

Article

A Study on the Machinability and Environmental Effects of Milling AISI 5140 Steel in Sustainable Cutting Environments

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Abstract: AISI 5140 steel is an alloy frequently used in the manufacturing and automotive industries. This steel alloy is shaped using different manufacturing methods and cooling is required during this process. This research study included the milling of AISI 5140 steel utilizing various cutting settings and cooling/lubrication procedures. For this purpose, two cutting speeds (75–100 m/min), two feed rates (0.075–0.100 mm/rev), and four cooling media (dry, MQL, flood, nanofluid) were used. Then, 5% Mo nanoparticles were added to the nanofluid cutting fluid. Machinability and power consumption analyses were carried out using the input parameters selected in light of the manufacturer's recommendations and studies in the literature. The effects of sustainable cutting fluids and their parameters on machinability and power consumption were investigated through experiments. This study concluded that the use of nanofluid led to improvements in surface roughness, flank wear, and power consumption characteristics. It was determined that the flood environment is the most effective in reducing the cutting temperature. As a result, it is predicted that nanofluid cutting fluids can be used during machining.

Keywords: AISI 5140 steel; milling; machinability; nanofluid; power consumption



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1. Introduction

In today's world where technology is rapidly developing, the processing of high-performance materials for industrial applications is of critical importance in terms of the efficiency and quality of production processes [1]. In this context, metalworking operations require controlling various parameters that arise while processing the material. Some of these parameters directly affect outputs such as machinability features and energy consumption [2]. Material machinability is a crucial determinant of production process efficiency and end-product quality in the metalworking industry [3]. Particularly in difficult-to-machine materials such as high-strength steels, appropriate cooling techniques can significantly affect machining performance [4,5].

One of the important materials that need to be investigated in terms of machining performance is AISI 5140 steel. AISI 5140 steel consists of alloy components that provide high strength, hardness, and wear resistance [6,7]. This material is generally used in tools such as bearings, gears, shafts, gearboxes, axles, pipe and rod applications requiring high strength and hardness, screwdriver bits, and drill bits due to its suitability for hot processing and moderate weldability [8]. The high chromium concentration in the chemical composition of this steel, known as manufacturing steel for its many applications, might provide challenges in terms of its machinability [9]. Due to the mechanical [10], chemical [11,12], and thermal effects occurring during the processing of this material, surface roughness (Ra) and tool wear are inevitable. When evaluating tool life in the context of machining, flank and crater wear are frequently the primary types of tool wear considered [13]. Several research studies on AISI 5140 steel may be found in the literature. Kahraman [14] utilized

the Taguchi method to analyze the turning performance of AISI 5140 steel and determine the most effective cutting parameters for reducing surface irregularity. A minimum R_a could be achieved under the following conditions: a cutting depth of 0.5 mm, a feed rate (f_n) of 0.2 mm/rev, and a rotation speed of 2000 rpm. An investigation was undertaken by Aslan [15] to assess the effects of various machining parameters such as depth of cut, cutting speed (V_c), f_n , cutting force on cutting tool tip side attrition, vibration levels, and cutting force. The analysis of variance (ANOVA) method was used in the investigation. Consequently, it was discovered that the occurrence of vibration and cutting pressures during the turning process has a substantial impact on V_b . In another study, Grzesik and Wanat [16] conducted a research study where they analyzed the roughness of the surface of a component during the continuous cylindrical dry turning of AISI 5140 steel. The results suggest that hard turning produces unique surface profiles and microstructures, exhibiting R_a values of approximately 0.25 mm, which are comparable to the outcomes obtained through post-grinding. Kuntoğlu et al. [17] examined the vibration and R_a characteristics of AISI 5140 steel by employing the response surface approach. The optimal cutting conditions were ascertained through the manipulation of cutting velocities, f_n , and cutting edge angles. The results of the study revealed that the most significant influence on the increase in axial vibration (65.8%) and surface irregularity (69.4%) was the input rate. The primary determinants of radial vibration (75.5%) and tangential vibration, conversely, were the cutting edge angle and V_c .

