Submerged Machining of Steel and Aluminum

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ABSTRACT

Machining is the process of removing material in the form of chips. It is the most widely used technique in manufacturing. It especially comes into play when specific dimensions and surface properties are required. One of the most important forms of machining is milling. This procedure can take place in either dry or submerged environment. Many parameters can be controlled during milling, and they affect the quality of the obtained surface.

This study considers milling in a submerged environment. The cutting fluid used is useful in reducing friction and heat generated during the process. Two types of materials are used for work-pieces: Steel CK45, and Aluminum Al6015. The study investigates the effect of five parameters on the roughness and hardness of the machined surface. These parameters are depth of cut, spindle speed, feed rate, tool size, and number of cuts. The effect of each parameter alone is studied by conducting a series of experiments where one parameter is varied while the remaining four are kept constant. Many researchers conducted studies about this topic in order to optimize the cutting parameters and obtain the best surface properties. Other studies focused on creating models that predict the surface roughness for a given set of parameters.

In this study, it was found that a smaller depth of cut is better for the surface roughness (a value of 0.4 mm is recommended for both steel and aluminum). The feed rate is also recommended to be kept at a smaller value because a higher feed rate leads to a larger cutting force and more surface roughness. This is specially significant for aluminum. The optimal value for the feed rate was found to be 1000 mm/min. For better surface quality, the high spindle speed is required, and low speeds are not to be used in order to avoid failure in the milling. In these experiments, failure occurred at a speed of 1000 rpm while the best roughness was achieved at 4000 rpm for both materials. Fewer cuts are encouraged since they consume less time and produce better surface roughness. Specifically, two cuts lead to the best surface quality in both steel and aluminum. Finally, smaller cutting tools are advised for lower roughness values. The best to use is a small size tool while the large one caused failure due to the formation of large irregular chips.

For steel, the combination that yielded the lowest roughness value was speed = 4000 rpm, feed rate = 1000 mm/m, depth of cut = 0.6 mm, number of cuts = 1, tool size = 12 mm. For this combination, Ra = 0.5 µm.

As for aluminum, the combination that yielded the lowest roughness value was speed = 4000 rpm, feed rate = 1000 mm/m, depth of cut = 0.6 mm, number of cuts = 2, tool size = 50 mm. For this combination, Ra = 0.3 µm.

Keywords: Chips, Milling, Submerged, Friction, Heat, Steel, Aluminum, Roughness, Hardness, Feed rate, Depth of cut, Speed, Number of cuts, Tool diameter, CK45, Al6015.

ÖZ

Makine isleminde parcanin cips şeklinde uzerinden alınması işlemidir.uretim alaninda en cok kullanilan islemdir.bu islem ozellikleolculendirilmesi hassas olan ve yuzey ozellikleri gerekmekte olan parcalar icin kullanilir.En onemli makina islemlerinden birisi frezedir.Bu islem hem kuru yuzeyde hemde sulu yuzeyde yapilabilir.Bu islem boyunca bircok sey kontrol edilebilir ve kaliteli yuzeyler elde edilir.

Bu islem frezenin su icinde yapilmasini arastiriyor.Kesme sivisi surtunmeyi azaltmak icin faydali ve uretilen maddenin daha fazla isinmamasini saglar.Parcalar iki tip malzemeden olusmaktadir.celik CK45 ve aliminyum AL6015.Bu calisma bes tane etkenin uzerine arastirilmistir.Bunlar kesme bicagin donme hizi, ilerleme hizi,bicak olcusu ve kesme sayisi.Her etkenin tesiri arastirilmasi; bazi deneyler yapilarken parametlerden birisi degisitirilmis diger dordu sabit kalmistir.Arastirmacılar optımum kesım parametrelerını bulmak ıcın ve en iyi yuzey özelliklerini elde etmek için arastırmalar yapmıslardır. Genel olarak diğer çalışmalar parçaların yüzey pürüssüzlüğü üzerine yapılmıştır.Parametlerin etkisine odaklanılmıştır.

Bu çalışmada, küçük kesme derinlikleri daha iyi yüzey pürüssüzlüğünü elde etme yöntemleri bulunmaktadır. İlerleme hızının küçük olması önerilmektedir.Çünkü yüksek ilerleme hızları daha fazla kesme gücüne ve daha kötü yüzey elde etmemize sebep olur.Bu özellikle aliminyum için önemlidir.İlerleme hızı için optimum değer 1000mm/dk.Daha iyi yüzey kalitesi için yüksek kesme hızı gereklidir ayrıca düşük hızda frezede hataları azaltmak için kullanılmamaktadır.Bu deneyde hataların genelde 1000rpm hızda en iyi yüzeyin ise 4000rpm’de olduğu iki farklı parçada deneyler test edilmiştir.Az kesimle üretilen parçalara daha az zaman harcanılmış ve daha iyi yüzsey pürüssüzlüğü elde edilmiştir.Özellikle iki defa kesilen parçalarda en iyi yüzey pürüssüzlüğü elde edilmiştir.Bu parçalar aliminyum ve çeliktir.Düşük yüzey kalitesi elde etmek için küçük kesme bıcaçları kullanılmaktadır.Küçük boyutlu bıçaklar, büyük boyutlu bıçaklara göre daha kullanışlıdır çünkü büyük boyutlu bıcaklar daha büyük çapakları oluşturuyor buda daha büyük hatalara sebebiyet veriyor.

Çelik için en düşük pürüssüzlük değeri elde etmek için bu kombinasyon gerekmektedir; 4000rpm, ilerleme hızı 1000rpm kesme derinliği 0.6mm, kesim sayısı 1, bıçak büyüklüğü 12mm.Bu kombinasyon bize Ra=0.5µm verir.

Aluminyum için en düşük pürüssüzlük değeri elde etmek için bu kombinasyon gerekmektedir.Hız 4000rpm, ilerleme hızı 1000rpm, kesme derinliği 0.6mm, kesim sayısı 2, bıçak büyüklüğü 50mm.Ra=0.3µm.

Anahtar Kelemeler: cips, frez, su icinde, sürtünme, isi, celik, aluminyum, purusuzluk, sertlik,kesme hizi, kesme derinligi, hiz, kesme sayisi, bicak olcumu, CK45, AL6015.

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LIST OF ABBREVIATIONS

Al	Aluminum
CK	Steel
HV	Vicker’s Hardness
Ra	Average Arithmetic Value of Rough
mm	Millimeter
N/mm^2	Newton per Millimeter square
kN/mm^2	Kilo Newton per Millimeter square
kg/dm^3	Kilogram per Decimeter cube
W/mK	Work per meter Kelvin
Rm	Tensile Strength
Re	Yield Strength
Si	Silicon
Mn	Manganese
S	Sulfur
Cr	Chromium
Cu	Cupper
Fe	Iron
Mg	Magnesium
Ti	Titanium
Zn	Zinc
F	Force
kgf	Kilogram force

• d	Average diagonal for hardness
• mm/min	Millimeter per minute
• rpm	revolution per minute
• µm	Micrometer
• No	Number
• σ	Standard deviation
• WC	Tungsten Carbide
• CNC	Computer Numerical Control
• BUE	Built Up Edge

Chapter 1

INTRODUCTION

1.1 Background

1.1.1 What is Machining

By definition, machining is “the process of removing the material in the form of chips by means of a wedge-shaped tool” [1]. It is one of the most, if not the most, critical manufacturing processes. When the work-piece is metallic, the process could be called metal cutting. We can distinguish two aspects of machining: machining of ductile materials, and machining of brittle materials. Ductile materials can sustain a significant amount of plastic deformation before failure occurs, whereas, in brittle materials, very little plastic deformation is observed [1]. Machining induces shear, bending and compression in the workpiece, as well as “heat generation due to plastic deformation” [2].

1.1.2 Significance

Machining is widely used in the manufacturing industry. Its importance comes into play when tight tolerances on dimensions, finishes, and surface quality are required [2] [3]. It is used when a specific shape, with a particular size, is required. It is also useful in obtaining certain surface properties. However, machining becomes much more expensive in the case of high volumes and is not recommended for such cases. Its applications include manufacturing parts for automobiles, airplanes, and other machines. Another field of machining that has been emerging lately is micro milling.

Micro milling consists of the machining and fabrication of miniaturized parts, using "miniature, fine-grained carbide end mill" [4]

1.1.3 Machining Techniques

Machining can be divided into five major types:

1- Drilling
2- Turning
3- Milling
4- Grinding
5- Chip formation

Experiments were accomplished in this project using mill machining.

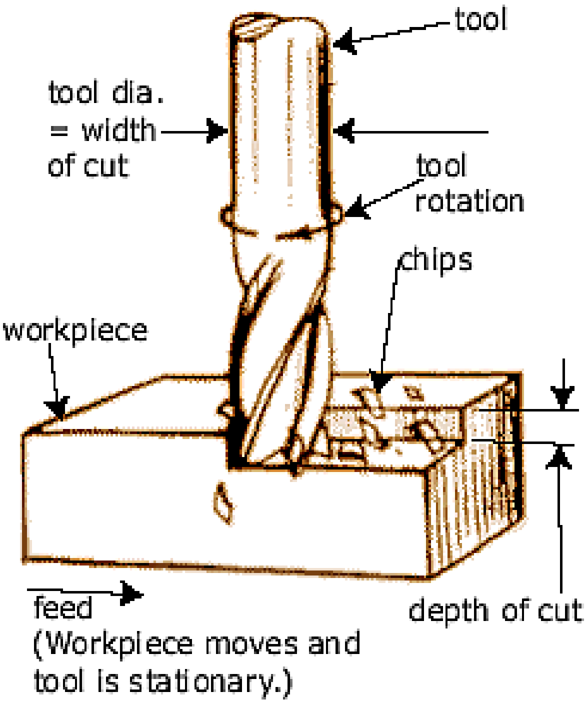


Figure 1: Typical milling parameters [5]

Milling, alongside drilling, is the most important metal cutting process. However, it has some limitations. Because of many degrees of freedom associated with the milling process, cutting of the workpiece is less accurate than some other processes, such as turning. The issue can be solved nonetheless if extremely reliable fixtures are used to hold the workpiece in place during the cutting [6]. If a desired object is not axially symmetric, the most efficient way to fabricate it is through milling.

Milling is commonly done by the use of Computer Numerical Control (CNC) machine, which will be highlighted later on in this thesis.

Fig.1 shows the main parameters of a milling machine. They are the cutting tool diameter, the feed rate, the depth of cut and the tool rotation speed (referred to as spindle speed). We can also notice the formation of chips, which are the product of the cutting process. As will be shown in later chapters, the size and type of these chips play a vital role in the surface properties of the machined workpiece, namely the roughness and hardness.

End mills are the most widely spread type of mills, as they are capable of cutting both vertical and horizontal surfaces [7].

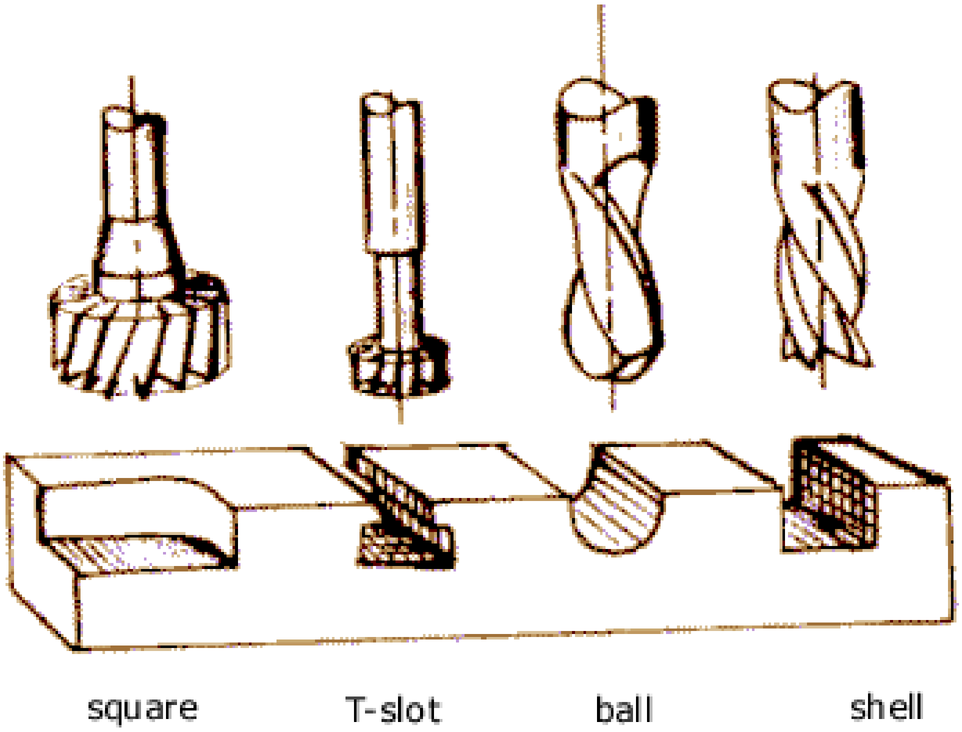


Figure 2: Typical tool heads [8].

Tool heads used for our experiments are cutters and inserts, which are presented in chapter 3. The typical tool heads that are used in mill machining are shown in Fig.2.

1.2 Motivation

In view of the above advantages and conveniences, mill machining is an important and flexible machining technique that is widely used in many industries. To use mill machining effectively and take full advantage of its capabilities, experiments and tests should be run to understand fully and comprehend the effect of every parameter involved in the milling process.

As the industries, in general, automotive and aeronautical, in particular, become more involved, new stringent requirements appear as to the properties of the machined surfaces that are used as parts in manufacturing. The properties are mainly surface quality features that include, but are not limited to, roughness and hardness.

Surface hardness is one of the requirements where parts are mating to reduce wear. This is done through heat treatment processes, and thus we need to invest cost to do so. A lot of heat is generated during machining which, if used for quenching of materials being machined, can improve the hardness of the surface layer. With this idea in mind, the machining was performed in a tank full of coolant, the cooling action of which is expected to cause quenching/chilling of material during machining and thus may increase the surface hardness.

Moreover, the use of cutting fluids in machining has many benefits [9]. It helps in lubricating the work-piece in case of low-speed machining, removing chips formed away from the cutting area, protecting the finished surface against corrosion and increasing tool life [9][10][11].

