cutting condition was examined, it was found that wet cutting condition gave lower surface roughness value in all experiments. It was observed that the surface roughness value in wet cut decreased by maximum 12.9% and this reduction rate was observed in the test performed at 47.12 m / min cutting speed and 0.04 mm / tooth feed. Again, the lowest difference between these two cutting conditions was seen in the experiment with 3.1% and 78.5 m / min cutting speed and 0.05 mm / tooth feed. In addition, an average surface roughness of 7.7% was decreased.

When the change between dry cut and MQL condition is examined, it is seen that surface roughness in all experiments performed under MQL condition gives lower results than dry cut. The greatest difference between these two cooling conditions was at a cutting speed of 47.12 m / min and a feed of 0.04 mm / tooth, resulting in a 26.6% reduction in surface roughness. The lowest reduction rate was 8.7% with 78.5 m / min cutting speed and 0.04 mm / tooth feed. In addition, it has been found that the use of MQL reduces surface roughness values by 14.4% on average compared to dry cutting.

When the difference of surface roughness values between wet cutting and MQL condition is examined, it is seen that MQL condition gives lower surface roughness value in all experiments than wet cutting condition. The highest difference between these two cooling conditions was 13.9% reduction in the cutting speed of 47.12 m / min and 0.04 mm / tooth feed. The lowest difference was found in the experiments with a cutting speed of 3.5% to 78.5 m / min and 0.04 mm / tooth feed. It was found that the MQL condition caused an average decrease of 7.3% in surface roughness values compared to wet cutting.

The highest reduction ratio for the surface roughness values were at the same cutting speed of 47.12 m / min and same feed of 0.04 mm / tooth for all three comparison. Furthermore, the MQL condition gave the lowest surface roughness in all experiments, regardless of feed or cutting speed. The second lowest surface roughness value was given by wet cutting and the highest surface roughness value by dry cutting.

4.2.2 Rough Cutting Experiments

4.2.2.1 Effect of Ultrasonic Vibration on Surface Roughness in Rough Cutting

In order to see the effect of the cutting depth on the surface roughness, 3 mm cutting depth experiments were performed. The experiments were performed at two different cutting speeds to see the effect of the cutting speed and three separate feeds to see the effect of the feed. At the same time, the same experiments were repeated under MQL conditions with the condition of dry cutting to see the effect of the cooling medium. Finally, in order to see the effect of ultrasonic vibration, experiments were performed both with ultrasonic vibrations and without ultrasonic vibration. The results can be seen in Table 4.9.

Table 4.9 Ra Value of Rough Cut Experiments

Exp. #	**3 mm Depth of Cut Experiments**					
	Spindle Speed (rpm) | Cutting Speed (m/min)	**Feed (mm/tooth)**	**Dry-NU**	**DRY-U**	**MQL-NU**	**MQL-U**
1	1500/47,12	0,03	1,809	1,018	1,371	0,882
2		0,04	1,905	1,110	1,461	1,012
3		0,05	2,147	1,504	1,846	1,407
4	2500/78,5	0,03	1,563	1,316	1,478	0,853
5		0,04	1,802	1,497	1,664	1,251
6		0,05	2,297	1,728	1,953	1,651

The ultrasonic vibration effect in dry cutting with 3 mm depth of cut is shown in Figure 4.28.

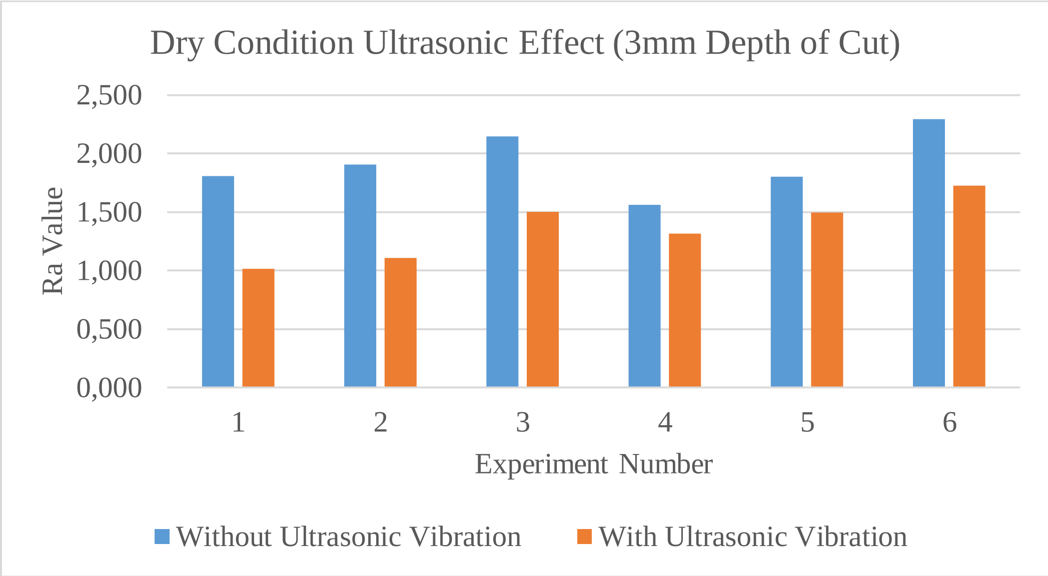


Figure 4.28 Dry condition with ultrasonic vibration effect on Ra value of rough cut

When the ultrasonic effect of dry cutting was investigated, the highest reduction rate was found in the experiments performed at 47.12 m / min cutting speed and 0.03 mm / tooth feed and this rate was 43.7%. Minimum reduction was observed at cutting speed 78.5 m/min and 0.03 mm/tooth feed with 15.8%. Average reduction is 28.8% in dry cutting condition when ultrasonic vibrations were applied.

The ultrasonic vibration effect in MQL condition with 3 mm depth of cut is shown in Figure 4.29.