The effects of using different cooling/lubrication (c/l) conditions during machining on machining performance are also an important research topic [18]. Usca et al. [19] examined the machining properties of AISI 5140 steel under various c/l conditions, including dry, minimum quantity lubrication (MQL), and cryogenic liquid nitrogen (cryo-LN₂). As a result, Cryo-LN₂ gave good results in all machinability parameters compared to dry media. Kara et al. [20] investigated the efficiency of the cooling and cutting parameters that were used in the cylindrical grinding process of AISI 5140 steel. According to their research, the cryogenically treated samples achieved the most favorable R_a . In another study, Yıldırım et al. [21] evaluated the effects of a dry environment, traditional cutting fluid, and MQL system. They concluded that lowering the use of cutting fluid resulted in improved machining performance. In recent years, the use of nanofluids as a c/l environment has provided significant improvements in machinability and processing efficiency. It has been observed that cooling lubricants containing nanoparticles may have higher specific surface areas and heat transfer coefficients compared to pure cutting oils [22,23]. Nanoparticles have the ability to decrease the amount of friction between surfaces and enhance resistance to wear by forming a thin layer of a lubricating coating [24–27]. Nanoparticles can exhibit a more stable performance at high temperatures, which may be advantageous due to the high temperatures that occur during processing [28]. Consequently, they enhance the lubricating effectiveness and tribological characteristics of the coolant [29,30]. Yıldırım [31] investigated the machinability of AISI 420 steel under a nanofluid cutting fluid and a cryogenic coolant containing 0.5% graphene nanoplates by volume. Consequently, the study determined that cryogenic cooling outperformed the nanofluid in terms of surface temperature, chip shape, tool life, and tool wear. However, the nanofluid exhibited superior performance in R_a and surface topography. Maruda et al. [32] examined the machining performances of Ti6Al4V Titanium alloy by performing the turning process in different c/l environments such as dry machining, pure MQL technique, and MQL technique with the addition of copper nanoparticles. They stated that after the addition of copper nanoparticles of different sizes, the least tool crater and side wear occurred in the MQL environment with the smallest copper addition, and that this gave better results compared to dry and pure MQL. In another study, Yıldırım et al. [33] investigated the machinability of nickel-based Hastelloy C4 alloy in three different vegetable oil environments with the addition of TiO₂ and SiO₂ nanoparticles. As a result, it was found that machining with corn oil and TiO₂ nanofluid provided a 58.57%, 53.18%, 36.1%, and 34.88% improvement in R_a , tool wear, power consumption (Pd), and cutting temperature (Tc), respectively, compared

to dry machining. Makkesana et al. [34] examined the impact of incorporating graphite and molybdenum disulfide into a nanofluid–MQL system on tool wear, machinability, and microhardness during the machining of Inconel 625. While sunflower oil with MoS₂ produced better Ra results than other conditions, it was noted that nano MQL had beneficial outcomes in terms of tool wear and Tc.

According to the literature, the process of machining materials causes a substantial rise in temperature in the cutting area, which plays a crucial role in determining the quality of the product. Despite the widespread use of traditional cutting fluids for heat dissipation in machining, they pose a significant risk to the environment and the well-being of workers. Hence, it is important to ascertain eco-friendly and user-centric substitutes for conventional cutting fluids. Within this framework, nanoparticles are believed to provide a potential solution to issues related to Ra and temperature management by facilitating the creation of a protective coating during material processing. Although there are partial studies on the machinability of AISI 5140 steel in the literature, there are no studies on its machining performance under nanofluid cooling fluids containing nanoparticles. Therefore, in this study, output parameters such as tool wear, Ra, Tc, and energy consumption during the milling of AISI 5140 steel were investigated using a new nanofluid coolant with molybdenum additives and compared with machining parameters under different c/l conditions.

2. Materials and Methods

2.1. Workpiece and Cutting Tools

In this experimental study, AISI 5140 manufacturing steel was used as the workpiece. The metal industry often utilizes AISI 5140 steel due to its notable strength and hardness characteristics. AISI 5140 steel has a hardness of 238 HB, a tensile strength of 804 N/mm², and an elongation at break of 21%. All test samples were cut into Ø50 × 20 mm dimensions and made ready for milling. Table 1 displays the chemical makeup of the samples.

Table 1. Chemical composition of the test samples (AISI 5140) [19].

