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A Comparative Evaluation of Dry-MQL Turning Applications for AISI 5115 Steel

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ABSTRACT

This study investigates the effect of various machining variables on cutting forces and surface roughness during turning of AISI 5115 steel in dry and MQL environments. While the experiments were carried out using two different feed rates, four different cutting speeds and constant depth of cut, the effects of them and their different levels on surface roughness and cutting forces were analyzed by reference to full factorial experimental design. The prominent findings of the research are as follows: The lowest surface roughness was obtained at 90 m/min cutting speed and 0.15 mm/rev feed rate in both mediums. The lowest cutting force was obtained at 135 m/min cutting speed, 0.15 mm/rev feed rate in dry environment and at 50 m/min cutting speed and 0.15 mm/rev feed rate in MQL environment. It was determined that there was an average 6.90% reduction in cutting force and an average 12.2% reduction in surface roughness in MQL condition. As a result, it was observed that machining in MQL conditions gave better results than dry conditions. These results show that the MQL method improves the machining performance compared to dry machining.

Keywords: *Turning, MQL (minimum amount of lubrication), Dry Environment, Surface Roughness, Cutting Force*

MQL Uygulaması ile AISI 5115 Çeliğinin Tornalama Performansının Değerlendirilmesi

ÖZET

Bu çalışma, AISI 5115 çeliğinin kuru ve MQL ortamlarında tornalanması sırasında çeşitli işleme değişkenlerinin kesme kuvvetleri ve yüzey pürüzlülüğü üzerindeki etkisini araştırmaktadır. Deneyler iki farklı ilerleme, dört farklı kesme hızı ve sabit kesme derinliği kullanılarak gerçekleştirilirken parametrelerin ve farklı seviyelerinin yüzey pürüzlülüğü ve kesme kuvvetleri üzerindeki etkisi tam faktöriyel deney tasarımı referans alınarak analiz edilmiştir. Araştırmanın öne çıkan bulguları aşağıdaki gibidir: En düşük yüzey pürüzlülüğü her iki ortamda da 90 m/dak kesme hızı ve 0,15 mm/dev ilerleme hızında elde edilmiştir. En düşük kesme kuvveti, kuru ortamda 135 m/dak kesme hızı ve 0.15 mm/dev ilerleme hızında, MQL ortamında ise 50 m/dak kesme hızı ve 0.15 mm/dev ilerleme hızında elde edilmiştir. MQL koşulunda kesme kuvvetinde ortalama %6,90 ve yüzey pürüzlülüğünde ortalama %12,2 azalma olduğu tespit edilmiştir. Sonuç olarak, MQL koşullarında işlemenin kuru koşullara göre daha iyi sonuçlar verdiği gözlemlenmiştir. Bu sonuçlar, MQL yöntemininkuru işlemeye nazaran işleme performansını iyileştirdiğini göstermektedir.

Anahtar Kelimeler*: Tornalama, MQL (minimum yağlama miktarı), Kuru Ortam, Yüzey Pürüzlülüğü, Kesme Kuvveti*

1. INTRODUCTION

Machining is the process of removing chips from a workpiece to bring it to the desired dimensions. The main motivation in machining methods is to ensure the effectiveness of the process of turning materials into smaller pieces suitable for the purpose they will serve. The most widespread use of machining methods is the turning method due to its features such as its suitability for mass production, surface quality, precision processing, compatibility with technological developments and cost efficiency [1, 2]. Turning performance in hardened metals is a phenomenon that can be evaluated through parameters such as tool wear, tool life, surface roughness, cutting temperature, cutting force, etc. [3-7]. The increase in production speed due to the developments in the manufacturing industry necessitates a rise in the speed of cutting during the machining of the workpiece. However, the high temperatures associated with high cutting speed caused by friction during machining can damage the workpiece and cutting tool. This manifests itself with surface roughness, which is an undesirable surface quality indicator. To avoid these problems, it is essential to control the temperature in the machining area. Although the traditional cooling method is a very effective method in