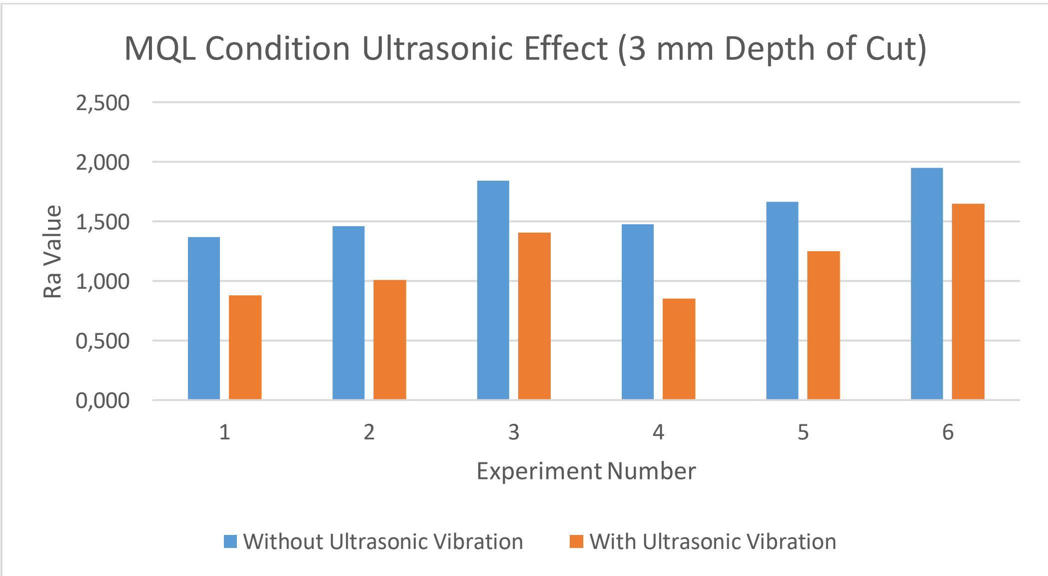


Figure 4.29 MQL condition with ultrasonic vibration effect on Ra value of rough cut

The maximum reduction rate with ultrasonic vibration in MQL cutting was 42.3% with 78.5 m / min cutting speed and 0.03 mm / tooth feed. %. The lowest decrease in the results obtained in the experiment with a cutting speed of 78.5 m / min and 0.05 mm / tooth feed was 15.4%. On average, a reduction of 28.7% was observed when ultrasonic vibration was used in MQL experiments.

As seen in the results of the experiment, the maximum decreases in both cooling environments were at the same feed level also it is seen that the ultrasonic vibrations applied on the cutting tool reduce the surface roughness regardless of the coolant, cutting speed and feed. When we look at the highest reduction rates, it is seen that 42.3% reduction in MQL condition and 43.7% decrease in dry cutting condition are almost the same. Although these reduction rates were obtained at different cutting speeds, both were obtained at the same feed 0.03 mm / tooth. When we look at the lowest rates of surface roughness reduction when ultrasonic vibration is applied, we observe that it is around 15% in both conditions and there is not much difference between them. In addition, the lowest reduction rates in both dry cutting and MQL conditions were observed at cutting speed of 78.5 m / min, but these results were obtained in experiments using different feeds. When ultrasonic vibrations were applied to the cutting tool in MQL condition and dry cutting, the reduction ratio of the surface roughness in both conditions was calculated as 28% and the difference between them was less than 1%.

The effect of the coolant condition and the ultrasonic vibrations together for rough cutting can be seen in Figure 4.30.

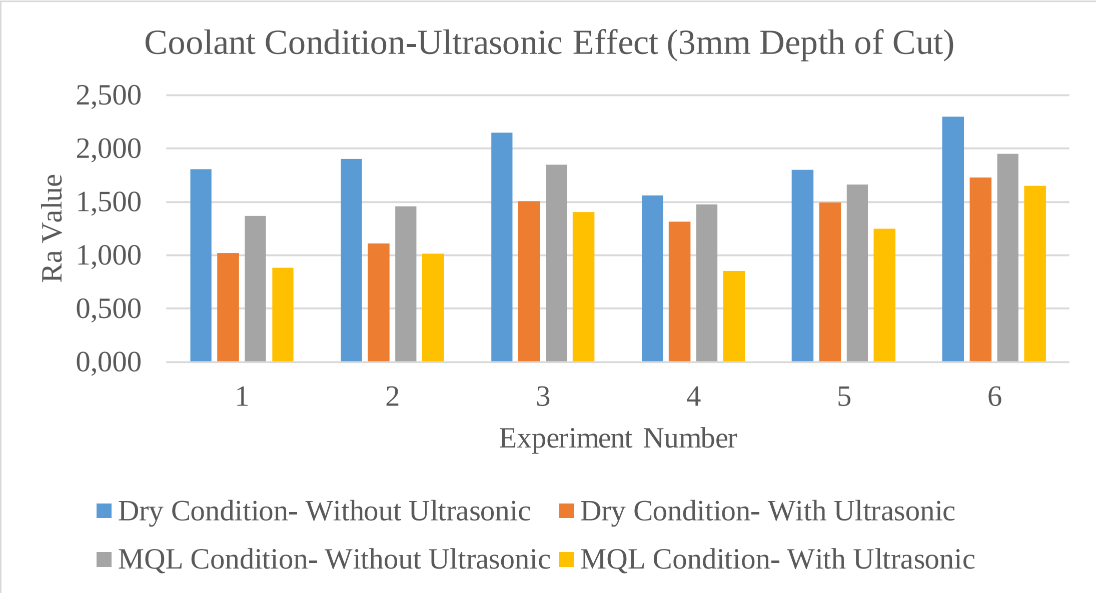


Figure 4.30 Coolant condition with ultrasonic vibration effect on Ra value of finish cut

The effect of the cooling medium and the ultrasonic vibrations together can be seen in Figure 4.30. As can be seen, the best surface roughness results were obtained in the experiments using MQL condition and ultrasonic vibrations. Second best surface roughness values come from the experiments performed by combining dry cutting with ultrasonic vibration. These are followed by ultrasonic vibration with MQL condition followed by dry cutting without ultrasonic vibration.

4.2.2.2 Effect of Coolant Condition on Surface Roughness for Rough Cutting Experiments

In rough cutting experiments the change in surface roughness in different cooling medium with and without ultrasonic vibrations are given in Figures 4.31 and 4.32.