Elements	C	Si	Mn	P	S	Cr	Fe
Range (%)	0.45	0.3	0.75	0.035	0.03	1	Balance

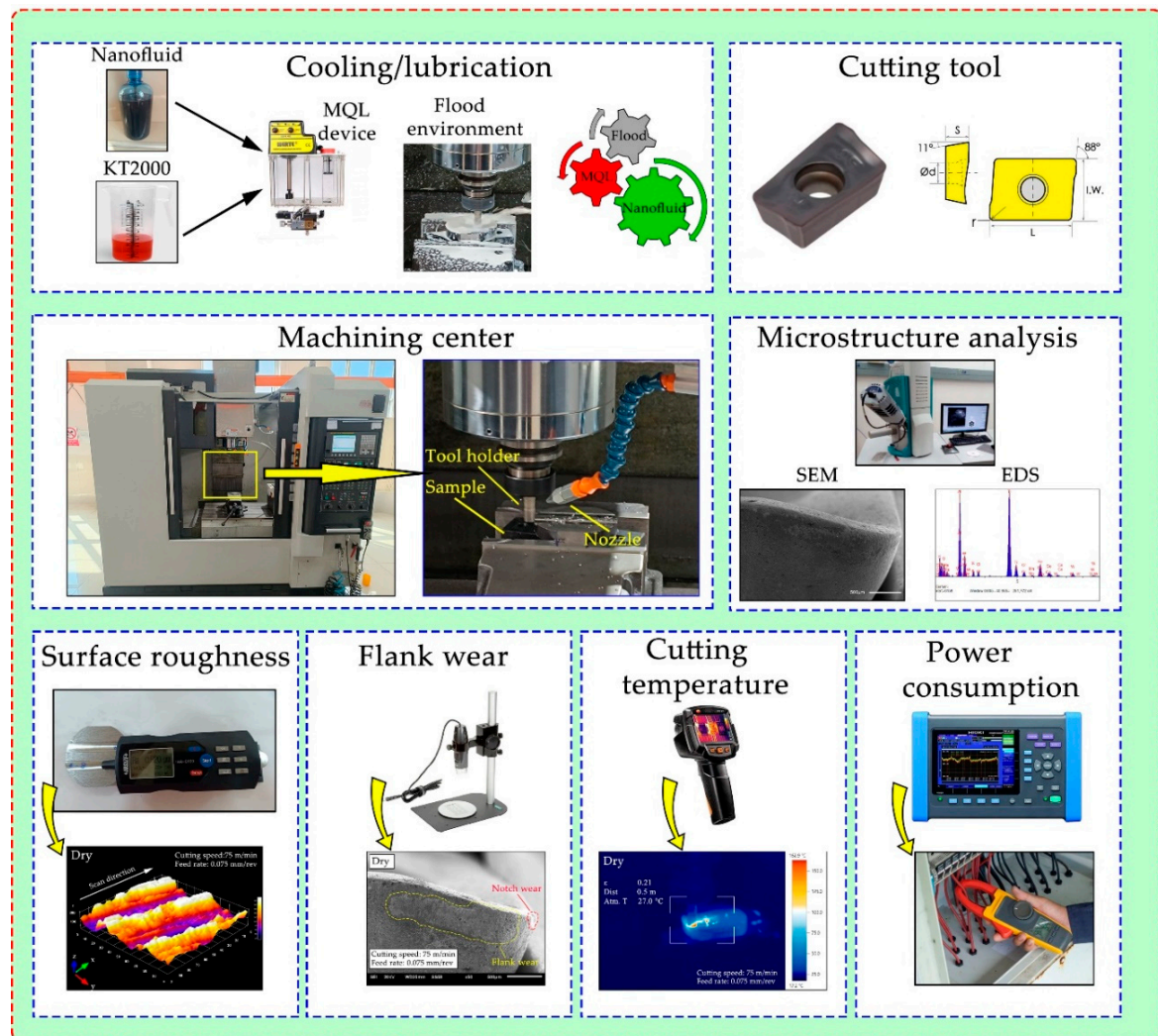
Coded HM 90 APKT 1003PDR IC908 inserts from Iscar, located in Konya, Türkiye, were used for the milling process. The cutting tool was coated with AlTiN by the physical vapor deposition (PVD) method and had a dark grey color. The insert, which had a corner radius of 0.8 mm, was affixed to a milling cutter with the designation ST90 AP10 D12 W12 L120 Z01 (Smoxh, Konya, Turkey). Inserts were substituted at the conclusion of each trial.

2.2. Machining Center and Experimental Stages

The studies were conducted using a 3-axis Dahlih MCV-860 milling machine from Dahlih in Taichung, Taiwan. The milling machine had a power capacity of 7.5 kW. The experiments were devised based on a comprehensive experimental framework, resulting in a total of 16 planned experiments. In the experimental design, 2 different Vcs (75–100 m/min), 2 different fns (0.075–0.100 mm/rev), and 4 different c/l environments were selected. The experimental design is shown in Table 2. The cutting settings were established and scheduled in accordance with the manufacturer’s guidelines and first testing. Before the experiments, the surfaces were cleaned by removing a layer from each sample for fair results. The “Zig” tool path and downward milling approach were implemented while maintaining a constant cutting depth of 0.5 mm. The experimental scheme is given in Figure 1.