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heat control, it has a handicap in terms of cost and environmental effects caused by high fluid consumption. Although cryogenic cooling, which prioritizes tool life and surface quality, is a shining method in high precision applications, it returns as an extra cost in applications requiring special equipment. The use of cutting fluid reduces friction in the machining zone and removing heat along with the chips. Since the utilization of cutting fluid has disadvantages, such as requiring additional equipment and being costly, the use of dry processing conditions is still encountered in experimental studies. However, the dry environment machining method also has its negative aspects: it cannot sufficiently remove the chip from the environment, it causes rapid and high tool wear, and it cannot maintain surface integrity and it cannot provide sufficient heat control [8-11]. The MQL method, which has been widely utilized in recent years, is an application in which the cutting fluid is infused to the point where the machining is performed with compressed air. Although it relatively limits lubrication, it does not fall the traditional lubrication method in terms of machining. It has positive aspects such as increasing the material surface quality and improving processing performance [12-14]. It promotes environmental and industrial sustainability by minimizing cutting fluid and waste management problems. It also eliminates the cost and environmental burden of disposal of waste fluids by reducing the use of coolant.

Steels are impressive with their high mechanical properties, suitability for processes such as machining, forging, rolling and lower costs compared to their equivalents. Classified as a premium, low carbon, low alloy hardining steel, AISI 5115 offers a balanced combination of properties and generally serves to increase hardness and wear resistance [15-17].This steel, which is considered medium hardness, has a soft inner surface and a harder outer surface, and has a high ability to absorb impacts [17]. This special steel is widely used in many areas such as machine parts, shafts, gears, pulleys, bearings, chains and mechanical components. Studies on steel, which is seen in the literature using the abbreviation 16MnCr5 for the German Institute for Standardization (DIN), are summarized below. Baykara and Atik [17] conducted a study on how the wear resistance of 16MnCr5 steel would be affected by different heat treatments. Arunkumar, Chandrasekaran [18], carried out a detailed investigation of the properties of the 16MnCr5 steel at different hardness values such as 55 HRC, 45 HRC, 40 HRC by applying heat treatment to the material at 500 ℃, 450 ℃, and 250 ℃, respectively. After applying tensile tests to the material with various hardnesses, the shaft was analyzed at full load capacity to determine the stress of the design. Arrabiyeh, Setti [19] performed a study on the grinding of 16MnCr5 steel with micro pencil grinding tools, which they observed to be widely used on brittle materials with different hardnesses to create micro surfaces. Mouralova, Matousek [20] contributed to the literature with their study on the analysis of surface layer formation after machining of AISI 5115 steel with effective wire electrical charge. Saini, Goyal and Bhandari [21] used the multiple response optimization method to optimize 16MnCr5 steel by wire electrical charge machining. In their study, they carried out an optimization study to determine the influence of electrode types, pulse on time, pulse of time, peak current, pulse off time factors on metal removal rate and surface roughness. According to the findings of the study, they observed that the most influence factor for the studied parameters was pulse duration. Topography parameters of hard turned and ground 16MnCr5 steel surfaces were experimentally investigated, tribology maps were used to determine the optimum cutting parameters in the study belongs to Molnar [22]. The study conducted by Carrera Espinoza, Alvarez Vera [23] is another study examining the tribological behavior of 16MnCr5 steel, and the effects of the different surface treatments on tribology as well as microstructural and mechanical properties are also included in the scope of the study. Jacob, Meurer and Bergs [24] focuses on the use of model ensemble approach to predict surface roughness in hard turning of 16MnCr5 steel in their research. In the study by Frölich, Magyar [25] AISI 5115 steel was evaluated for wear resistance in carburized, turned carburized and dry turned surface conditions. Molnar [26] performed a reseach on hard turning machining of hardened steel 16MnCr5. Utilizing regression analysis, full factorial experimental design, variance analysis and correlation analysis, the impacts of parameters such as, depth of chip, feed, cutting speed and cutting edge geometry on the topographical features of the part were studied by scanning the areas of the machined material surfaces. Balabanov, Balabanova and Agayev [27] presented a mathematical method for the estimation of cutting forces in machining of 16MnCr5 steel. The theoretical model, which allows the measurement of cutting forces and cutting parameters such as feed, spindle speed, chip depth, showed a deviation of not more than 4.72% compared to actual measurements. Mehmedoviü, Ekinoviü [28] analyzed the impacts of chip depth, feed and cutting speed parameters on the formation of white film in the machining of 16MnCr5 steel. The results showed that there is a close relationship between the white film thickness and the arithmetic deviation of the machined surface due to the differences the machining parameters in the machining of the workpiece. Szabó and Kundrák [29] studied the surface residual stresses during hard machining of 16MnCr5 steel with different rake angles. Molnar [30] investigated the changes in the asymmetric height distribution of the surfaces as a result of machining