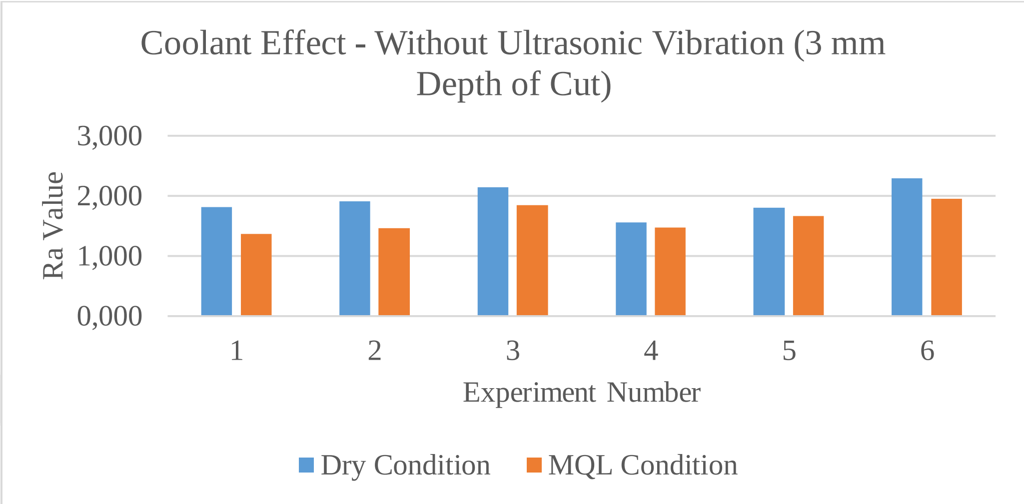


Figure 4.31 Effect of coolant condition without ultrasonic vibration on Ra value of rough cut

In order to investigate the effect of MQL application, which is one of the main subjects of the research, on surface roughness in rough cutting, it was compared with dry cutting condition. In addition, the experiments were performed both in the presence of ultrasonic vibrations and without using ultrasonic vibrations.

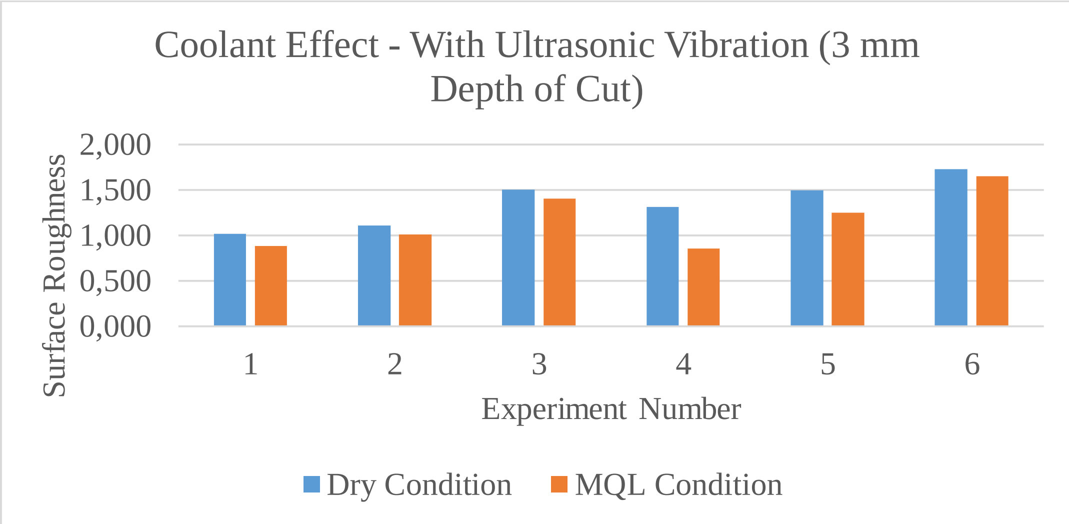


Figure 4.32 Effect of coolant condition with ultrasonic vibration on Ra value of rough cut

When we switched from dry cutting to cutting in MQL condition and no ultrasonic vibration was applied, the highest improvement was achieved at 24.21% at a cutting speed of 47.12 m / min and 0.03 mm / tooth feed. The lowest reduction rate was 78.5 m / min cutting speed and 0.03 mm / tooth feed, which was 5.4%. In addition, in these experiments performed without ultrasonic application, it was observed that the surface roughness values decreased by 14.9% on average compared to dry cutting when MQL was applied.

In the experiments where ultrasonic vibration was applied, when we changed dry cutting to MQL condition, the highest improvement with 35.18% reduction in surface roughness was observed in 78.5 m / min cutting speed and 0.03 mm / tooth feed parameters. The lowest reduction rate was 4.5% with 78.5 m / min cutting speed and 0.05 mm / tooth feed. In the experiments applied ultrasonic vibrations, the average of the reduction in surface roughness values given by MQL compared to dry cutting is 14.2%.

When the surface roughness values given by dry cutting in rough cutting under the effect of ultrasonic vibrations were examined, it was seen that the experiments performed with ultrasonic vibration always had better surface roughness. The highest improvement was achieved with a cutting speed of 48.12 m / min and a feed of 0.03 mm / tooth with a 43.7% reduction. The lowest decrease was seen in the cutting speed of 78.5 m / min and 0.03 mm / tooth feed with 15.8%. In general, when the ultrasonic vibrations were applied, it was seen that the surface roughness values of dry cut decreased 28.8% on average compared to the experiments without ultrasonic vibration. When the effects of the presence of ultrasonic vibrations on surface roughness values were examined in the experiments using MQL in rough cutting, it was found that the experiments applied ultrasonic vibration always gave lower surface roughness values. The highest rate of decrease was observed in 42.3% 78.5 m / min cutting speed and 0.03 mm / tooth feed experiments. The lowest decrease rate was 15.4% with 78.5 m / min cutting speed and 0.05 mm / tooth feed. When ultrasonic vibrations are applied in the use of MQL in rough cutting, the average surface roughness values of ultrasonic vibrations have decreased by 28.8% compared to no ultrasonic vibration experiments. In the light of the obtained data, MQL condition increases its efficiency and gives better surface roughness values when applied together with ultrasonic vibrations. In addition, although the difference between the MQL condition and the dry condition is reduced in the experiments using ultrasonic vibrations, this does not have a great effect due to the reduction of the average surface roughness. In both dry cutting and MQL experiments with ultrasonic vibration, the average decrease in surface roughness tests is 28% and is very close to each other. Regarding the surface roughness data of dry cut and MQL condition, regardless of the presence of ultrasonic vibrations, an average reduction of 14% was observed. However, when MQL is used with ultrasonic vibration, it is observed that there is an average decrease of 39.45% compared to dry section without ultrasonic vibration.