Therefore, to obtain the required properties, milling parameters such as depth of cut, feed rate, spindle speed and cutting tool size should be controlled and precisely chosen.

In this study, two different materials are chosen for the experiments: Steel CK 45 and Aluminum AL 6015. They are both used in machine parts since they provide excellent strength and other desirable mechanical properties.

1.3 Objective of Thesis

The objectives of this study are as follows:

1. Investigate the effect of various milling parameters (depth of cut, feed rate, spindle speed, cutting tool size, number of cuts) on the roughness and hardness of the workpiece in the case of CK45.
2. Investigate the effect of these same parameters for the case of AL 6015.

3. Testing of the mechanical behavior (roughness, hardness) of the materials under different testing conditions.
4. Draw conclusions as to the optimum values for each of the parameters above.

1.4 Thesis Organization

The following chapters of this thesis will include the following: In Chapter 2, a literature review of previous work related to the experiments on hand is presented; in Chapter 3, the methodologies and procedures that were followed to conduct the experiments are described, as well as the testing for roughness and hardness that was done after the milling; in Chapter 4, the different repetitions and their results are tabulated, and graphs showing the variation of the properties and presented and discussed; Chapter 5 highlights the key findings drawn, as well as recommendations for future work.

Chapter 2

LITERATURE REVIEW

2.1 Background

Milling is a widely used machining process that is known for its versatility and ability to achieve specific shapes in a better way than other processes [12]. It generates machined surfaces by removing a specified thickness of material from the workpiece [13]. For that purpose, milling employs a cutter head that rotates at a usually high speed. Of the many variations of milling, end milling is the most used in the industry, especially in the aerospace and automotive domains [14]. In end milling, the cutter rotates on a vertical axis, and the work-piece is placed perpendicular to the cutter.

However, one of the main issues that may be faced is that the machined surface does not meet the required specifications in term of surface quality and properties. In milling process friction plays a significant role. It always exist in between of work piece and cutter which leads to the generation of heat. This in turn affects the tool wear, tool life as well as the surface properties [15]. Because of that negative effect of friction, end milling may take place in a submerged environment, where the workpiece is placed in cutting fluid that works as lubricant and reduces friction and heat generation [6][7][8].

Moreover, and most importantly, the parameters used in CNC milling have the biggest effect on the properties of the machined surface. It follows logically that a significant amount of research was conducted on the impact of these parameters and their optimization that produce the desirable properties. Surface roughness is the most essential requirement in machining processes, since it directly affects the performance of the piece, in terms of strength, durability, creep, stress propagation, and others [16]. That is why the appropriate set of parameters should be chosen to obtain the required roughness.

The following section will briefly introduce some of the work conducted in related areas to this thesis, namely the study of the effect of milling parameters on the surface roughness and hardness.

2.2 Related Work

Many researchers investigated both the independent and co-dependent effect of milling parameters on surface roughness. Lou et al. [17] developed a model for predicting surface roughness in end milling, with the design variables being feed rate, spindle speed and depth of cut. The model was able to predict the surface roughness with an accuracy of 90% [17]. It was also determined in this study that feed rate is the most affecting parameter in the model.

Arokiadass et al. [18] investigated four parameters: feed rate, spindle speed, depth of cut, and different percentage weight of silicon carbide. Their effect was determined as to the surface roughness value Ra, and the main finding was that the depth of cut is least significant between these parameters.

Nicholas [19] focused his research on the effect of only the depth of cut on surface roughness of 6061 Aluminum. Jatin et al. [20] studied the effect of cutting speed, feed, and depth of cut on surface roughness in end milling. The work-piece was made of hardened die steel H-13. The main findings were that higher cutting speeds result in lower surface roughness. As for feed rate, the lower the feed rate, the lower the surface roughness. Also, high feed rates increase the tool wear rate that yields to an increase in the surface roughness. Finally, for the depth of cut, higher value will decrease the surface roughness.

Petru et al. [21] investigated cutting speeds and feed rates, with the material being high allow high-speed steel ASP 2023. Improved hardness values were noticed in high-speed machining. Also, increased feed rate leads to a decline in micro hardness up to a certain point, beyond which the micro hardness remains constant [22].

Philip et al. [23] used the response surface methodology (RSM) to study the effects of spindle speed, depth of cut and feed rate in end milling of stainless steel. For that purpose, a mathematical model was built to predict the surface roughness in terms of the parameters above. The equation resulting from the model showed that the feed rate was the most important factor influencing the surface quality. The main findings were that surface roughness decreased as the spindle speed was increased (500 to 1000 rpm). This paper recommends the use of a spindle speed of 1000 rpm. As for the feed rate, it was found that it should be kept low at a value of 40 mm/min since this value increases the surface of contact between workpiece and cutting tool. This would lead to higher cutting forces, and, therefore, a worse surface quality is achieved. Finally, it was determined that the surface roughness increases with the increase in depth of cut. That is also because a deeper cut increases the size of the chips, which in turn increases the friction and cutting forces. Therefore, the surface roughness is also increased in this case. The recommendation for the depth of cut was given as 0.4 mm. As for the interaction between the parameters, 3D surface plots were generated and studied. The optimum cutting condition found was at a spindle speed of 1000 rpm, a feed rate of 40 mm/min and a depth of cut 0.4 mm.

Similarly, Krolczyk et al. [24] also found the feed rate was the parameter that had most influence on surface roughness. This was done using RSM. Sai et al. [25] investigated the roughness and hardness of carbon steel during milling. It was found that a combination of low feed rate with high spindle speed improved the surface quality. At low cutting speeds, the formation of Built Up Edge (BUE) was observed which lead to reduced surface quality.

In their work, Tian et al. [26] studied the effect of milling parameters in “high-speed milling of titanium alloy TC17 with carbide cutting tools”. Their primary concern was surface micro hardness.

Thakur et al. [27] worked on nickel-based alloys that are used in the chemical and marine industries. Their study focused on the effect of cutting speed on surface integrity of Inconel 825. The study confirmed the tendency of this material for work hardening, as evidenced by the Vickers micro hardness test performed [28] [29].

Bernardos et al. [30] discussed the various approaches used by researchers to predict surface roughness of machined elements. Their paper focused mainly on turning and milling since they are the most widely used processes [31] [32]. According to [33], two main issues are faced in manufacturing. The first is finding the process parameters that will produce the required surface properties (roughness, hardness); the second is optimizing these parameters in order to maximize the productivity of the system [34] [35] [36]. Since the factors are many and are interrelated, it is difficult to establish their effect on the properties of the products. To overcome this problem, researchers try to develop models that “simulate the conditions during machining and establish cause and effect relationships between various factors and desired product characteristics”.

Michalik et al. [36] dealt with the machining of thin-walled components and studied the surface roughness obtained. They also worked on predicting analytically the surface roughness parameter, Ra. The experiments were conducted on thin wall components with thickness 10 mm in two phases: up milling and down milling. The apparatus used for milling was the 3-axis milling center. Other researchers, such as the one conducted by Lu et al. [37] also tried to develop analysis tools that related cutting parameters to surface properties and investigated optimization of cutting parameters in high-speed end milling.

In more related work, Rawangwong et al. [37] directly studied the effect of cutting parameters on surface roughness of aluminum allows that are used in many automotive and mold industries [38]. The factors considered in this study are the speed, feed rate and depth of cut. After conducting the experiments, it was found that the speed and the feed rate are the factors that most affected the surface roughness, whereas the depth of the cut had very little effect. In detail, a relationship was established between surface roughness Ra, speed, and feed. It was found that the roughness decreases as the speed increases while it increases as the feed increases. The formula relating the three parameters was Ra = 0.156 – 0.000024 speed +

0.000047 feed (speed in rpm, feed in mm/m). It is advised that this formula be used for a range of feed between 1000-1500 mm/m and speed between 2600-3800 rpm, with a maximum depth of cut 1 mm. After comparing the results of the experiments with the equation, it was found that the mean absolute percentage error was 3.6%. [39] and [40] also studied the effect of feed, speed and depth of cut in milling of aluminum.

Gupta et al. [41] investigated roughness of machined surface using PCA and Taguchi method. The experimental results showed that the surface roughness increased with the increase of feed rate. Also, the feed rate was found to be the most significant parameter, followed by the speed and depth of cut [42].

Hayajneh et al. [43] also studied the effects of spindle speed, feed rate and depth of cut on the surface roughness in end milling. They also built a multiple regression model that predicts the roughness value based on the input parameters. In this model, roughness Ra was the criterion variable, and the feed rate, speed and depth of cut are the predictor variables. This model, if accurate, can be later used for the optimization of cutting parameters, or for choosing parameters in a way to obtain a desirable surface roughness [43]. The model developed by [44] had an accuracy of 12%.

Ghani et al. [44] employed the Taguchi method to optimize the main milling parameters: feed rate, spindle speed and depth of cut. To analyze the effect of these parameters, many statistical approaches were used, namely signal-to-noise (S/N) ratio and Pareto analysis of variance. After analyzing the results, it was determined that the optimal combination for a good roughness value is high cutting speed, low feed rate and small depth of cut. Also, the interaction between the different parameters was also investigated and determined.

Chapter 3

METHODOLOGY

3.1 Material and Properties

In this project, we used Steel CK45 and aluminum Al 6015 as work-pieces. All work-pieces have as dimensions width = 300mm, length = 200mm, and thickness = 50mm.

CK45 has many applications in the industry, which include plastic molds, cold work die, and mold base, as well as constructional part. It is also used in machined and engineered parts. The chemical composition of CK45 is shown in table1.

Table 1: Chemical composition of CK45.

Grade	C%	Mn%	Si%	P	S
C45E	0.42-0.50	0.50-0.80	0.40	≤0.030	≤0.035

As for the mechanical properties of CK45, they are presented in Table 2. These properties were determined after various material tests, mainly the tensile test.

Table 2: Mechanical properties of CK45.

Property	**Value**
Tensile strength Rm	560-620 (N/mm^2)
Yield strength Re	275-340 (N/mm^2)
Breaking strain (L o = 5 do) A5	14-16 %
Impact energy AV (J)	≥25
Brinell hardness (HB 30)	175-210
Density	7.85 kg/dm^3
E-module	~ 210 kN/mm^2
Thermal conductivity coefficient (W/mK)	35-45
Thermal expansion coefficient (10-6/K)	11-14

This type of steel is known for its good properties, namely good machinability and high impact resistance. Fig.3 represents a typical CK45 work-piece.

Figure 3: Typical CK45 work-piece.

As for the Aluminum Al 6015, it has many applications in the aeronautical industry since it is strong, durable and light. Its chemical composition is shown in Table 3.fig.4 shows the Aluminum Al 6015 sheet used in experiments.

Table 3: Chemical composition of AL 6015.

Al	Cr	Cu	Fe	Mg	Mn	Ti	Si	Zn
97.4	0.10	0.10-0.25	0.10-0.30	0.80-1.1	0.10	0.10	0.20-0.40	0.10

Figure 4: Aluminum Al 6015 workpiece used in experiments.

3.2 Experimental Setup

The machining of the steel and aluminum sheets was conducted using the milling machine since it is easily available, inexpensive, and widely used in the industry.

Moreover, it is simple enough to use and serves well the purpose of the experiments that we conducted. Since the milling process was decided to be conducted in a submerged environment, a tank filled with soluble oil (cutting fluid) was used. The equipment, tools, experimental setup, and the procedures used to conduct the experiments are discussed in the following subsections.

3.2.1 CNC Machine

CNC milling is one is the most common machining processes. It is an established economical solution for the production of complex shapes [45]. These machines are usually classified according to their number of axes. Each machine has a specification for the movement range of its axes [45]. Usually, the X and Y axes are for horizontal movement while the Z axis (depth) is reserved for the tool spindle movement.

The Dugard ECO 760 3-axis CNC machine was used. Its specifications are shown in Table 4.

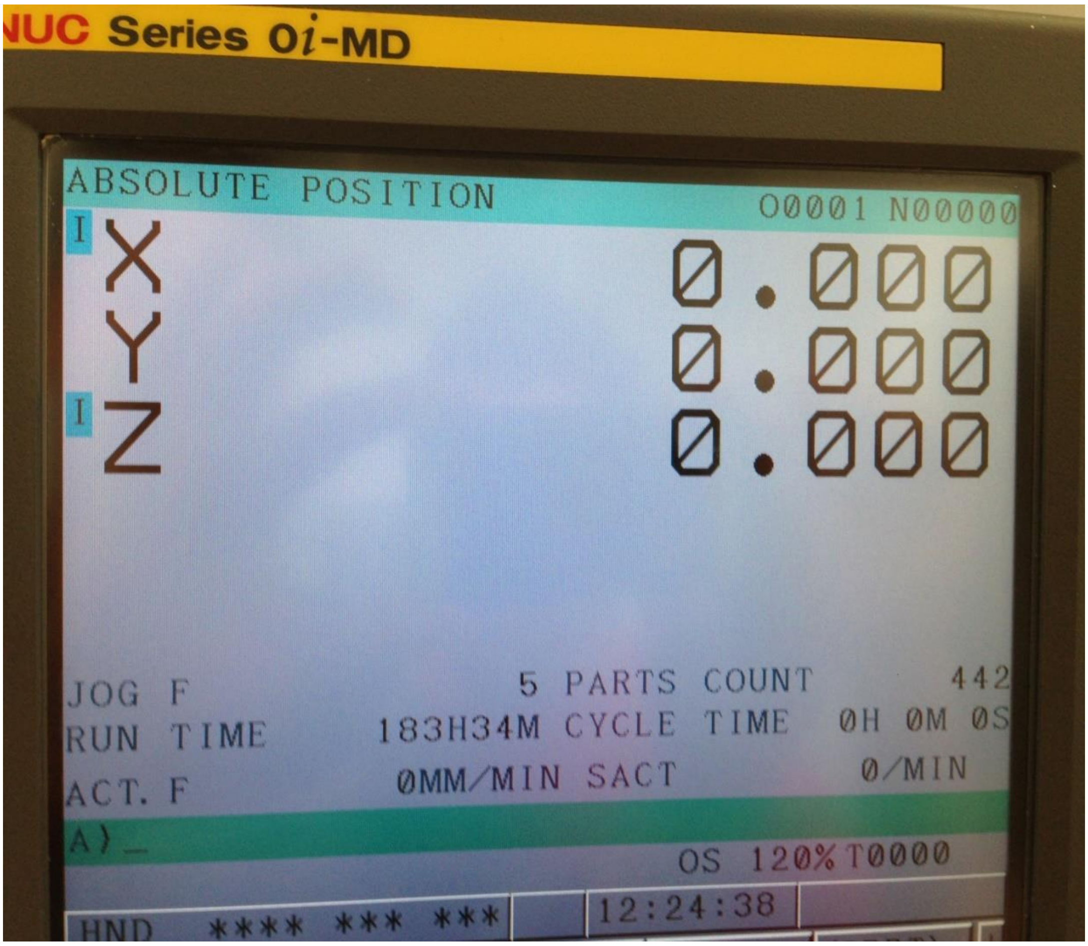
Table 4: CNC machine specification.