16MnCr5 hardened steel with hard turning and grinding methods. The feed, chip depth and cutting speed emphasized in the hard turning method, while in the grinding method, evaluations were made specifically in terms of grinding feed rate and revolutions per minute. Magalhães, Ventura [31] deals with the experimental and numerical modelling of residual stresses, cutting forces and tool wear in hard machining of AISI 5115 workpieces. The ability of the numerical model to estimate cutting forces and residual stresses with relative errors below 20% and tool wear with relative errors below 10% is associated with the suitability of numerical modelling of hard turning operations with different edge geometries. Molnár [32] performed a study on the analysis of cutting, surface roughness and residual stress factors in hard machined 16MnCr5 steel. Meyer, Köhler and Denkena [33] studied the impact of tool nose radius on tool wear and cutting forces in hard machining of AISI 5115 steel. Mondal, Das [34] performed the effects of feed and cutting speed on machining of hardened AISI 5115 using different cutting tool tips. In the study, where flat and wide flute chipbreaker TiC coated carbide tips were used. the effects of machining conditions were compared. It was concluded that the mentioned tips exhibited satisfactory performance in MQL conditions even when dry machining conditions could not be achieved uniformly. Agarwal, Suman [16] carried out a study on the optimization of CNC processing of 16MnCr5 steel utilizing TiN coated cutting tools. The main objective of the study was to obtain the machining conditions that obtain the surface roughness with the highest metal removal value using the Taguchi method The parameters that have a considerable impact on metal removal rate and surface roughness are feed rate and depth of cut, respectively. Demirpolat [3] carried out a study on the machining of 16MnCr5 steel under MQL and dry mediums utilizing a carbide-coated insert. In the research where different variations of depth of chip, feed and cutting speed were tested as processing parameters, it was seen that cutting temperature, surface roughness and cutting force values gave better results in the MQL case. Choudhury and Dhar [35] evaluated the chip depth, feed rate and cutting speed as input parameters and the tool wear, cutting temperature, dimensional deviation, surface roughness as output parameters in the machining of 16MnCr5. Results of the research showed that there was a considerable development in surface quality and a decrement in tool wear in the event of machining in MQL mediums compared to dry machining. Rizvi and Ali [36], carried out the optimization of machining parameters in the machining of 16MnCr5 steel in their research. In their study, they observed that the most effective parameter in improving ANOVA results was the machining depth.

In the processing of AISI 5115 hardened steel, judging by the literature review, it has been seen that the focus is on methods such as grinding, hard turning, wire electric discharge. Research on the turning of the material is relatively more limited. The goal of this article is to study the impact of various machining parameters on cutting forces and surface roughness in the machining of AISI 5115 steel by turning method in dry and MQL mediums. In the present research, the influences of cutting speed and feed parameters at different levels were examined as per a full factorial experimental design and (S/N) ratios were utilized to determine the best turning mediums.