Table 2. Comprehensive experimental design ($2 \times 2 \times 4$).

Milling Parameters	Unit	Levels			
		L1	L2	L3	L4
Cooling conditions	-	Dry	MQL	Flood	Nanofluid
Cutting speed, (Vc)	m/min	75	100	-	-
Feed rate, (fn)	mm/rev	0.075	0.100	-	-

**Figure 1.** Experimental scheme.

2.3. Cooling/Lubrication Environments

Experiments were planned in 4 different c/l environments (dry, MQL, flood, and Mo-based nanofluid) to determine optimum machinability performance during milling. The dry processing environment is evaluated within the scope of sustainability [35]. The coolant was transmitted to the cutting zone from a nozzle connected to the machine tool with a flood c/l environment. In MQL and nanofluid c/l environments, a Werte Micro STN-15 (Kar-Tes, Istanbul, Turkey) model system was used. The pressure used in the system was determined as 6 bar and the liquid flow rate was determined as 35 mL/h. The 3 mm diameter nozzle connected to the system was positioned at a distance of approximately 200 mm from the test sample. KT2000 synthetic oil with a hydrodynamic lubrication feature was used as the cutting fluid in the MQL environment. In the nanofluid environment, Mo nanoparticles were added to KT2000 synthetic oil. Mo nanoparticles were purchased from

the manufacturer (Nanokar, Istanbul, Türkiye). Technical details of Mo nanoparticles are provided in Table 3. The preparation process of the nanofluid is given in detail in Figure 2.

Table 3. Some properties of Mo nanopowders.

Properties	Value
Bulk Density (g/cm ³)	0.25
True Density (g/cm ³)	10.2
Color	black
Crystal Structure	cubic
Mean Particle Diameter (nm)	50
Specific Surface Area (m ² /g)	22.0–35.0