Spindle Speed Type	Air cooled, quick change
Spindle Speed	8000 rpm (opt 10000 rpm)
Feed Rate (X-Y-Z)	24 m/min
CNC controller	Fanuc 0iMD
X-axis travel distance	760
Y-axis travel distance	430
X-axis travel distance	460

The parameters studied (spindle speed, feed rate, depth of cut, number of cuts, tool diameter) are changed and controlled using this machine which is shown in

Fig.5.Moreover, Fig.6 shows an example of the computer numerical control machine display.

Figure 5: CNC machine.



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ABSOLUTE POSITION                 O0001 N00000
I X                 0.000
  Y                 0.000
I Z                 0.000

JOG F                 5 PARTS COUNT         442
RUN TIME        183H34M CYCLE TIME   0H  0M  0S
ACT. F          0MM/MIN SACT              0/MIN
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Figure 6: CNC display.

3.2.2 Cutters and Inserts

Cutters and inserts were used for the milling of the metal sheets. They are made of tungsten carbide. For smaller diameter cuts, cutters were used; for larger diameter cuts, inserts were used. The cutters have a diameter of 12 mm while the inserts (triangular shaped) have a thickness of 4 mm and sides of 1.5 cm each. Figure7 and figure8 shows a typical shell cutting head and insert used in the experiments.

Figure 7: Typical shell cutting head used.

Figure 8: Typical insert used.

3.2.3 Tank

A tank having dimensions of 40cm x 30cm x 20cm as shown in fig.9 is used to provide the submerging environment where the machining process would take place. It is made of compact aluminum sheets. The tank is filled with soluble oil (cutting fluid). The reason behind using submerged machining is that cutting fluids reduce friction at the cutting interface between the workpiece and cutting tool, as well as remove some of the heat generated during the cutting process [46]. Moreover, this submerged environment might contribute to the reduction of sub-surface damage and improve surface quality, in addition to a reduction in the rate of tool wear [46] [47]. Two fixtures (shown in later sections) are used in the tank as shown in figure12 to keep stable the work-piece during the milling.

Figure 9: Preparing the tank.

3.3 Experimental Plan

Five parameters are considered in this thesis: spindle speed, feed rate, depth of cut, tool diameter, and number of cuts. The main target is to study the effect of each of these parameters on the roughness and hardness and the machined surface, by trying different combinations and repetitions.

During the different repetitions done, four parameters were fixed, while the fifth was modified to study its effect. In total, nineteen repetitions for steel and aluminum each were conducted.

For steel, the repetitions are shown in tables 5 to 9. For aluminum, the repetitions are shown in tables 10 to 14.

3.4 Experimental Procedure

3.4.1 Milling Procedure

In this section, the steps followed during the milling procedure are briefly described. We start by placing the steel sheet in the tank. The tank is then fixed in the CNC machine as shown in fig.10. To set the work-piece in the reservoir, two fixtures are used, clamping the sheet well and preventing any movement. The soluble oil solution is then added to the tank, with an approximate volume of 1.5 liters. Then, the thermocouple is placed in the reservoir in order to measure the temperature during the milling process. It is connected to the temperature measurement device which is shown in fig.11, which in turn is connected to a computer that records the temperatures measured. Now that the setting is ready, the CNC is configured to the values of each particular repetition. Either the cutter or the insert is used, according to the cut diameter. Then, the cutting takes place over a distance of 250 mm.fig.13 shows an example of the milling operation in progress. When the cutting ends, the temperature measuring is stopped. After the milling is done, the work-piece is removed to measure the roughness and hardness of the surface. When all measurements are completed, the work-piece is smoothened using the CNC machine to obtain a level, flat, a homogenous surface that is adequate for the following repetition.

Figure 10: Placing the tank in the cnc machine.

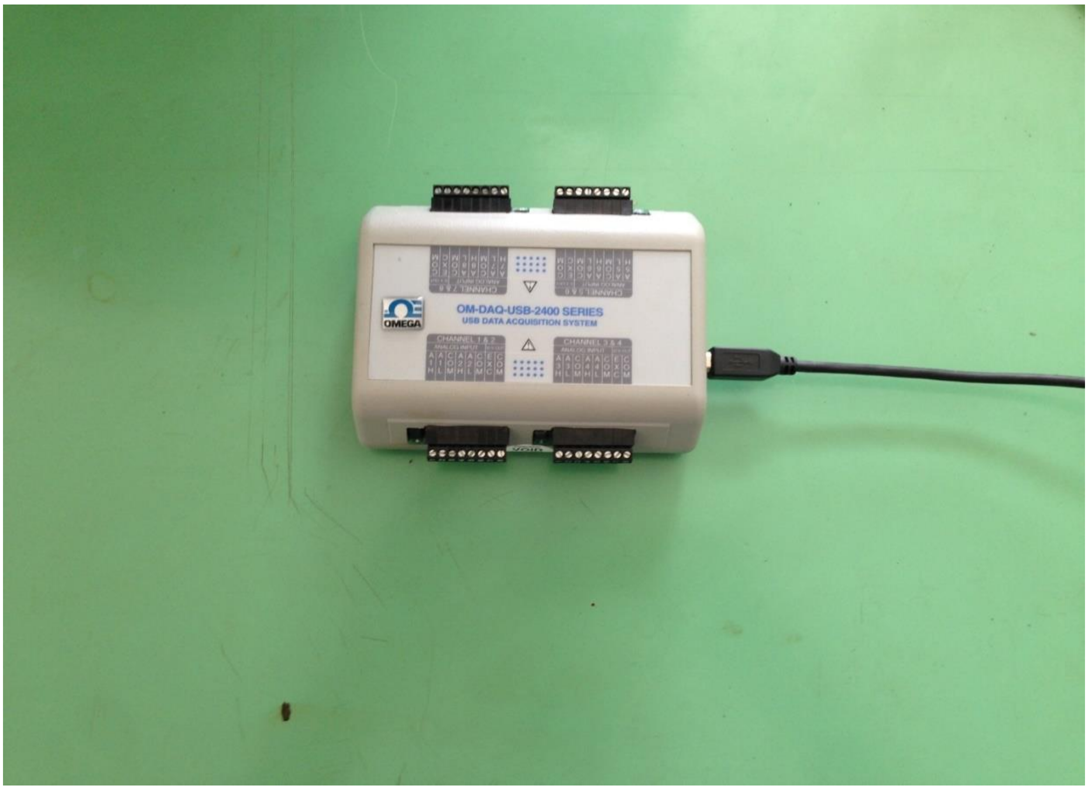

Figure 11: Device used to measure temperature during experiment.

Figure 12: Fixtures used to hold still the work-piece.

Figure 13: Milling operation in progress.

3.4.2 Roughness Test

After each repetition, the roughness of the machined surface was measured using a device called “Diavite MT-1”. This device measures Ra, the centerline average value of surface roughness, which is “the arithmetical average of the departure of the whole of the profile both above and below its centerline throughout the prescribed meter cut-off in a plane substantially normal to the surface” [48] as shown in fig.14.

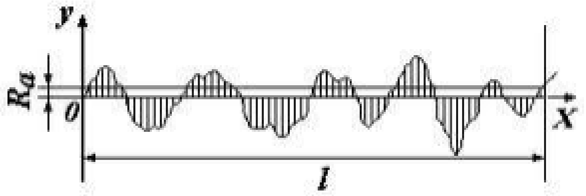

Figure 14: Average Surface Roughness [49].

The roughness tester is passed over the surface of the work-piece, and it automatically gives the roughness value. This process was repeated several times, in several locations of the machined surface, for more accuracy. The average of these obtained values is to be used later on for the analysis of the results.Figures15 and 16 represents the roughness device used.

Figure 15: Roughness device used to measure Ra.

Figure 16: Roughness device used.

3.4.3 Hardness Test

The hardness of the machined surface was measured using the Vickers hardness tester. This device use a diamond indenter with the form of a square-based pyramid [50]. Therefore, the resulting hardness value is in HV (Vickers Pyramid Number) and is calculated using the following formula:

$$\mathrm{HV} = \frac{1.854\,F}{d^2}$$

Where, F = 60 kgf for Aluminum

F = 100 kgf for Steel

And,

$$d = \frac{d_1+d_2}{2}$$

After the indenter causes deformation on the surface, the workpiece is placed under a microscope, and the diamond-shaped is observed. The two diagonals are measured as d_1 and d_2, and the average value d is used to calculate the hardness. The test is applied at different points in the sample, and the average hardness is employed in the results.Figures17, 18 and 19 shows examples of hardness device and tests used in the experiments.

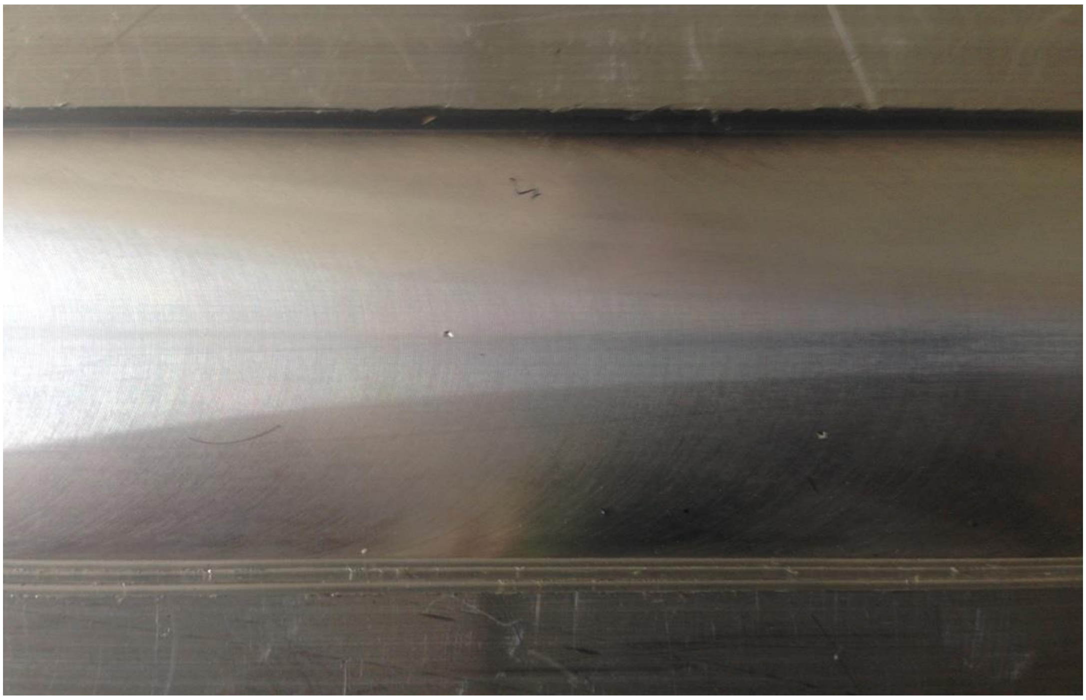

Figure 17: Example of hardness test measured at different locations.

Figure 18: Device used for hardness test (indenting phase).

Figure 19: Indenter of a Vickers Hardness Tester, Pyramidal Diamond.

Chapter 4

RESULTS AND DISCUSSIONS

The aim of the following experiments is the optimization of five parameters in the milling process, in order to obtain the best hardness and roughness of the machined surface. Previous studies mainly considered the depth of cut, feed rate, and spindle speed. In addition to these parameters, our research also focuses on tool diameter and number of cuts. For each of these five parameters, a set of repetitions was performed, where four parameters were fixed, and the fifth was modified.

4.1 Steel CK45

4.1.1 Depth of Cut

In the following set of repetitions, we modified the depth of cut to study its effect on the hardness and roughness. During the experiment, feed rate, speed, tool diameter and number of cuts are kept constant at 3000 mm/m, 4000 rpm, 50 mm and 1, respectively. The depth of cut was increased from 0.4mm to 1mm in increments of 0.2mm.

Table 5 summarizes the repetitions discussed in this section, as well as the roughness and hardness measured after the milling was done.

Table 5: Repetitions performed on CK45 with a depth of cut as a variable.

	Depth of cut (mm)	Feed (mm/min)	Speed (rpm)	Tool diameter (mm)	Number of cuts	Roughness (µm)	Hardness (Vickers)	Explanations
R1	0.4	3000	4000	50	1	3.2	228.028	
R2	0.6	3000	4000	50	1	4	228.697	
R3	0.8	3000	4000	50	1	4.9	259.347	
R4	1	3000	4000	50	1	*	*	Failed

As we can see in R4, a failure occurred during the machining process. The reason for this failure is that the combination of parameters chosen in R4 is out of the capacity of the milling machine. The depth of cut is high and material is hard, which made the cutting process stop after a certain time. The main issue that caused the interruption of the cutting is that the chips are continuous, thick and brittle. This prevented the machine from cutting any further.

As for the results of the experiments, Figures 20 and 21 show the values of roughness and hardness for each of the repetitions, respectively.