2. MATERIAL AND METHOD

2.1. Experimental Setup

In Figure 1, there is a visual of the general schematic of experiment for study including highlights. For this study, AISI 5115 (DIN 16MnCr5) workpiece was provided, and the material was cylindrical in shape with a diameter of 45 mm and a length of 600 mm. Additionally, each experiment was carried out with a machining length of 400 mm. The properties of the material, which is one of the hardened steel types, is given in Table 1. Machining parameters were selected by examining the studies in existing literature and according to the hypothesis established in accordance with the purpose of the experiment, taking into account both material properties and the recommendations of the cutting tool company. The full factorial experimental design, which is preferred because it is an optimum approach since it includes all possible combinations of different machinability parameters [37], was used to specify the feed rate and cutting speed values with their levels. The machining parameters and their levels mentioned above are shown in Table 2.

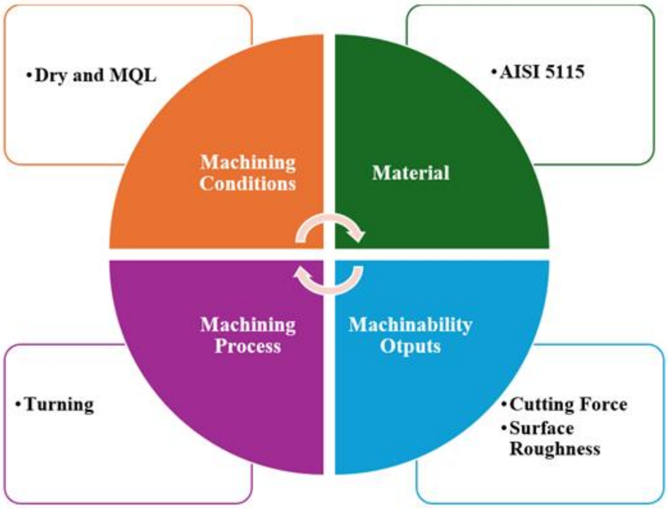

Figure 1. General schematic of experiment.

Table 1. Chemical composition-AISI 5115 [3].

Element (weight %)	P %	C %	Mn%	Si%	Cr%	Fe%
AISI 5115	0.02	0.16	1.20	0.40	1.10	Bal.

Table 2. Machinability parameters/levels.

Exp. No.	Cutting speed (m/min)	Feed rate (mm/rev)	Cutting depth (mm)
1	50	0.15	0.2
2	60	0.15	0.2 0.2
3	90	0.15	0.2
4	135	0.15	0.2
5	50	0.3	0.2
6	60	0.3	0.2
7	90	0.3	0.2
8	135	0.3	0.2

2.2. Cutting Tool, Cutting Conditions and Experiments

Machine tool specifications are presented in Table 3. Cutting tool and tool holder selection was made according to the applications commonly used in the manufacturing sector. As can be found in the literature [38], TiN coated cutting tool was used in accordance with ISO 3685. Machining experiments were carried out in dry and MQL cutting conditions by changing the cutting tools in each experiment. Cutting tool clearance angle was 7°, cutting edge length was 9 mm, cutting tip thickness was 4.97 mm and corner radius was 0.8 mm. STN 15 Micro Lubrication System, the specifications of which are presented in Table 4, environmentally friendly sunflower oil obtained from renewable resources was used. Sunflower oil is a safe oil because it does not contain harmful compounds, so it is a favourable choice among environmentally friendly lubricants [39]. In the MQL system, oil lubricating fluid was sprayed to the machining area from 20 mm and used at 6 bar pressure and 45° nozzle angle. In the study, the influence of two different parameters and levels on surface roughness and cutting force were reseached by the turning method. A total of 16 machining experiments, designed with the full factorial method, were carried out on De Lorenzo S547-8899 lathe. Cutting force signals measured with Kistler 9275 dynamometer were recorded in the computer environment. After processing, surface roughness values were measured from three different points using Mahr Perthometer M1 device and evaluated by taking the averages. Roughness taken into consideration was determined by taking the differences of the highest/lowest values from the roughness measurements and taking the average of the three. Surface roughness measurements were customized according to DIN EN ISO 4287. Figure 2 shows the experimental setup.