4.2.3 Discussion on Effect of Ultrasonic Vibrations on Surface Roughness

The fact that the ultrasonic vibrations applied in z direction to the cutting tool have an improvement over the surface roughness can be explained as follows; in the experiments where ultrasonic vibrations are applied, the cutting tool and workpiece are not in continuous contact but in intermittent contact. As a result, the tip of the cutting tool is separated from the workpiece 19000 times per second and reengaged. Higher stresses during the cutting operation of Ti-6Al-4V, continuous contact between cutting tool and workpiece and lower thermal conductivity of Ti-6Al-4V, increase the temperature in cutting zone severely and this increase in temperature of cutting zone expedite tool wear and decrease the machined surface quality considerably. By applying ultrasonic vibrations this continuous interaction between cutting tool and workpiece is eliminated and as cutting tool tip comes out of contact with the workpiece 19000 times per second, it can escape from the friction and cool down. In this way, the heat accumulated on the cutting tool is reduced, and with the decreasing heat, the cutting tool does not lose its sharpness and creates a more uniform surface.

The reason for the improvement in surface roughness when the ultrasonic vibration is applied is the highest in the MQL condition, second in the wet cutting condition and finally in the dry cutting condition; When ultrasonic vibrations are applied to the cutting tool, there is a gap between the cutting tool and the workpiece in the vibration cycle that occurs when the cutting tool is separated and reassembled from the workpiece. Coolant in MQL and wet cooling processes may easily enter this gap between the cutting tool and the workpiece and cool down both workpiece and cutting tool surfaces. When the cutting tool leaves the workpiece, the tool tip may take time to cool down, as well as coolants entering this gap, which can further increase the cooling rate and improve tool performance. Since the MQL condition is known to be a more efficient technique than the normal coolant condition the surface roughness improvement rate of the MQL condition was higher [12], [13], [71]. In addition, the effect of the MQL condition is further explored in the following section.

4.2.4 Discussion on Effect of Coolants on Surface Roughness

The highest surface roughness improvement of the experiments using MQL can be explained as follows; MQL is an aerosol structure which is sprayed in aerosol form. Unlike solely liquid form, this form can penetrate the cavities at the micron level. Thanks to this feature, MQL can penetrate in every detail that comes into contact with each other between the cutting tool and the workpiece. In this way, the friction between tool and workpiece decreases significantly. Ester based oil used in MQL method. Ester based oils have a very high lubricating effect as well as low evaporation temperatures [101]. The aerosol penetrates into the cutting zone and decrease concentrated heat of cutting zone immediately. The lubricating effect and the ability to reduce the cutting zone temperature have also been found in the use of normal coolant. However, since it is not as efficient as MQL [13], surface roughness improvement remained limited level. Since none of these conditions can be seen in dry cutting, it has the highest surface roughness values.

4.2.5 Discussion on Effect of Feed, Cutting Speed and Depth of Cut on Surface Roughness

The results of cutting parameters (feed, cutting speed and depth of cut) also studied in this research. The average surface roughness values are lower in finish cut than rough cut. The reason for this increase is thought to be due to the increased vibration of the cutting tool and deterioration of the stability of the cutting tool because higher amount of chip removal in rough cut experiments. The cutting tool with reduced stability may vibrate while removing chips, leaving more marks on the surface. This increases the average surface roughness.

The cutting speed and feed followed similar trend and increased the surface roughness same at both finish cut and rough cut. Surface roughness increased as feed and cutting speed increased regardless of ultrasonic vibration or cooling medium in both cutting depth experiments. Increasing surface roughness can be explained as when the cutting speed increases, the cutting time getting higher and this results as higher the contact time between the cutting tool and the workpiece so this leads to the higher the friction and higher the cutting zone temperature. This resulting temperature cannot be thrown away by chips because of the low thermal conductivity of Ti-6Al-4V, but it accumulates on the cutting tool and causes softening. The tool which starts to lose its hardness loses its wear resistance and starts to wear, and the surfaces cut by the wearing tool are not uniform. Therefore, surface roughness decreases with increasing cutting speed. Increased surface roughness with increasing feed depends on the increased amount of chip, with increasing feed starts to increase friction, which leads to increased temperature. In addition, increasing feed will create vibration on the cutting tool and thus destabilize the cutting tool, resulting in the increased roughness of the surface. These effects are consistent with the results of many studies [102], [103], [104].

4.2.6 Discussion on 3D Surface Profile Images

3D surface profiles measured on an optical microscope named Alicona Infinite Focus. Measurements made with MahrSurf match those with Alicona Infinite Focus. The reason why all surface roughness measurements are not performed at Alicona Infitine Focus is to avoid long measurement times and costs. However, the surfaces measured at Alicona Infinite Focus have been selected careful so that all parameters can be compared.

The maximum cutting speed of 78.5 m / min and the highest feed of 0.05 mm / tooth were selected as the cutting parameters for 3D profile measurement. The aim of this selection is to see the differences in the conditions where the technically highest surface roughness is obtained.

The effect of ultrasonic vibration in dry cutting, the effect of the cutting depth and finally the effect of the cooling medium can be seen in the figures. In all images, the figures on the left side show the surfaces where ultrasonic vibration is applied, while those on the right show those that do not have ultrasonic vibration. The color bars next to the figures show how close the surface recesses are to zero. The reason for changing the bar spacing in each graph is due to the very high surface roughness in some experiments. The deeper the color, the deeper the surface. Traces on the left side are deeper than the surface on the right side. These traces also cause an increase in surface roughness values. In addition, a more uniform surface was obtained in the experiments using ultrasonic vibrations. Thanks to this uniform surface, better surface roughness is obtained.