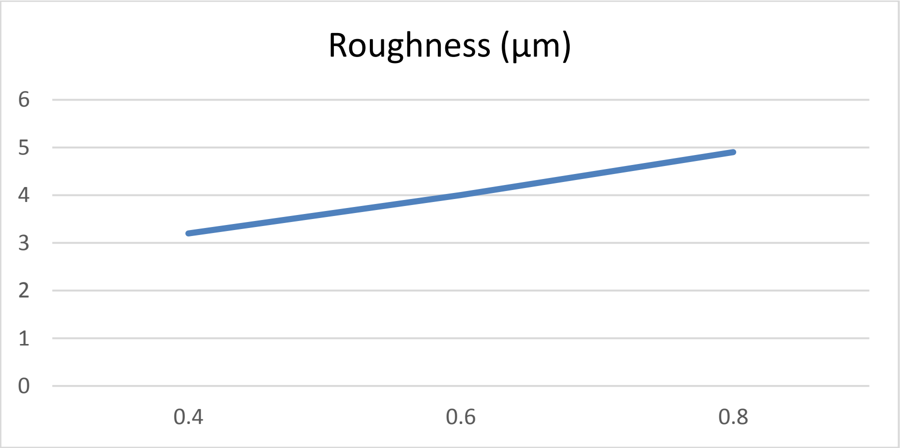

Figure 20: Variation of roughness with a depth of cut (CK45).

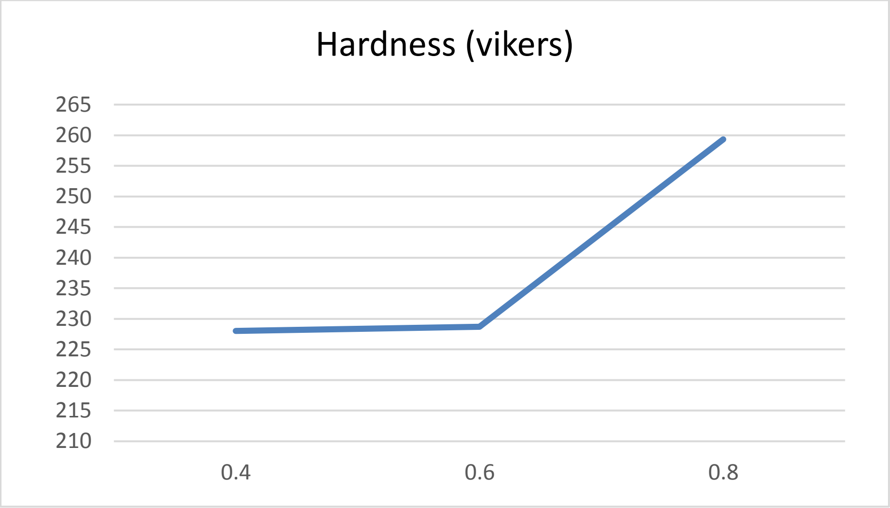

Figure 21: Variation of hardness with a depth of cut (CK45).

Both the hardness and the roughness increase as we increase the depth of cut. We can notice the almost linear increase of the roughness with the rise in depth of cut. This is because a deeper cut is naturally more difficult for the cutter, and that would yield on a rough surface.

For a depth of cut of 0.4 mm, we obtained the best roughness value of 3.2 µm while a depth of cut of 0.8 mm yielded of bad surface roughness of 4.8 µm. A depth of cut equal to 1 mm resulted in a failure, so it is better to avoid this value.Figures22 and 23 shows the work pieces after repetitions 1 and 4 are done.

Figure 22: Work-piece after R1.

Figure 23: Work-piece after R4.

4.1.2 Feed Rate

In the following set of repetitions, the effect of feed on the hardness and roughness is investigated. Therefore, we modified it in the repetitions, going from 1000 to 4000 in increments of 1000. During the experiment, depth of cut, speed, tool diameter and number of cuts are kept constant at 0.6 mm, 4000 rpm, 50 mm and 1, respectively.

Table 6 summarizes the repetitions discussed in this section, as well as the roughness and hardness measured after the milling was done.

Table 6: Repetitions performed on CK45 with feed rate as a variable.

	Feed (mm/min)	Depth of cut (mm)	Speed (rpm)	Tool diameter (mm)	Number of cuts	Roughness (µm)	Hardness (Vickers)
R5	1000	0.6	4000	50	1	1.5	237.518
R6	2000	0.6	4000	50	1	2.4	234.061
R7	3000	0.6	4000	50	1	3.7	240.101
R8	4000	0.6	4000	50	1	4.1	250.676

No failure occurred in any of these repetitions. Plots showing the variation in roughness and hardness are presented below in figures 24 and 25, respectively.

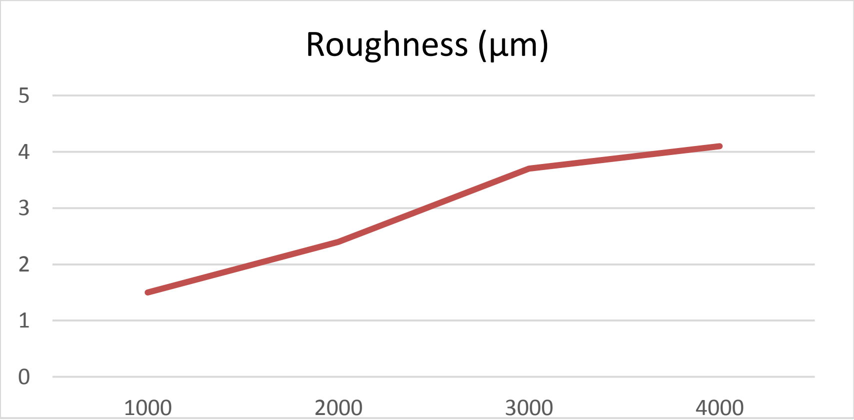

Figure 24: Variation of roughness with feed rate (CK45).

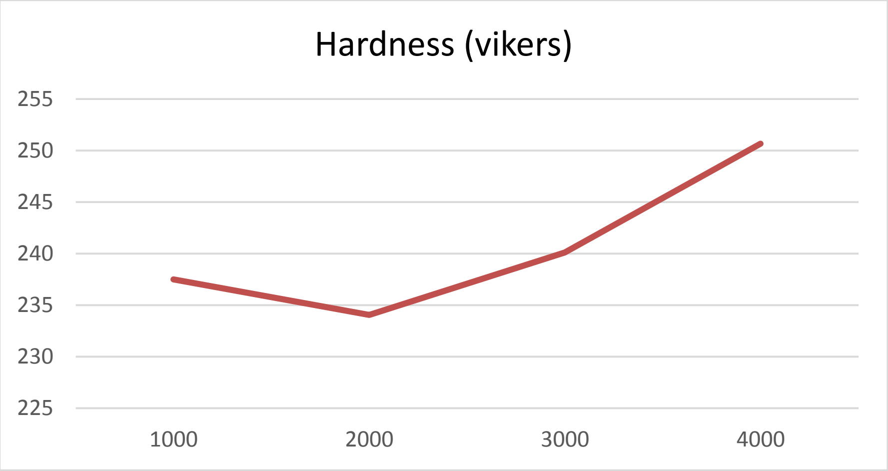

Figure 25: Variation of hardness with feed rate (CK45).

It is evident that the roughness increases with the rise of the feed rate. Low feed rate is therefore required to obtain a smoother surface and avoid poor quality surface. This result can be explained by the fact that at low feed rate, the chips formed are continuous and, therefore, there is less friction between the work piece and the cutting tool. As the feed increases, the chips become more and more discontinuous, and they become lodged between the cutter and the work piece, which results in an interruption in the cutting and gives a rougher surface.Figures26, 27, 28 and 29 show the work pieces and formation of chips after repetitions 5 and 8 are done.

Figure 26: Irregular, thick, discontinuous chips.

Figure 27: Work-piece after R5.

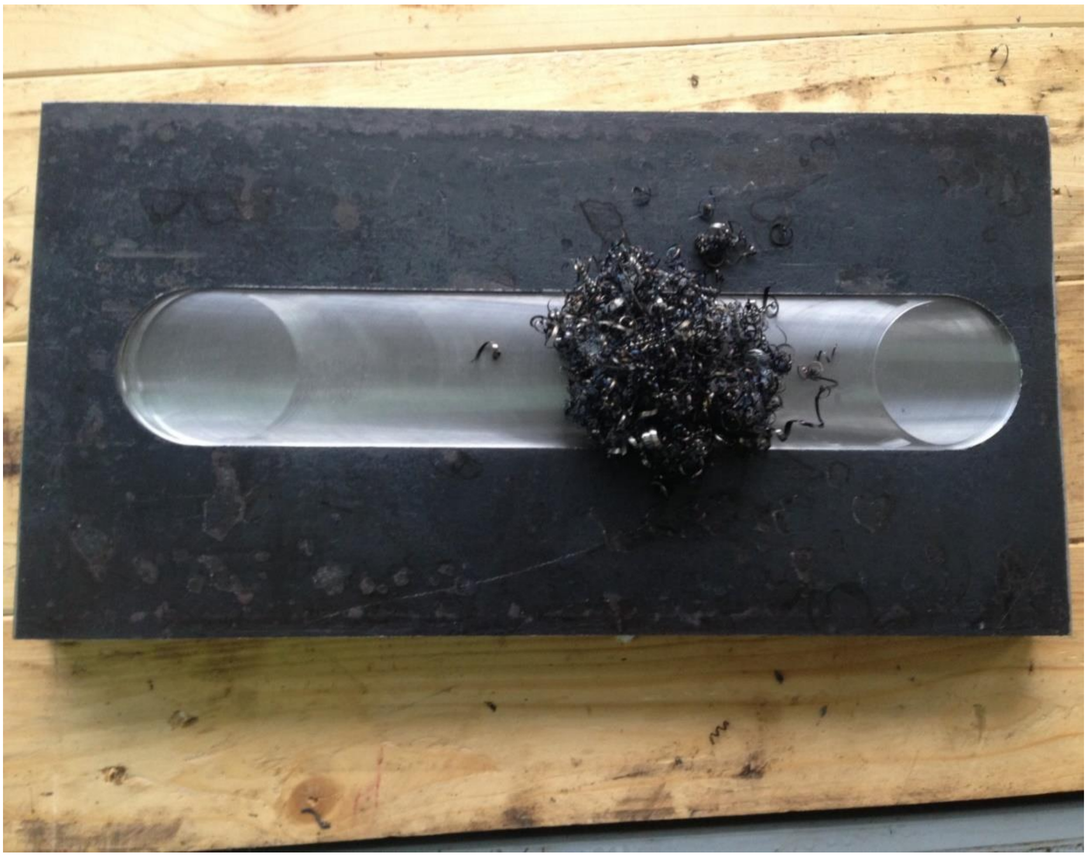

Figure 28: Work-piece after R8.

Figure 29: Formation of discontinuous chips affecting surface roughness.

As for the hardness, the general behavior appears to be an increase in hardness with the rise in feed rate, from a value of 237 Vickers at a feed of 1000 mm/m, to 250 Vickers at a feed of 4000 mm/m.Fig.30 shows an example of smooth continuous chip formation.

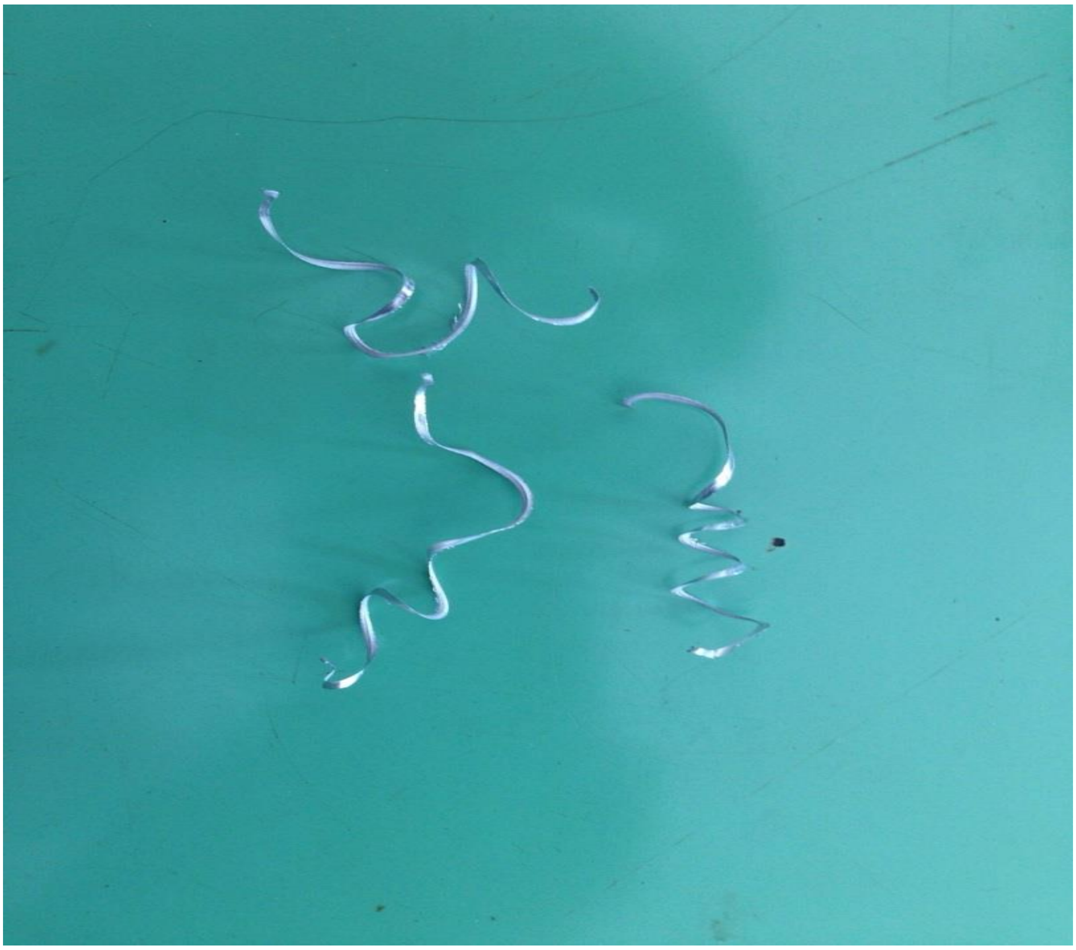

Figure 30: Example of smooth continuous chip formation.

4.1.3 Speed

To study the effect of the spindle speed on the roughness and hardness of the surface, we fixed all parameters except the speed. During the experiment, depth of cut, feed rate, tool diameter and number of cuts are kept constant at 0.6 mm, 3000 mm/m, 50 mm and 1, respectively.