Table 3. Machine tool specification.

Maximum workpiece diameter, mm	460
Distance between chuck and tailstock, mm	1500
Spindle speed range, rev/min	25-1800
Spindle speed number, piece	12
Feed range, mm	0.04-2.46
Number of feeds, piece	122
Maximum tool holder size, mm	25x25
Motor power, kW	5.5

Table 4. Micro lubrication system specification.

Supply voltage, V	230-24 AC/DC
Operating voltage, V	24 AC/DC
Power consumption, Watt	5
Air pressure,bar	4-6
Oil quantity, stages	24
Oil quantity min.,ml	0.0012
Oil quantity max.,ml.	0.028
Oiling interval, sec	0.1-10
Operating temperature, °C	-15-70
Reservoir, L	1.5
Viscosity range, cst.	2-30

Figure 2. Experimental setup.

3. RESEARCH FINDING

3.1. Surface Roughness

In machining, chip accumulation is seen as a significant problem during the processing of materials. The reason for this is that the accumulated chip formed during the machining of the part negatively affects the surface quality due to the adhesion of the cutting tool [21]. It is thought that the cutting speeds should be increased in order to prevent the formation of accumulated chips. When Figure 3 is given, which shows the average surface roughness varying according to machining parameters and cutting environments, increasing cutting speeds generally affected the surface roughness values (except for high feed and cutting speed values). With the increase of the cutting speed and the feed movement caused by the cutting tool movement, a reduction in the walls occurs. Therefore, during machining, the cutting tool removes chips from the workpiece more easily and better quality surfaces are produced. Since the increase in machining speeds makes the machinability relatively easier, it increases the surface quality of the part, as in [22-24]. The same was observed in the machining of AISI 5115 hardened steel, in dry machining, the worst surface finish was obtained for the combination of 60 m/min cutting speed and 0.15 mm/rev feed rate respectively, while the best surface finish was obtained at 90 m/min cutting speed and 0.15 mm/rev feed rate respectively. Replacing dry environment with MQL did not change the experimental combinations that gave the worst and best surface properties. However, it is clear that the surface roughnesses for MQL environments are in all cases lower than those under dry conditions. This can be explained by the oil film layer formed between the workpiece and the cutting tool interface in the MQL environment, which allows the chips generated during machining to be more easily removed from the cutting medium [40-42]. Rising the feed positively affected the surface quality for the cutting speed values of 50 m/min and 90 m/min in both dry and MQL machining mediums.