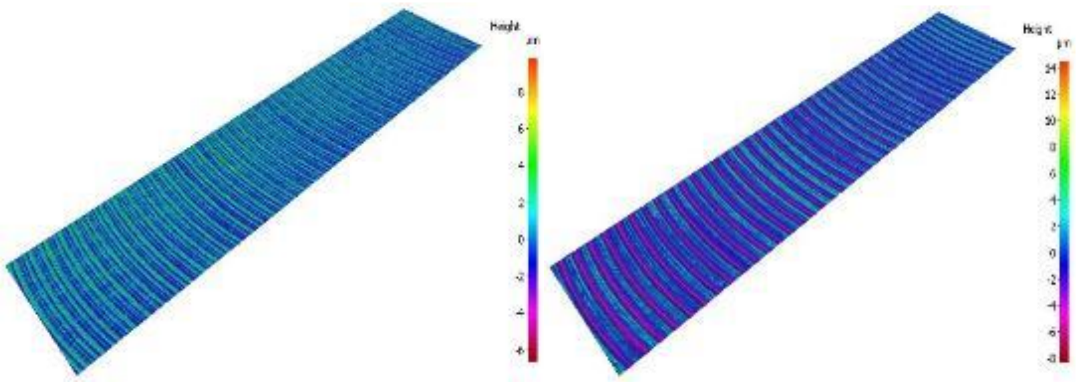


Figure 4.33 3D Surface Profiles of Finish Cut, Dry Condition, With (Left) Without (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

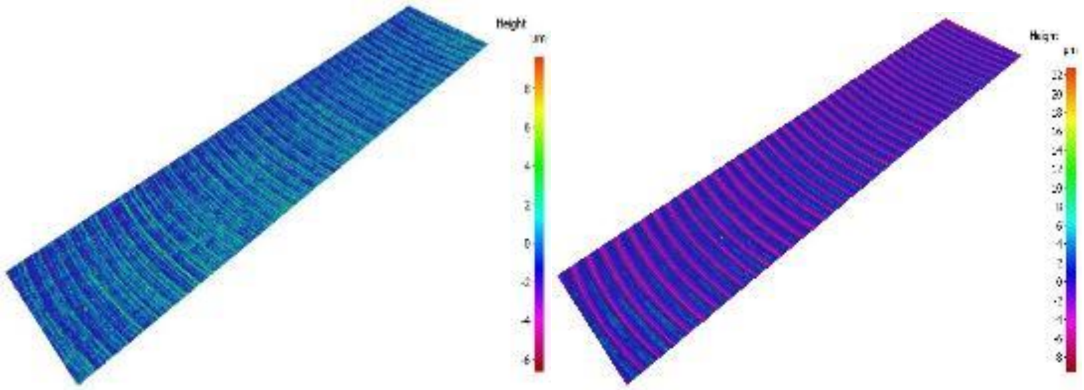


Figure 4.34 3D Surface Profiles of Rough Cut, Dry Condition, With (Left) Without (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

Regardless of the cooling conditions and the depth of cut, all experiments where ultrasonic vibrations are applied show almost the same color throughout the surface, proving a more homogeneous surface. Furthermore, when the color bar is examined, it is seen that the surfaces giving the color closest to 0 are also observed. As shown in Figure 4.33, the colors where ultrasonic vibrations are applied are very close to 0. In fact, it can be seen in Figure 4.34 that almost no tool marks are seen in the ultrasonic vibrating experiments on the finish cut and the whole surface is very homogeneously green. In this image, the green color indicates the surface roughness value from 0 to 0.5 µm. On surfaces where ultrasonic vibration is not applied, deeper marks and darker colors are observed. It is also observed that the surface does not have a homogeneous color distribution. This inhomogeneity also greatly affects the average surface roughness. In the experiments where ultrasonic vibrations are not applied, the surface roughness values are up to 1.5 µm depending on other parameters.

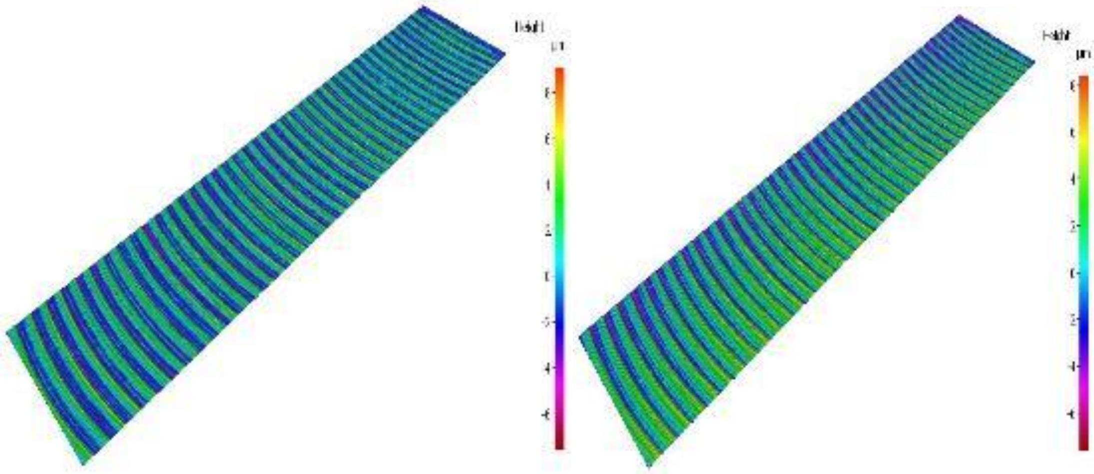


Figure 4.35 3D Surface Profiles of Rough Cut, Wet Condition, With (Left) Without (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

Another prominent output relates to cooling conditions. As can be seen, the surface roughness is close to zero in the MQL cooling method as it can be seen from Figure 4.36, blue color shows Ra value around between 0-1 µm and this means a much better result than dry cutting conditions which color range is vary between dark blue to and red and Ra value variates between 1-1.5 µm. Wet cuts are between MQL and dry cuts, although darkness of the colors is not as high as dry cuts. When the images in dry cut are examined, we see that there are darker colors than MQL condition. This color scale from dark blue to red proves that the surface traces are deeper than MQL. Furthermore, there is no homogeneous color distribution on the surface and the colors change along the surface. When we look at the images made in wet cuts, it can be said that it is exactly between MQL and dry cuts. Neither light colors as MQL nor dark colors as dry cuts were obtained. The color scale generally ranges between dark green and blue. In addition, surface homogeneity is better than dry cut, but not as uniform as in MQL condition. While the surface of the images in MQL condition is between 0-0.5 µm, this range increases to 0.7 / 0.8 µm in wet section and it is above 1 µm in dry section.