The spindle speed of the four repetitions was 1000, 2000, 3000, and 4000.

Table 7 summarizes the repetitions discussed in this section, as well as the roughness and hardness measured after the milling was done.

Table 7: Repetitions performed on CK45 with speed as a variable.

	Speed (rpm)	Depth of cut (mm)	Feed (mm/min)	Tool diameter (mm)	Number of cuts	Roughness (µm)	Hardness (Vickers)	Explanation
R9	1000	0.6	3000	50	1	*	*	Failed
R10	2000	0.6	3000	50	1	5	285.745	
R11	3000	0.6	3000	50	1	4.5	198.269	
R12	4000	0.6	3000	50	1	4.2	195.961	

As we can see in R9, the trial failed because the cutting tool broke as it is shown in fig.31. The results were discarded from this set.Fig.32 shows the work piece obtained after repetition9 is done.

Figure 31: Broken Cutting tool from R9.

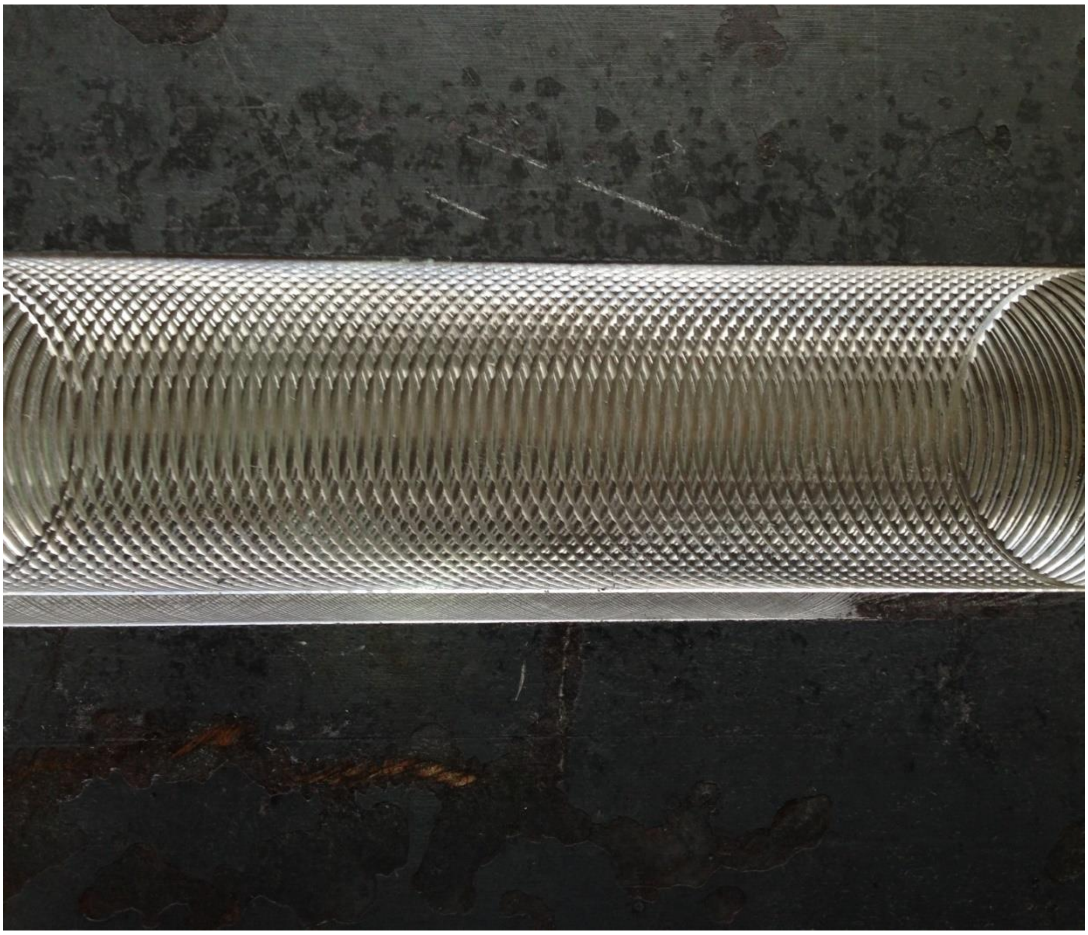

Figure 32: Work-piece after R9.

Figures 33 and 34 show respectively the variation of roughness and hardness of the surface versus the spindle speed.

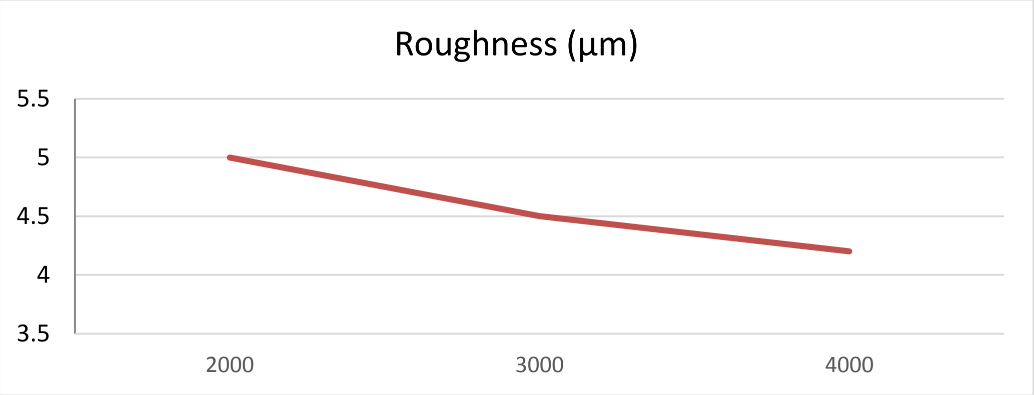

Figure 33: Variation of roughness with spindle speed (CK45).

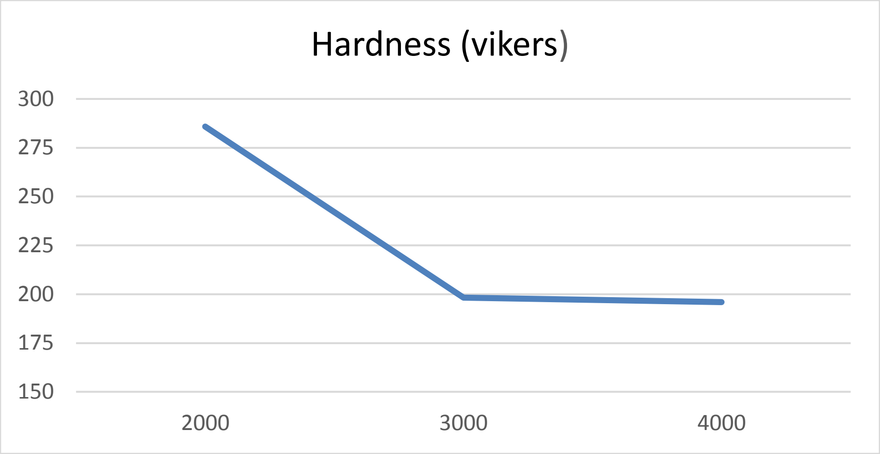

Figure 34: Variation of hardness with spindle speed (CK45).

From fig.33, it is observed that surface roughness decreases with increased spindle speed. At a speed of 4000 rpm, we obtained a roughness of 4.2 µm while a speed of 2000 rpm gave a roughness as high as 5.0 µm. This result is expected because, at low spindle speeds, discontinuous chips are formed and deposited between the cutting tool and workpiece, which causes high friction between the two. This high resistance leads to some interruptions in the cutting process, in addition to more energy, high temperature, and a poor surface quality. With the increase in spindle speed, the friction between the workpiece and cutting tool decreases, because the chips formed are continuous. This would lead to a better surface quality that is smooth.

The hardness also decreases with the increase in spindle speed, from a value of 285 Vickers at 1000 rpm to 195 Vickers at 4000 rpm. Figures 36 and 37 show the work pieces obtained after repetitions 10 and 11 are done.


Figure 35: Work-piece after R10.


Figure 36: Work-piece after R11.

4.1.4 Number of Cuts

In this section, the effect of the number of cuts is to be determined. Four repetitions, with 1, 2, 5, and 8 cuts respectively were performed. During the experiment, depth of cut, feed rate, speed and tool diameter are kept constant at 0.6 mm, 1000 mm/m, 4000 rpm and 50 mm, respectively.

The repetitions and results for hardness and roughness are shown in the table 8:

Table 8: Repetitions performed on CK45 with number of cuts as a variable.

	Number of cuts	Depth of cut (mm)	Feed (mm/min)	Speed (rpm)	Tool diameter (mm)	Roughness (µm)	Hardness (Vickers)
R13	1	0.6	1000	4000	50	1.5	230.554
R14	2	0.6	1000	4000	50	1	217.623
R15	5	0.6	1000	4000	50	1.2	183.559
R16	8	0.6	1000	4000	50	4	198.68

Figures 37 and 38 show the variation of roughness and hardness of the surface versus the number of cuts, respectively.

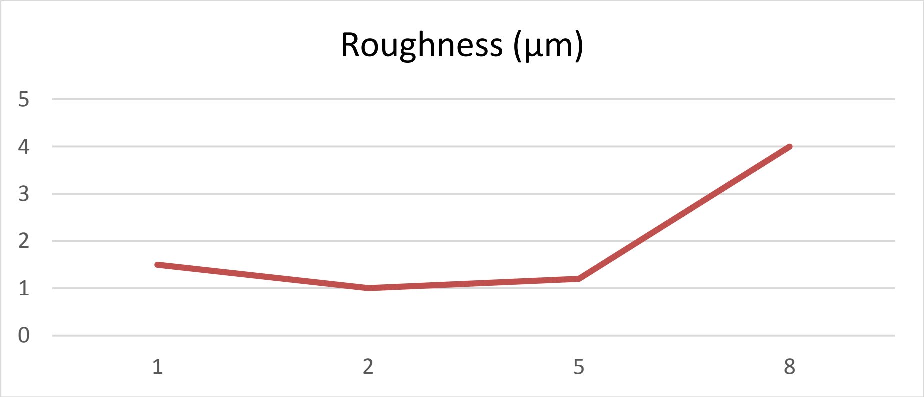

Figure 37: Variation of roughness with number of cuts (CK45).

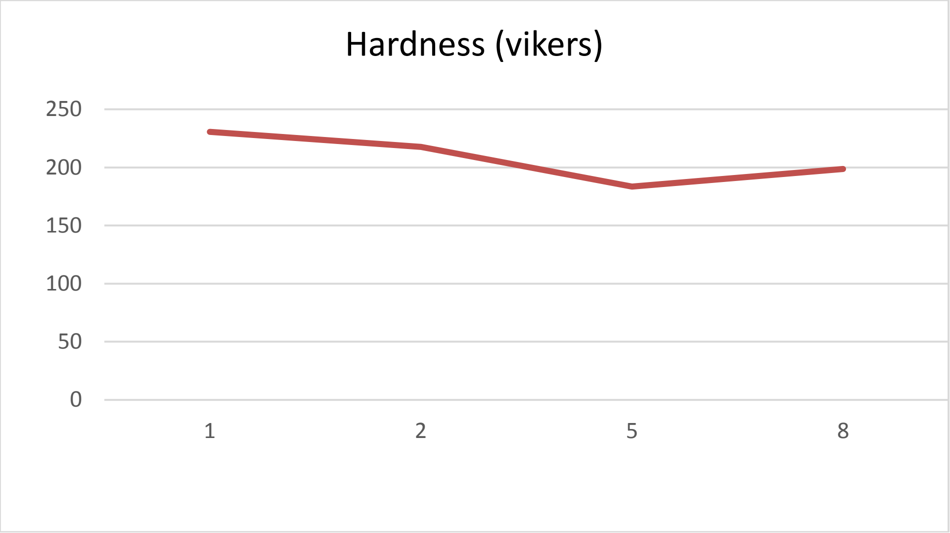

Figure 38: Variation of hardness with number of cuts (CK45).

The general behavior of the machined surface appears to be an increase in roughness as the number of cuts increases. This is probably because the more the number of cuts, the more chips are formed and deposited between the workpiece and the cutting tool, which increases the friction. However, we can notice a big rise in the roughness at 8 cuts, where Ra=4 µm. For a lower number of cuts, Ra is in the range of 1.2-1.5 µm.

As for the hardness, it decreases with the increase in number of cuts. This can be attributed to the surface's lowered resistance to plastic deformation, caused by the wear imposed by the repeated cycles of cutting. At one cut, the hardness is 230 Vickers, and at three cuts it decreased to 183 Vickers only.Fig.39 shows the work piece after repetition 15 is done.

Figure 39: Work-piece after R15.

4.1.5 Tool Diameter

The final parameter considered in this project is the tool diameter. Three sizes were used for this purpose: small (12 mm), medium (50 mm), and large (100 mm). During the experiment, depth of cut, feed rate, speed and number of cuts are kept constant at 0.6 mm, 1000 mm/m, 4000 rpm and 1, respectively.

The repetitions and results for hardness and roughness are shown in the table below:

Table 9: Repetitions performed on CK45 with tool diameter as a variable.

	Tool diameter (mm)	Depth of cut (mm)	Feed (mm/min)	Speed (rpm)	Number of cuts	Roughness (µm)	Hardness (Vickers)	Explanations
R17	12	0.6	1000	4000	1	0.5	203.923	
R18	50	0.6	1000	4000	1	1.8	242.004	
R19	100	0.6	1000	4000	1	*	*	Failed

As is shown in table9 above, failure occurred in repetition 19, where the large cutting tool was used. The chip formation caused this failure. Big, irregular chips formed and interrupted the process, causing the CNC machine to stop. Therefore, roughness and hardness were only obtained for small and medium tool size.

The following two plots shown in Figures 40 and 41 represents the variation of roughness and hardness of the surface versus the tool diameter.