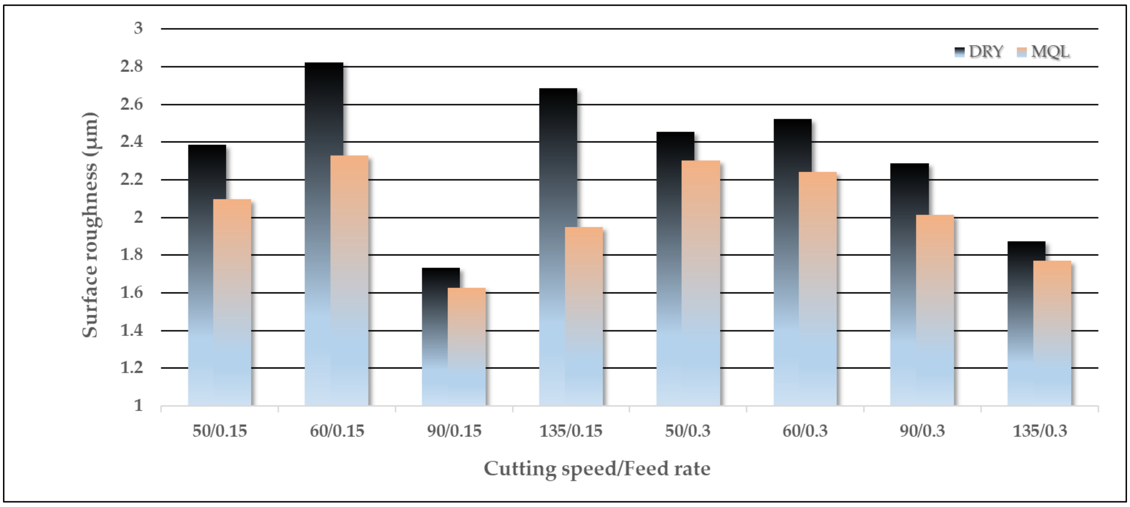

Figure 3. Surface roughness variation vs. cutting speed and feed rate.

S/N (Signal/Noise) ratio is main criterion for analyzing experimental data. This ratio expresses the ratio of a signal to the background noise factor, exemplified by humidity and ambient temperature [43, 44]. According to the smallest-best approach in Taguchi experimental design method, S/N ratios for surface roughness in dry and MQL mediums are given in Figure 4, respectively. According to the graph, the change in cutting speed in dry and MQL mediums corresponds to the S/N worth of surface roughness in the graph. In addition, it can be seen that high feeding level is more effective in experiments conducted in dry conditions, while low level is more effective in MQL results.

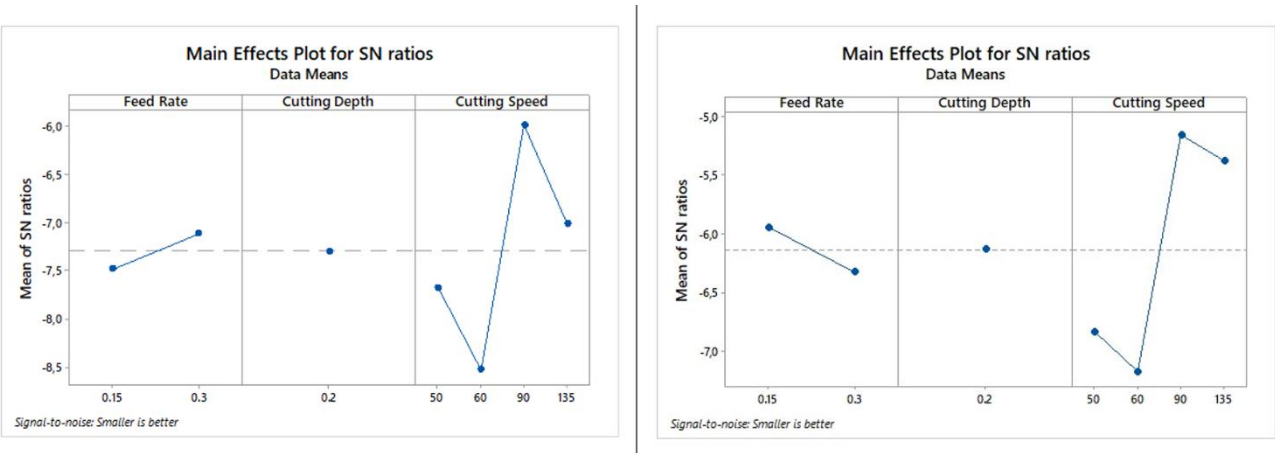

Figure 4. S/N ratio plot for average surface roughness under dry and MQL conditions, respectively.