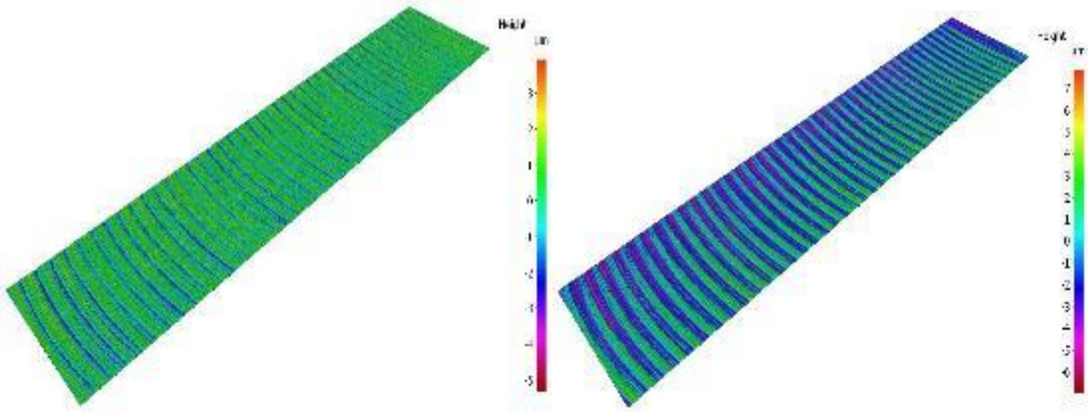


Figure 4.36 3D Surface Profiles of Finish Cut, MQL Condition, With (Left) Without (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

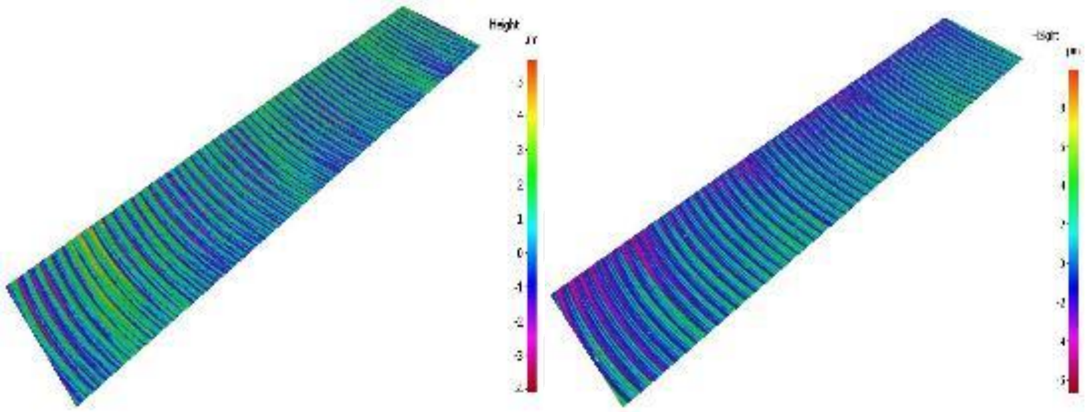


Figure 4.37 3D Surface Profiles of Rough Cut, MQL Condition, With (Left) Without (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

The differences between cutting depths are also clearly seen. In the finished cuttings, green colors are the majority and surface roughness values are close to 0, while the rough cuttings are darker in color. In addition, tool marks are more clearly seen on rough cut images. Homogeneity changes with deeper traces and the uniformity of the surfaces in the finish cutters is better than the images in the rough cuttings. It has been observed that the surface roughness increases with the same conditions as the stability of the cutting tool decreases due to the increasing cutting depth.

4.2.7 Discussion on Optical Microscope Images

Another feature of the Alicona Infinite Focus is the optical microscope. This is especially the 50-fold magnification images were obtained. The obtained images were examined with the cooling conditions, the effect of ultrasonic vibrations and the differences caused by cutting depth. All images were taken from the same area of the surface in the experiments. In this way, it was aimed to prevent different results in the surface roughness values of the tool wear that may occur with wear of the cutting tool. In experiments where images are taken, the cutting speed and feed are always constant, only the ultrasonic vibration, the cooling medium and the cutting depth have changed. The selected cutting speed is 78.5 m / min and the selected feed is 0.05 mm / tooth. The aim of selecting a cutting speed of 78.5 m / min and 0.05 mm / tooth feed is the most extreme cutting parameters in the experimental design. The surface roughness values obtained by Mahr Surf were observed that the highest surface roughness values were determined by these cutting parameters independent of ultrasonic vibration and cooling environment. In this way, it is understood that the clearest results will be in these measurements in visual observation of the parameters examined. The effects of ultrasonic vibration, the effect of the cooling medium and the depth of cut on the surface images of the following figures were examined comparatively. The only change in the images placed in each figure (top and bottom) is the effect of ultrasonic vibrations, but as the figures change, the effects of cooling medium and cutting depth are also examined.