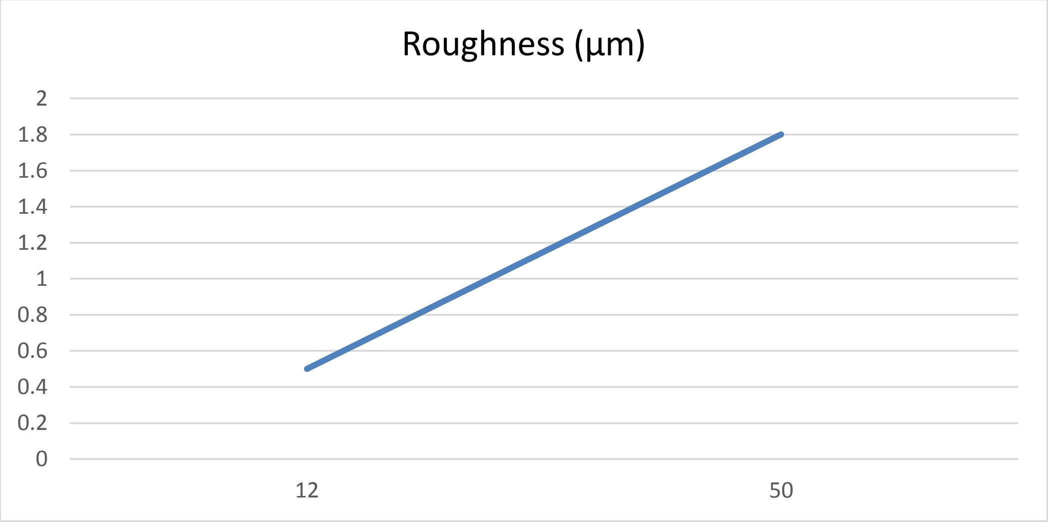

Figure 40: Variation of roughness with tool size (CK45).

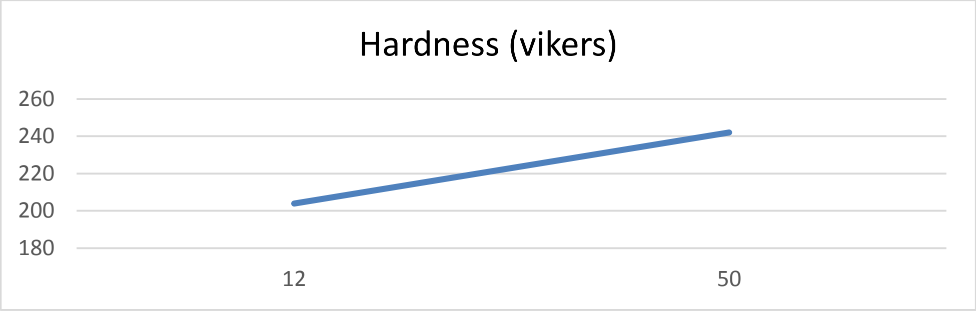

Figure 41: Variation of hardness with number of cuts (CK45).

Although only two points are available for this parameter, we can deduce that a smaller tool diameter gives lower roughness value. For the little tool, Ra = 0.5 µm, which is a very low and good value for the surface roughness. This value increases to 1.8 using the medium tool. That is logical since a smaller cut would result in a clean cut, and, therefore, a smooth surface that is almost free of irregularities. As for the hardness, it increases with larger tool diameter, from 204 to 242 Vickers, at small and medium size respectively. Figures 42 and 43 show the work piece after repetitions17 and 19 are done.

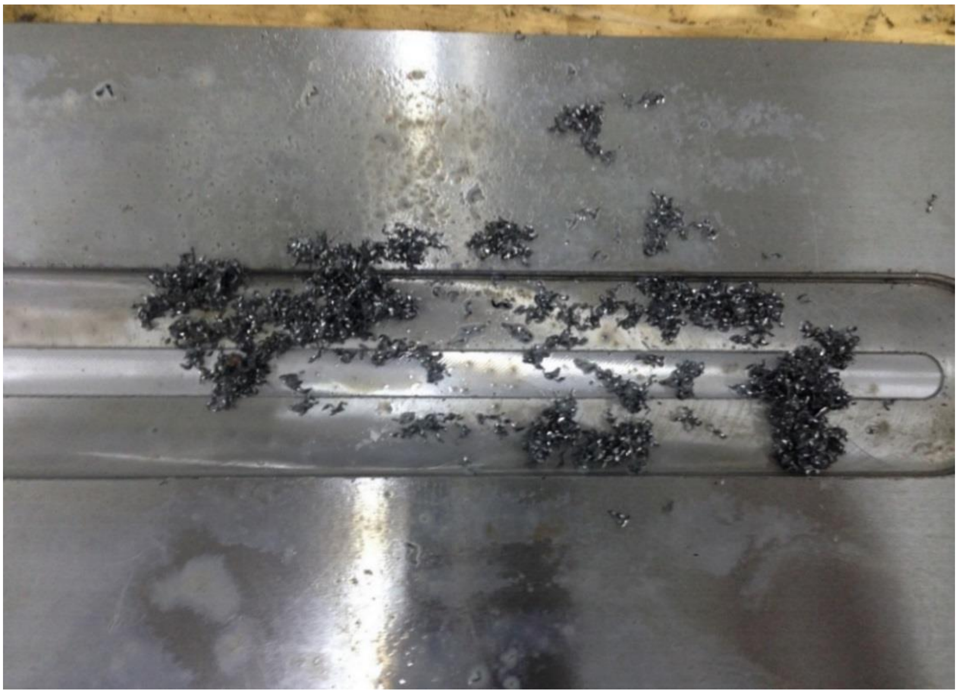

Figure 42: Work-piece after R17.


Figure 43: Work-piece after R19.

4.2 Aluminum Al 6015

4.2.1 Depth of Cut

In the following set of repetitions, we modified the depth of cut to study its effect on the hardness and roughness. During the experiment, feed rate, speed, tool diameter and number of cuts are kept constant at 3000 mm/m, 4000 rpm, 50 mm and 1, respectively.

The depth of cut was increased from 0.4mm to 1mm in increments of 0.2mm.

Table 10 summarizes the repetitions discussed in this section, as well as the roughness and hardness measured after the milling was done.

Table 10: Repetitions performed on Aluminum with depth of cut as variable.

	Depth of cut (mm)	Feed (mm/min)	Speed (rpm)	Tool diameter (mm)	Number of cuts	Roughness (µm)	Hardness (Vickers)
R1	0.4	3000	4000	50	1	1.5	111.798
R2	0.6	3000	4000	50	1	1.8	99.943
R3	0.8	3000	4000	50	1	1.9	107.552
R4	1	3000	4000	50	1	3.6	106.92

As for the results of the experiments, figures 44 and 45 show the values of roughness and hardness for each of the repetitions, respectively.

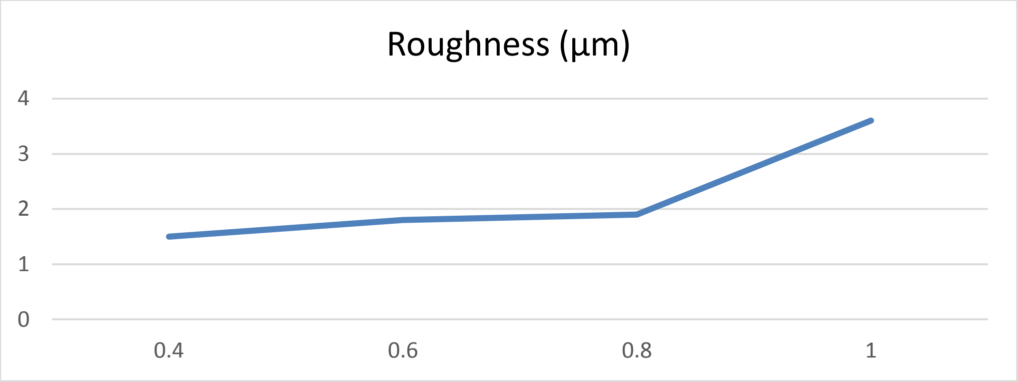

Figure 44: Variation of roughness with a depth of cuts (Aluminum).

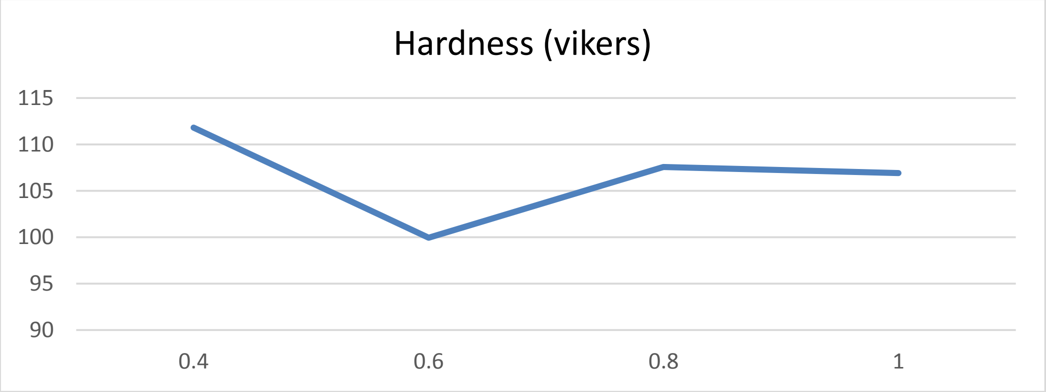

Figure 45: Variation of hardness with a depth of cuts (Aluminum).

We can notice that the roughness increases as we increase the depth of cut. At a depth of cut 0.4 mm, Ra = 1.5 µm. This value becomes enormous, Ra = 3.6 µm at a depth of cut 1 mm. Similarly to steel, this is likely because a deeper cut is naturally more difficult for the cutter, and that would yield on a rough surface. As for the hardness, we can notice that an increase in the depth of cut results in a decrease in the hardness of the surface. We also notice that case where the depth of cut is 0.6mm. In this configuration, the value obtained for hardness was very low compared to the remaining three configurations, which might suggest an error in this particular experiment.

4.2.2 Feed Rate

In the following set of repetitions, the effect of feed on the hardness and roughness is investigated. Therefore, we modified it in the repetitions, going from 1000 to 4000 in increments of 1000. During the experiment, depth of cut, speed, tool diameter and number of cuts are kept constant at 0.6 mm, 4000 rpm, 50 mm and 1, respectively.

Table 11 summarizes the repetitions discussed in this section, as well as the roughness and hardness measured after the milling was done.

Table 11: Repetitions performed on Aluminum with feed rate as a variable.

	Feed (mm/min)	Depth of cut (mm)	Speed (rpm)	Tool diameter (mm)	Number of cuts	Roughness (µm)	Hardness (Vickers)
R5	1000	0.6	4000	50	1	0.6	109.156
R6	2000	0.6	4000	50	1	1.4	103.944
R7	3000	0.6	4000	50	1	2.3	105.673
R8	4000	0.6	4000	50	1	4.5	124.565

Plots showing the variation in roughness and hardness are presented below in Figures 46 and 47.

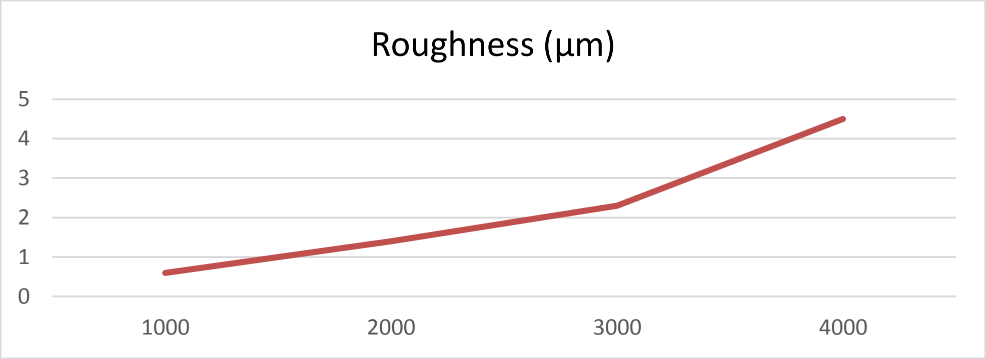

Figure 46: Variation of roughness with feed rate (Aluminum).

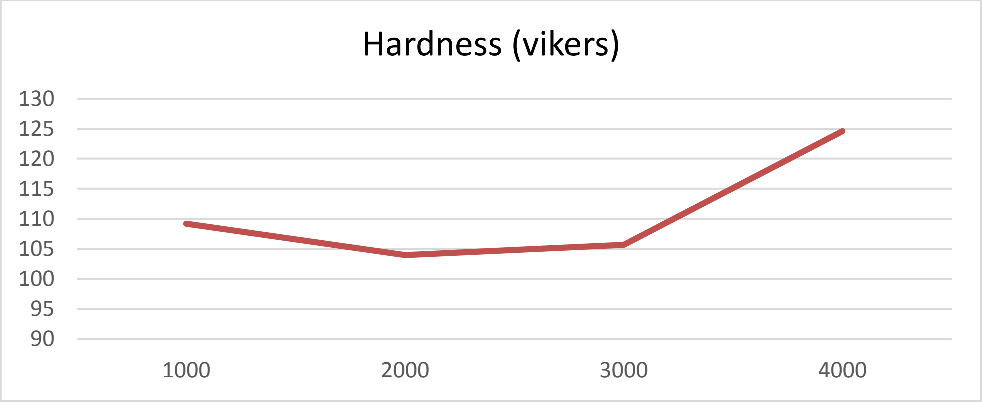

Figure 47: Variation of hardness with feed rate (Aluminum).

It is evident that the roughness decreases with the decline of the feed rate. The behavior is almost linear for that matter. The slope of the variation is significant. At a feed rate of 1000 mm/m the roughness Ra = 0.6 µm. It is seven times that value at a feed of 4000 mm/m, with Ra = 4.5 µm. Low feed rate is therefore required to obtain a smoother surface and avoid poor quality surface. This result can be explained by the fact that at low feed rate, the chips formed are continuous and, therefore, there is less friction between the workpiece and the cutting tool. As the feed increases, the chips become more and more discontinuous, and they become lodged between the cutter and the workpiece, which results in an interruption in the cutting and gives a rougher surface.

As for the hardness, the general behavior appears to be an increase in hardness with the rise in feed rate, expect for the first experiment that yielded a slightly higher roughness value than the two succeeding repetitions.Fig.48 shows the work piece obtained after repetition 5 is done whereas Figures 49 and 50 show the formation of chip and the work piece after repetition 8 is done.