Chip depth, feed rate and cutting speed are as important as cutting angle and cutting tool geometry for chip angle and control in workpiece machining [45]. As the chip depth increases, rougher surfaces are obtained, while improvements in surface quality occur as the depth decreases [46]. The cutting tool geometry chosen in this study had a significant effect on the removal of surface roughness. Considering the comparison between dry machining and machining with MQL application in the study carried out with constant chip depth, more favorable results were obtained in machining in MQL environment.

3.2. Cutting Force

The assortment in the machining force according to the processing parameters and cutting mediums are given in Figure 5. In general, it is possible to say that the cutting force values increase with the increase in cutting speeds in both cutting conditions. It is well recognized from the literature that the heat in the machining zone rises with growing cutting speeds and therefore the chip is more easily removed from the part [47, 48]. The growing in cutting forces with rising cutting speeds is consistent with the results of studies in literature [5, 49] and it can be said that the reason for the raise is tool wear. It is observed that the cutting force increases with increasing feed rate both dry and MQL environments. In both machining environments, it is also seen that the cutting force rises with increasing progress. At higher feed speeds, since the chip section increases with higher resistance to processing, more force is needed in cutting [50]. It is an expected result that lower cutting force is obtained in MQL conditions than in dry conditions due to the decrease in the temperature formed at the tool-chip interface in MQL environment machining and therefore easier chip removal from the part [51]. In a more general sense, it can be said that in almost all experimental conditions, the cutting force values obtained in machining in MQL environment are lower than those obtained in dry machining. Maximum cutting force values were found in dry machining with 0.3 mm/rev feed and 135 m/min cutting speed and in MQL machining with 0.3 mm/rev and 60 m/min cutting speed.

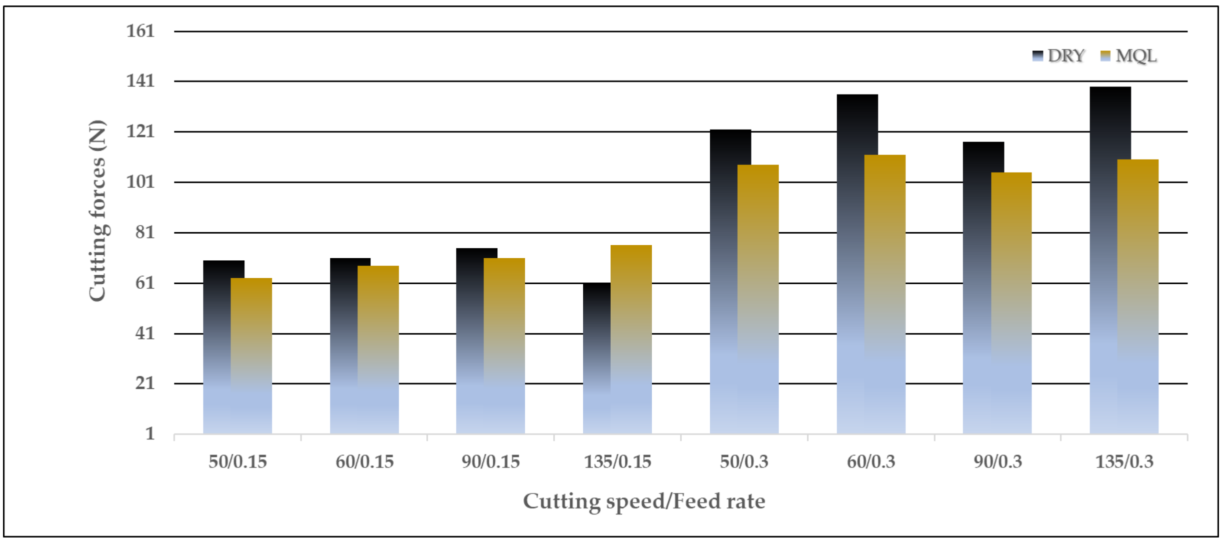

Figure 5. Cutting force variation vs. cutting speed and feed rate.