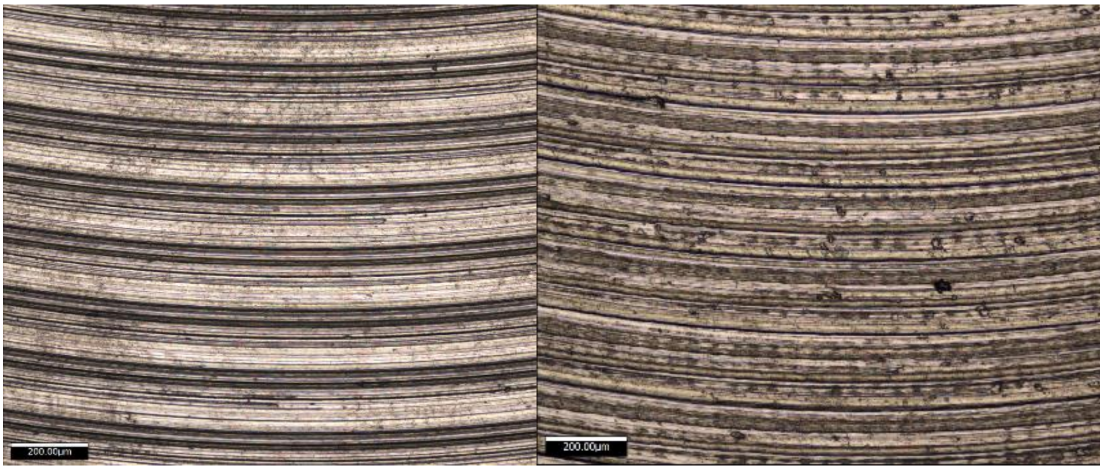


Figure 4.38 Optical Microscope Images of Finish Cut, Dry Condition, Without (Left) With (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

Figure 4.39 Optical Microscope Images of Rough Cut, Dry Condition, Without (Left) With (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

As the images show, a more uniform structure is seen on the surfaces where ultrasonic vibration is applied. In addition, the images in experiments without ultrasonic vibration have deeper marks. These deep marks match the 3D surface measurement. On ultrasonic vibrated surfaces, instead of these dark colors, we see brighter and lighter colors. In addition, a more uniform surface appears in the experiments with ultrasonic vibration. Ultrasonic vibration applied surfaces also appear surface images similar to fish-flakes. The reason for this fish-flake image is the vibrations applied 19000 times per second. Thanks to these vibrations, the contact of the cutting tool with the workpiece is interrupted in a regular way, which gives us this image. That is, when the cutting tool and the surface of the workpiece are not continuously and regularly separated from each other, it can be said that sharper, darker and non-uniform surfaces are produced.

Figure 4.40 Optical Microscope Images of Finish Cut, Wet Condition, Without (Left) With (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

It is also seen that different images are obtained in the same cutting conditions except with the cooling environment. The most uniform surface is seen in the experiments using MQL. At the same time, MQL is the condition where deep traces are the lowest in both ultrasonic vibration and without ultrasonic vibration experiments. The images in the wet cut are less bright and less uniform than the images in MQL. Since there is no effective cooling method as MQL, such images are encountered. The images in the dry cut are darker and deeper than the MQL and wet cut. In addition, the lowest uniformity was obtained in these sections. Some burn marks were also detected on the images. These burn marks are estimated to be from splashing chips from the cutting zone. It was found that MQL cooling and ultrasonic vibrations were used together with the lowest burn marks. As shown in Figure 4.39, these burns were found to be the highest in dry cutting.

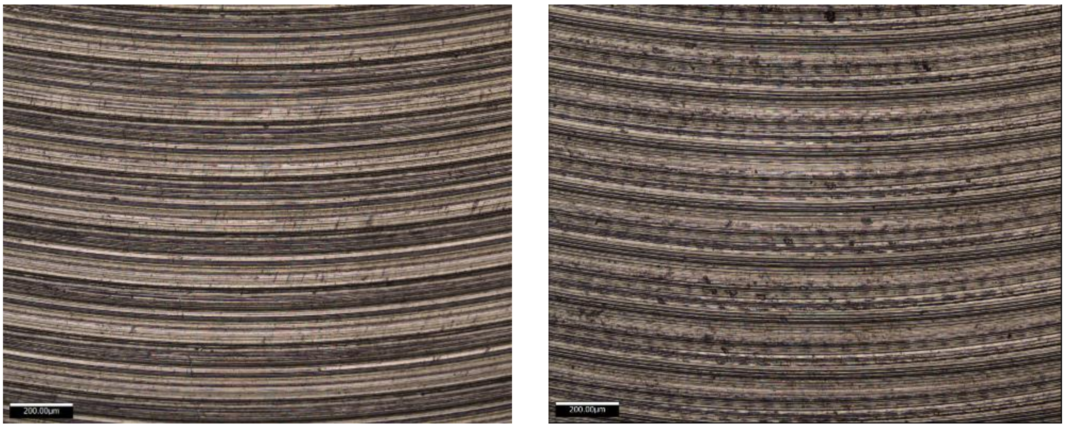


Figure 4.41 Optical Microscope Images of Finish Cut, MQL Condition, Without (Left) With (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

Figure 4.42 Optical Microscope Images of Rough Cut, MQL Condition, Without (Left) With (Right) Ultrasonic Vibration (78.5 m/min, 0.05 mm/tooth)

Another data obtained from the images is related to the depth of cut. The images in Figures 4.38, 4.40 and 4.41 were taken from the finish cut, while the images in Figures 4.39 and 4.42 were taken from rough cut experiments. Rough cut experiments clearly show darker and deeper traces. Tool marks are more pronounced and burn marks are also quite high. When looking at the finish cut images, there are lighter color marks. In addition, the presence of tool marks is less pronounced. Burn marks are also less than rough cuts.

Both microscope and 3D surface images and surface roughness values measured with stylus matched each other. In all experiments, it was seen that the experiments using ultrasonic vibration gave better surface roughness results than the experiments without ultrasonic vibration. In addition, it was observed that the experiments using MQL gave the best surface results, followed by wet cutting and the worst surface roughness results were obtained by dry cutting. When the depth of cut is examined, it is seen that the surface roughness results obtained from the tests performed on the finish cut are better than the rough cut. Finally, with the increase of feed and cutting speed, surface roughness results have increased. All these findings were measured independently of other parameters.