Figure 48: Work-piece after R5.

Figure 49: Chip formed from R8.

Figure 50: Work-piece after R8.

4.2.3 Speed

To study the effect of the spindle speed on the roughness and hardness of the surface, we fixed all parameters except the speed. The depth of cut, feed rate, tool diameter and number of cuts are kept constant at 0.6 mm, 3000 mm/m, 50 mm and 1, respectively.

The spindle speed of the four repetitions was 1000, 2000, 3000, and 4000.

Table 12 summarizes the repetitions discussed in this section, as well as the roughness and hardness measured after the milling was done.

Table 12: Repetitions performed on Aluminum with speed as a variable.

	Speed (rpm)	Depth of cut (mm)	Feed (mm/min)	Tool diameter (mm)	Number of cuts	Roughness (µm)	Hardness (Vickers)
R9	1000	0.6	3000	50	1	>5	failed
R10	2000	0.6	3000	50	1	>5	123.127
R11	3000	0.6	3000	50	1	>5	110.575
R12	4000	0.6	3000	50	1	2.6	126.972

In R9, the hardness could not be measured due to the extreme waviness of the surface. We also notice that for speeds below 4000 rpm, the roughness obtained was greater than 5 µm. Therefore, no plot is needed to show the variation of the roughness. Only a speed of 4000 rpm yielded an acceptable roughness of 2.6. The slope of the change is significant. At a feed rate of 1000 mm/m the roughness Ra = 0.6 µm. It is seven times that value at a feed of 4000 mm/m, with Ra = 4.5 µm.

Fig. 51 shows the variation of the hardness of the surface versus the spindle speed.

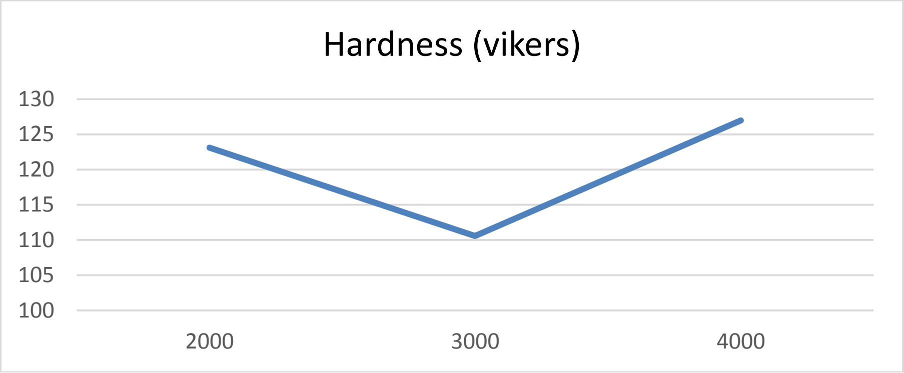

Figure 51: Variation of hardness with spindle speed (Aluminum).

It is observed that the hardness behavior is random, and no conclusion can be drawn in this case. This randomness could be attributed to the low spindles speeds that appear to create bad work-pieces, roughness-wise and hardness-wise.Figures52 and 53 show the chips and the work piece obtained after repetition 9 is done whereas Figures 54 and 55 show the work pieces obtained after repetitions 10 and 11 are done.

Figure 52: Work-piece after R9.

Figure 53: Chips formed from R9.

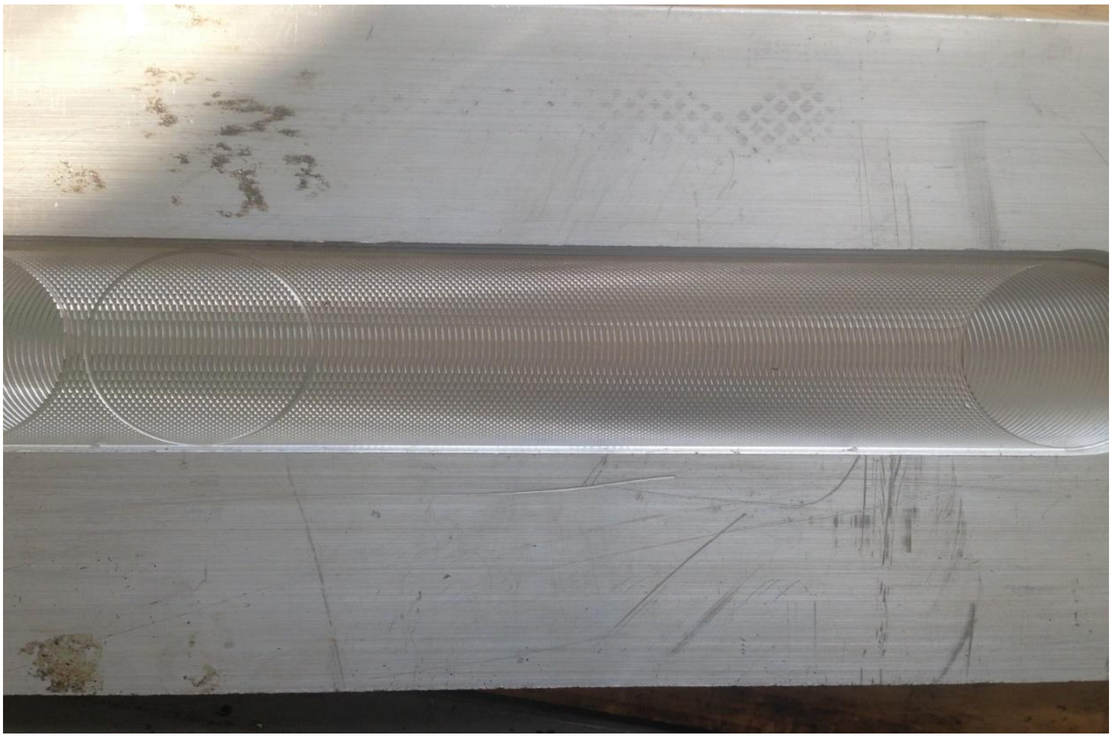
Figure 54: Work-piece after R10.

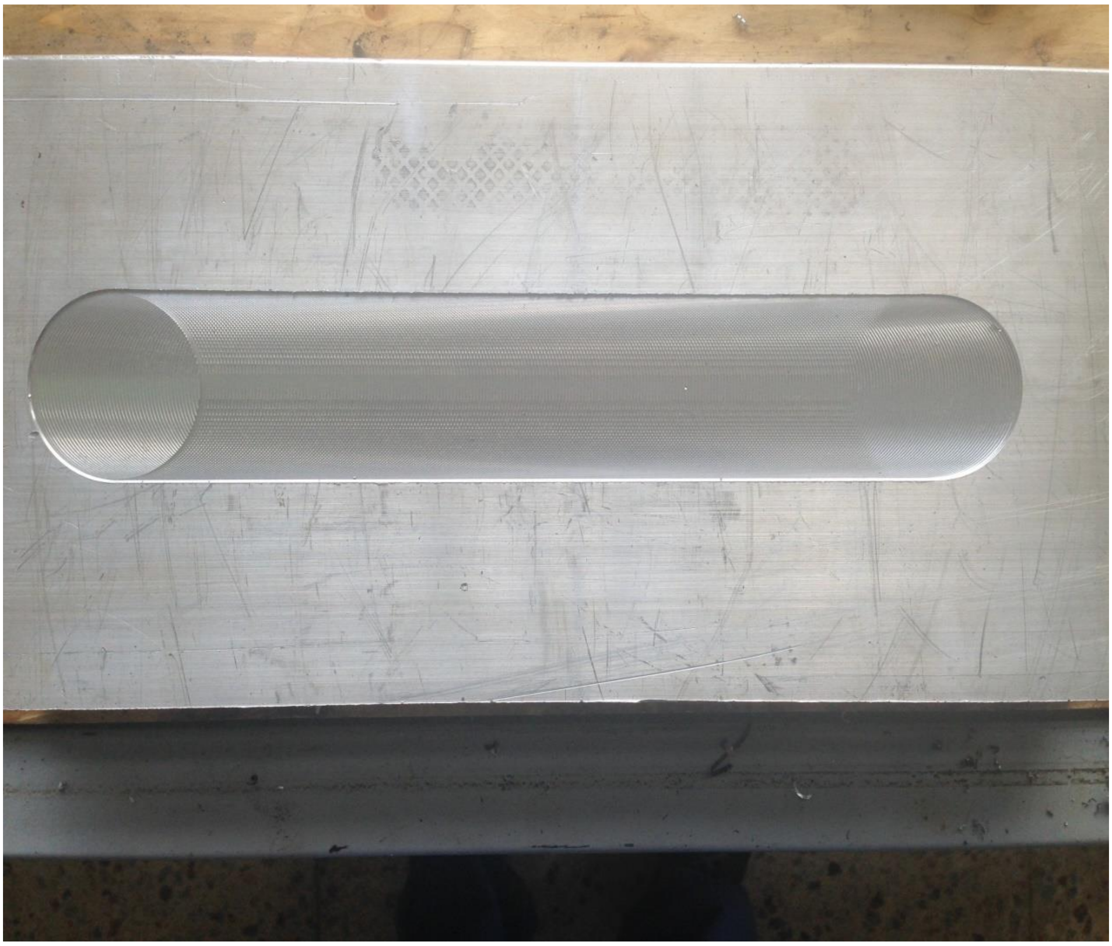
Figure 55: Work-piece after R11.

4.2.4 Number of Cuts

In this section, the effect of the number of cuts is to be determined. Four repetitions, with 1, 2, 5, and 8 cuts respectively were performed. During the experiment, depth of cut, feed rate, speed and tool diameter are kept constant at 0.6 mm, 1000 mm/m, 4000 rpm and 50 mm, respectively.

The repetitions and results for hardness and roughness are shown in table 13:

Table 13: Repetitions performed on Aluminum with number of cuts as a variable.

	Number of cuts	Depth of cut (mm)	Feed (mm/min)	Speed (rpm)	Tool diameter (mm)	Roughness (µm)	Hardness (Vickers)
R13	1	0.6	1000	4000	50	0.6	108.247
R14	2	0.6	1000	4000	50	0.3	99.283
R15	5	0.6	1000	4000	50	0.6	107.025
R16	8	0.6	1000	4000	50	0.6	109.264

Figures 56 and 57 show the variation of roughness and hardness of the surface versus the number of cuts.

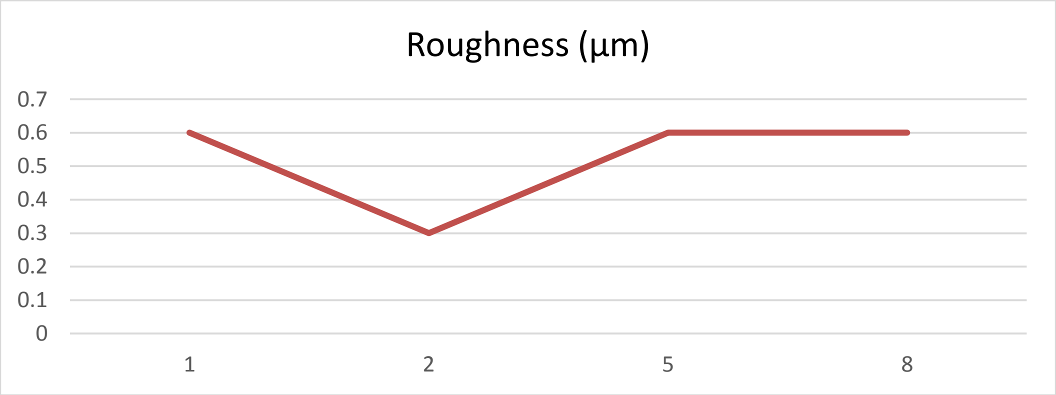

Figure 56: Variation of roughness with number of cuts (Aluminum).

Figure 57: Variation of hardness with number of cuts (Aluminum).

Except for the repetition where the number of cuts is 2, both the roughness and the hardness seem to be constant. If we discard R14, we can conclude that the number of cuts has no effect on the roughness and hardness of the machined surface for aluminum. And Ra = 0.6 for all cuts.Figures58, 59, and 60 show the work pieces obtained after repetitions 14, 15 and 16 are done.

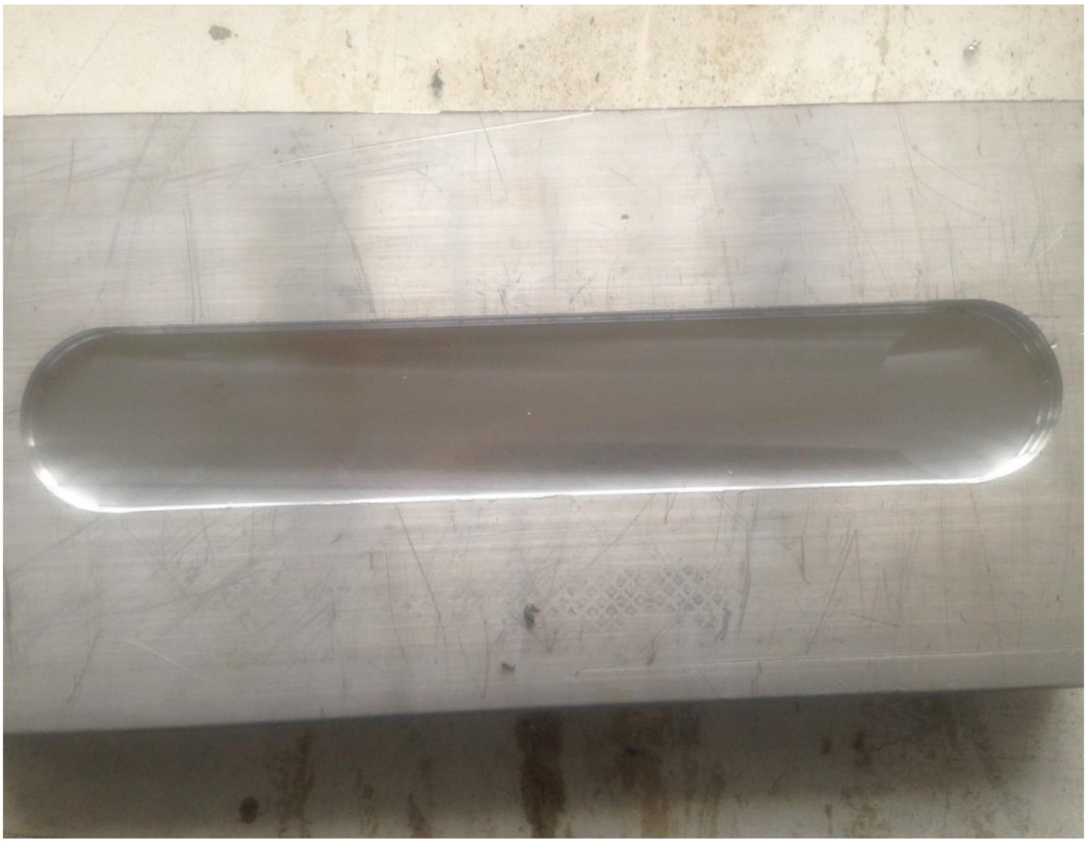

Figure 58: Work-piece after R14.