S/N ratios for cutting force in MQL and dry conditions are given in Figure 6 respectively. While the cutting speed value that minimizes the cutting forces is 50 m/min, keeping the feed at 0.15 mm/rev serves the purpose of reducing the cutting force. Although there are no significant differences between MQL and dry mediums, it can be said that the machining situation in the MQL condition also indicates a cutting speed of 50 m/min and a feed of 0.15 mm/rev.

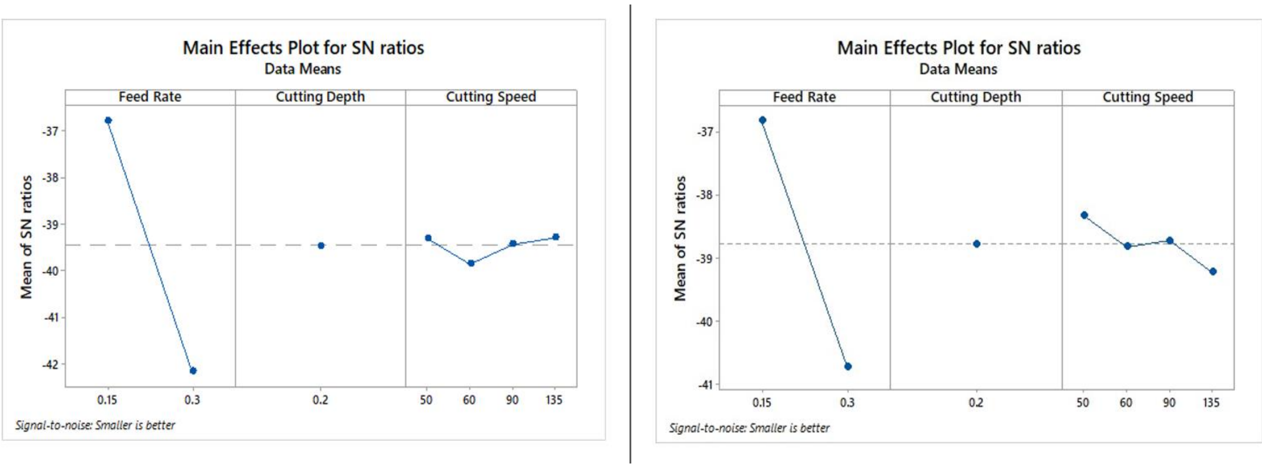

Figure 6. S/N ratio plot for average cutting forces under dry and MQL conditions, respectively.

4. CONCLUSIONS AND DISCUSSIONS

This paper focuses on the machinability of AISI 5115 steel by turning in MQL conditions compared to dry conditions. The fact that there is no satisfactory information yet about the machinability of this material in the MQL environment reveals the originality of the study. The study characterizes the effects of various cutting parameters on surface roughness and cutting force.

The major findings of the research results are summarized below ;

- When all the variables within the scope of the experiment are evaluated together, it is seen that the cooling environment is the most influential of all variables. So much so that, with all other parameters remaining the same, it was observed that there was a significant decrease in the surface roughness value by changing the cooling environment from dry environment to MQL environment. It is also seen that there is a crucial decrease in cutting force values in the MQL method because cutting fluid penetrates well between the workpiece and the cutting tool. When the comparison of machining under the two working conditions is made, it is seen that machining under MQL mediums gives better results. In MQL conditions, an average 6.90% reduction in cutting force and 12.2% reduction in surface roughness occurred. In addition, it can be said that MQL is an effective option in terms of environmental impacts and cost effectiveness compared to dry conditions

Although the fact that the study does not address the impact of cutting tool geometry on the experimental parameters does not prevent it from contributing to science, it is anticipated that its evaluation will provide opportunities for future research. By taking this study as a reference, which provides a framework that will form the basis for more comprehensive studies, studies can be conducted in which the effects of cutting parameters/levels on more parameters can be evaluated interactively and the process can be optimized.

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