When the combination of the test parameters was examined, it was seen that the best surface roughness results were obtained by using ultrasonic vibrations and MQL together. This is followed by a combination of ultrasonic vibration and wet cutting. The third best results were experiments using ultrasonic vibrations and dry cutting. This information clearly shows that all experiments with ultrasonic vibration give better surface roughness results than non-applied tests. In addition, although it is known that surface roughness is reduced with MQL in conventional milling, it is seen that even dry cutting gives better results in ultrasonic assisted milling. However, it is seen that they are most suitable to use together to increase the effect of both ultrasonic vibration and MQL.

CHAPTER 5

5 Conclusions and Future Works

Ultrasonic assisted machining is a process that has increased considerably in recent years and has led to significant improvements, particularly in the processing of difficult-to-cut materials such as Ti-6Al-4V. At the same time, minimum quantity lubrication is a more effective method of covering the missing aspects of conventional cooling processes. In this study, uniaxial vibrations were given to the cutting tool on Z axis and minimum quantity lubrication method were used in the milling process of Ti-6Al-4V material. These two methods were used together for the first time in this study. Systematic experiments were successful and the cutting forces and surface roughness outputs were examined. In addition to ultrasonic vibrations and minimum quantity lubrication techniques, feed, cutting speed and depth of cut have also been studied to see the effect of other cutting parameters. As a result of the experiments, the conclusions obtained with cutting forces are as follows;

- Ultrasonic assisted milling technique can work in harmony with minimum quantity lubrication method.

In finish cut experiments,

- Ultrasonic assisted milling gives higher cutting forces than conventional milling, regardless of all other parameters.
- In the combination of cooling conditions with ultrasonic vibrations, the lowest cutting forces were associated with the wet cutting condition, followed by the minimum quantity lubrication and dry cutting, respectively.
- When the effect of cooling conditions on cutting forces in conventional milling was investigated, it was seen that the lowest cutting forces were obtained in experiments using minimum quantity lubrication. This was followed by the wet cutting condition, while the highest cutting forces were observed in dry cutting.

- In both ultrasonic assisted milling and conventional milling, the cutting forces increased with the increasing feed.
- Although it was obtained that the cutting forces in the dry and wet cut experiments were not significantly affected by the cutting speed, it was observed that the cutting forces decreased as the cutting forces increased in the minimum quantity lubrication used experiments.

In rough cut experiments,

- In all experimental results using ultrasonic assisted milling, it is seen that cutting forces decrease compared to conventional milling.
- In both ultrasonic assisted milling and conventional milling, when using minimum quantity lubrication technique, lower cutting forces are achieved than dry cutting.
- It was found that the best combination for the lowest cutting forces was obtained by using ultrasonic assisted milling and minimum quantity lubrication techniques used together
- It was observed that the cutting forces increased with the increase of feed and cutting speed, independent of other parameters.

In comparison to the finish cut and rough cut,

- The cutting forces were higher in the rough cut.
- Although it is seen that the use of ultrasonic assisted milling in the finish cut increases the cutting forces, it is seen that the ultrasonic assisted milling in rough cut reduces the cutting forces. At this point, it is seen that the use of ultrasonic assisted milling at higher cutting depths can give more efficient results.
- If conventional milling is used in both finish cut and rough cut, it is seen that preferring minimum quantity lubrication technique over wet and dry cutting increases the process efficiency by giving lower cutting forces.

Surface roughness was measured by Mahr PS1 Pocket Surf 6910214. Then, with Alicona Infinite Focus, 3D surface profiles and optical microscope images of the surfaces were obtained. When the surface roughness results, which are the other part of the study, were examined, the same results were obtained in both finish cut and rough cut. The conclusions obtained are as follows;

- In all experiments using ultrasonic assisted milling, lower surface roughness than conventional milling was obtained. Fish-flakes images were obtained on the surfaces of these experiments which were examined by optical microscope and it was seen that they had a uniform structure.
- When the cooling conditions were compared, it was seen that the lowest surface roughness values in all experiments were obtained by using minimum quantity lubrication method. When the 3D surface images were examined, it was found that the experiments that used minimum amount of lubrication yielded the images closest to zero.
- When the effects of other cutting parameters, feed and cutting speed, were examined, it was found that the increase of both adversely affected the surface roughness and led to high Ra values.
- It was found that the lowest surface roughness values were obtained by the combination of ultrasonic assisted milling and minimum quantity lubrication techniques at the finish cut. When the 3D surface images obtained with this combination are examined, it is seen that the most homogeneous surfaces and the lowest tool marks are obtained in these experiments. In addition, the lowest surface burns and lighter colored surfaces were observed on the surfaces examined by optical microscope.
- It was observed that the highest surface roughness values were obtained as a result of experiments using traditional milling and dry cutting in rough cut. When the 3D surface images of these experiments were examined, it was seen that the most inhomogeneous and highest Ra values were obtained. In the optical microscope examination, it was observed that the surface burns were the most and the images with the deepest and darkest traces were obtained in these experiments.

Recommendation for Future Works

- One of the subjects of this thesis is ultrasonic assisted milling which is formed by applying ultrasonic vibrations on Z axis to cutting tool. The ultrasonic vibrations can also be given to the X and Y axes, which can be in the form of workpiece vibrations. In this way, the effects of 2 or 3 axis ultrasonic assisted milling can be studied.
- Also in this thesis, minimum quantity lubrication using an external nozzle was studied. For further studies, the effect on process efficiency can be investigated using multiple nozzles. The effects of the application of through spindle, another form of minimum quantity lubrication, can also be investigated. Finally, the effect of cooling on nanoparticle can be investigated in minimum quantity lubrication processes.
- For the first time in this thesis, the effect of minimum quantity lubrication combination with ultrasonic assisted milling with ultrasonic vibration on Z axis cutting tool is studied. The results were very positive. In future studies, this promising field of research can be further developed by investigating the combined effects of the more advanced versions mentioned in the previous articles.
- In this study, cutting forces and surface roughness were investigated. As is known, cutting tool wear is also one of the most important factors affecting cutting quality. In subsequent studies, the effects of ultrasonic assisted milling and minimum quantity lubrication on the cutting tool can also be investigated. Again, the effect of these processes on chip formations and their effect on residual stresses are also promising issues.

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