Figure 59: Work-piece after R15.


Figure 60: Work-piece after R16.

4.2.5 Tool Diameter

The final parameter considered in this project is the tool diameter. Three sizes were used for this purpose: small (12 mm), medium (50 mm), and large (100 mm). During the experiment, depth of cut, feed rate, speed and number of cuts are kept constant at 0.6 mm, 1000 mm/m, 4000 rpm and 1, respectively.

The repetitions and results for hardness and roughness are shown in table 14.

Table 14: Repetitions performed on Aluminum with tool diameter as a variable.

	Tool diameter (mm)	Depth of cut (mm)	Feed (mm/min)	Speed (rpm)	Number of cuts	Roughness (µm)	Hardness (vikers)
R17	12	0.6	1000	4000	1	0.7	104.956
R18	50	0.6	1000	4000	1	0.9	105.951
R19	100	0.6	1000	4000	1	1.4	106.502

Figures 61 and 62 show the variation of roughness and hardness of the surface versus the tool diameter.

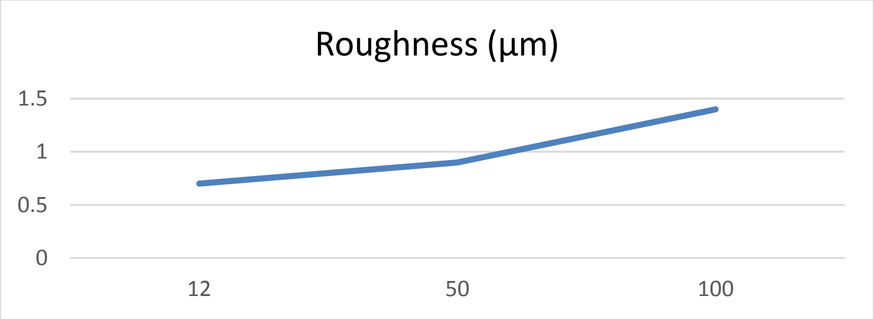

Figure 61: Variation of roughness with tool diameter (Aluminum).

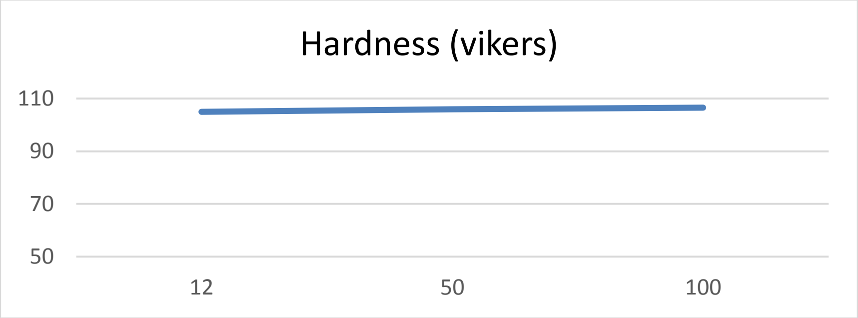

Figure 62: Variation of hardness with tool diameter (Aluminum).

It is noted that the roughness increases when a bigger tool diameter is used. As for the hardness, it is almost constant, with very little variation between the three experiments. We can conclude that the tool diameter has little to no effect on the hardness.Figures63 and 64 show the work pieces obtained after repetitions 17 and 19 are done.

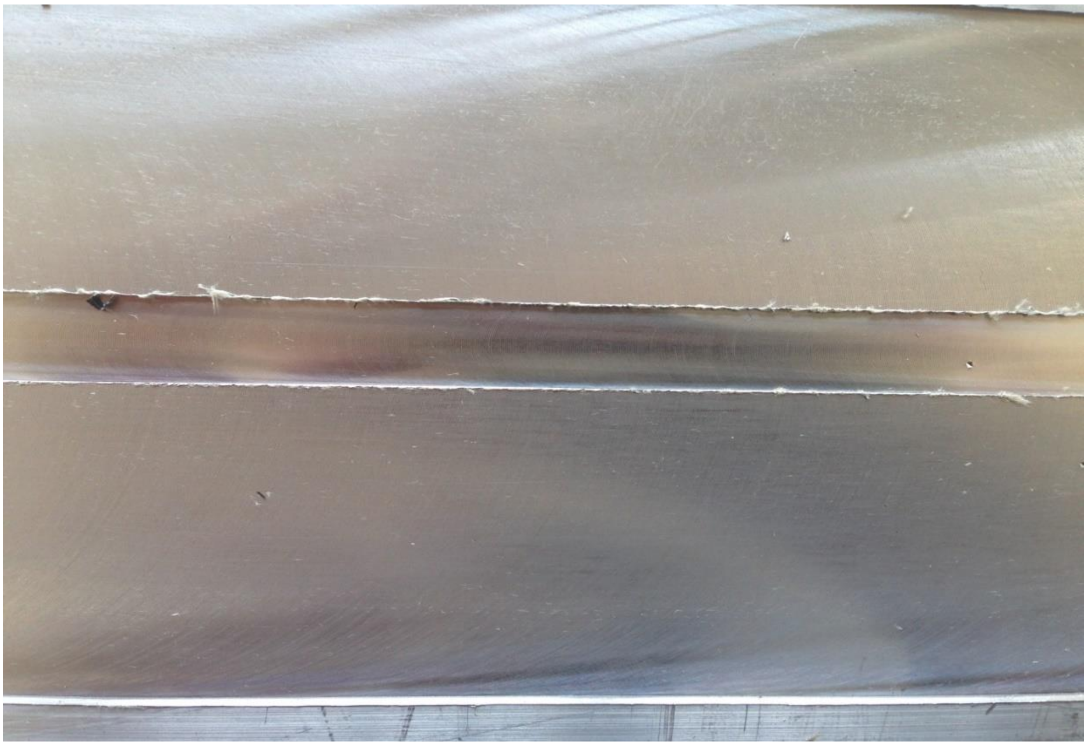

Figure 63: Work-piece after R17.

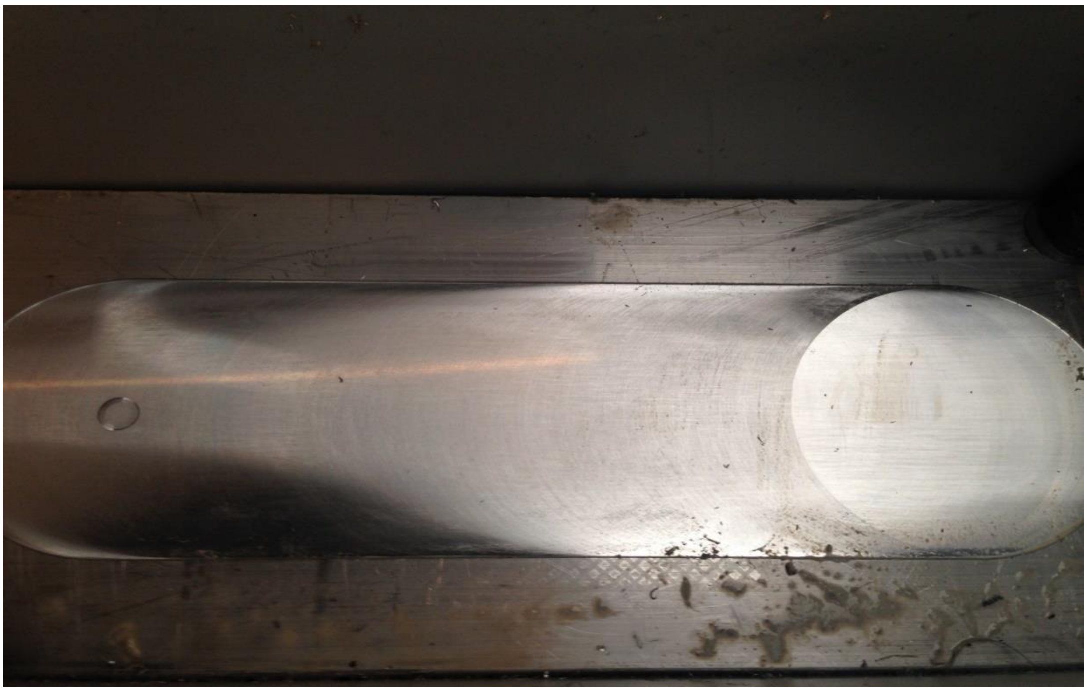

Figure 64: Work-piece after R19.

4.3 Standard Deviation and Percent Error

In order to verify the results of the repetitions and check their reliability, duplicate combinations were created from different sets. For example, while R2 studied the effect of depth of cut, R7 the effect of feed rate and R12 the effect of spindle speed, these three repetitions have the same parameters. Therefore, their results should be more or less identical. The same goes for R5, R13, and R18. For that purpose, the standard deviation is calculated for both roughness and hardness that were obtained from these three sets.

The formula for the standard deviation is:

$\sigma = \text{sqrt}\ [\ \Sigma\ (\ X_i - X\ )^2 / (N - 1)\ ]$

Also, the Standard Error of Sample Means (SE) is calculated.

$SE = \sigma / \text{sqrt}\ [N]$

The following tables represents the repeated repetitions that were done for both steel CK45 and aluminum Al6015.

Table 15: First set of identical repetitions for steel.

Repetition (Steel)	Roughness(µm)	Hardness(Vickers)
R2	4	228.697
R7	3.7	240.101
R12	4.2	195.961

For the above set,

$\sigma_{\text{roughness}}$ = 0.25166 µm

$SE_{\text{roughness}}$ = 0.145

σ_{hardness} = 22.91301

SE_{hardness} =13.45

Table 16: Second set of identical repetitions for steel.

Repetition (Steel)	Roughness(µm)	Hardness(Vickers)
R5	1.5	237.518
R13	1.5	230.554
R18	1.8	242.004

For the above set,

$\sigma_{\text{roughness}}$ = 0.17321 µm

$SE_{\text{roughness}}$ = 0.1

σ_{hardness} = 5.76952

SE_{hardness} = 3.33

Table 17: First set of identical repetitions for aluminum.

Repetition (Aluminum)	Roughness(µm)	Hardness(Vickers)
R2	1.8	99.93
R7	2.3	105.673
R12	2.6	126.972

For the above set,

$\sigma_{\text{roughness}}$ = 0.40415 µm

$SE_{\text{roughness}}$ = 0.233

σ_{hardness} = 14.24722

SE_{hardness} = 8.2256

Table 18: Second set of identical repetitions for Aluminum.

Repetition (Aluminum)	Roughness(µm)	Hardness(Vickers)
R5	0.6	109.156
R13	0.6	108.247
R18	0.9	105.951

For the above set,

$\sigma_{\text{roughness}}$ = 0.17321 µm

$SE_{\text{roughness}}$ = 0.1

σ_{hardness} = 1.65176

SE_{hardness} = 0.9536

The values for standard deviation and standard error are relatively small, which indicates that the tested results are reliable and accurate.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Main Conclusion

In this study, the effect of variation of the depth of cut, feed rate, speed, number of cuts and tool diameter on surface roughness and hardness of steel CK 45 and aluminum AL 6015 was investigated. The key findings drawn are:

1. An increase in the depth of cut for steel leads to a higher hardness, but it causes a high roughness in the surface. For aluminum, the roughness has the same behavior, whereas the hardness decreases with the increase in depth of cut. The failure occurred at the highest value for depth of cut. Therefore it is not recommended.

2. High feed rate, like the depth of cut, leads to a high hardness but also a high roughness value. This applies to both steel and aluminum. A small value is recommended for better surface quality. In particular, the feed rate is crucial in the roughness value of Aluminum (varies from 0.6 µm for feed = 1000 mm/min to 4.5 µm for feed = 4000 mm/min)

3. The spindle speed affects the roughness in a way where high speeds give better surface quality, i.e. low roughness value. However, the hardness also

decreases with high speeds. For Aluminum, in particular, low speeds yielded a roughness value Ra > 5 µm and, therefore, need to be avoided.

4. An increase in the number of cuts appears to cause an increase in the roughness, and a decrease in the hardness. Therefore, fewer cuts are recommended, especially since it is faster, and less heat is generated. This parameter has almost no effect on Aluminum.

5. Bigger tool diameter leads to a higher value for both the roughness and the hardness. Smaller size tool heads are preferred.

6. For steel, the combination that yielded the lowest roughness value was speed = 4000 rpm, feed rate = 1000 mm/m, depth of cut = 0.6 mm, number of cuts = 1, tool size = 12 mm. For this combination, Ra = 0.5 µm.

7. As for aluminum, the combination that yielded the lowest roughness value was speed = 4000 rpm, feed rate = 1000 mm/m, depth of cut = 0.6 mm, number of cuts = 2, tool size = 50 mm. For this combination, Ra = 0.3 µm.

5.2 Recommendations and Future Works

1. To obtain more accurate results, more experiments and repetitions are needed.

2. A larger set of data would enable us to relate better the milling parameters to the machined surface properties, and would allow us to understand fully their effect.

3. Perform more advanced statistical analysis to correlate the different parameters.

4. Study the effect of each parameter by performing more than 1 set of repetitions, i.e. using different values for the fixed parameters.

5. Develop a mathematical prediction model based on the experiments performed, and verify its accuracy by comparing with other data.

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