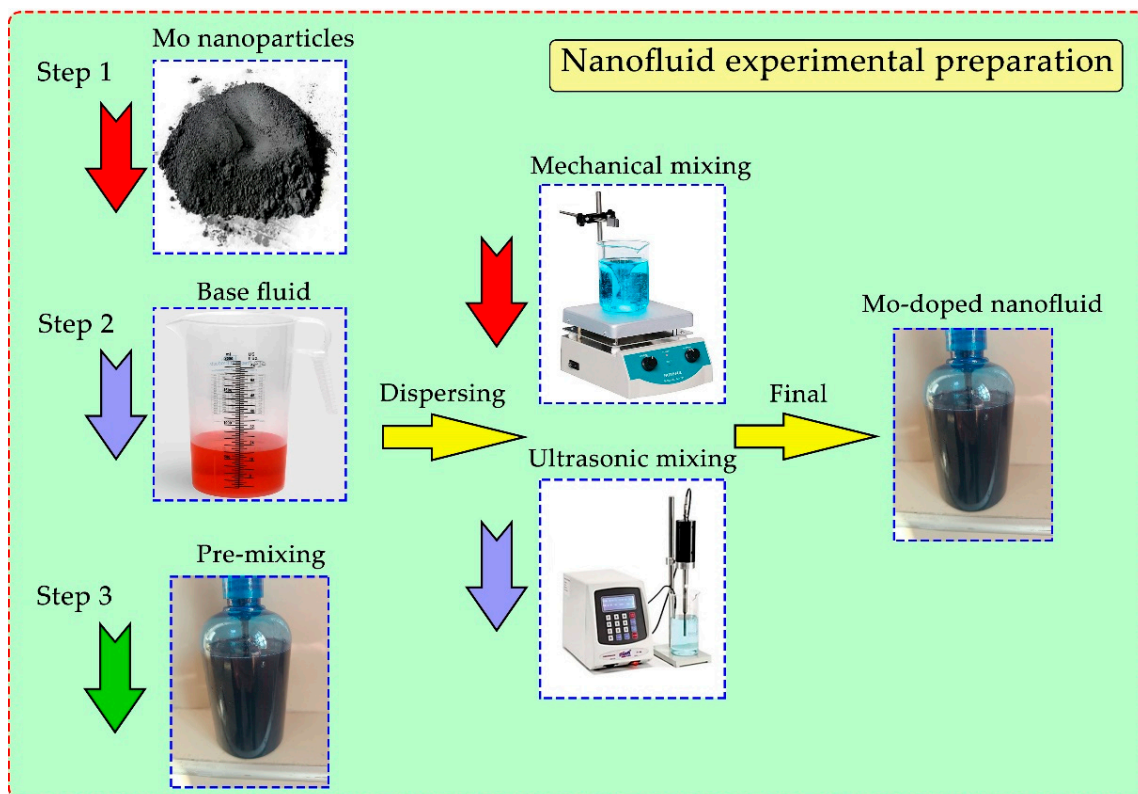


Figure 2. Nanofluid preparation process.

Cutting fluids were created by adding Mo nanoparticles into KT2000 synthetic oil at a rate of 0.5 wt.%. A total of 500 mL of nanofluid was prepared for each cutting environment. Nanoparticles were added into synthetic oil and blended in a mechanical mixer for approximately 5 min. It was then mixed by ultrasonic sonication for approximately 30 min.

2.4. Measuring Instruments

An investigation was conducted to examine the impact of cutting parameters and cutting/lubrication conditions on the milling process of AISI 5140 steel. Analyzed in this particular context were machinability properties and Pd. Insize ISR-C100 Ra equipment, located in Beijing, China, was used to assess the surface quality. Five measurements were collected from various parts of each sample, and the average Ra values were recorded. The temperatures in the cutting zone were measured using a Testo 871 thermal camera model (Testo, Istanbul, Turkey). The distance between the cutting zone and the thermal camera is 400 mm. An Insize ISM PM200SB optical microscope model manufactured in Suzhou New District, China, was used to identify any defects present on the lateral edges of the cutting tool. SEM, EDS, and mapping investigations conducted on a JEOL JSM 6510 SEM

instrument (Jeol, Tokyo, Japan) successfully identified the wear processes taking place on the cutting tool. The HIOKI PW 3198 power analyzer, which was made by Hioki in Nagano, Japan, was used in order to determine the milling machine's power usage. The amount of power consumed was calculated using the data obtained from the device using special software. A diagram representing the wear mechanisms is given in Figure 3.

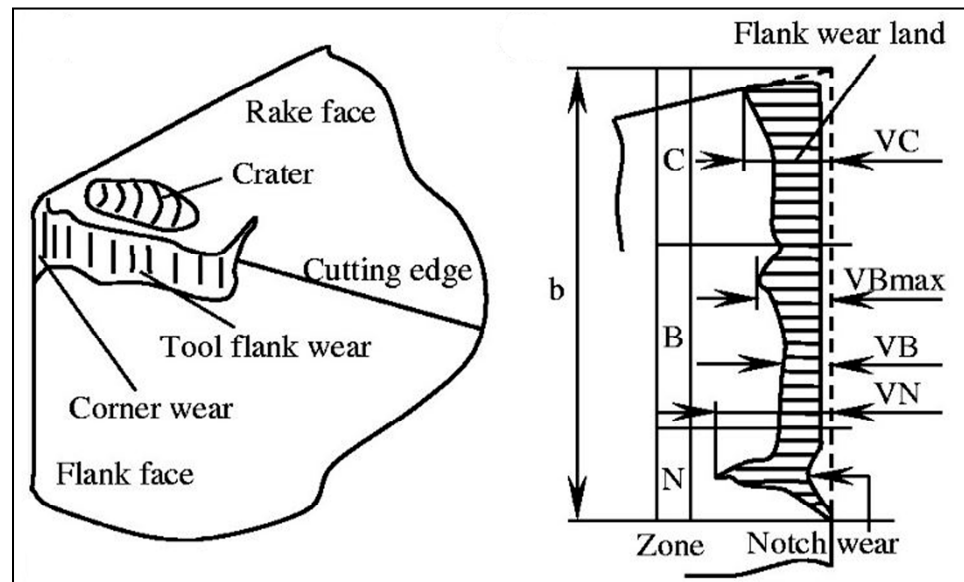


Figure 3. The diagram represents the wear mechanisms [36].

3. Results and Discussions

In this experimental study, machinability (surface roughness, tool wear, and cutting temperature) and power consumption analyses of AISI 5140 manufacturing steel under different c/l conditions (dry, MQL, flood, and nanofluid) were carried out. The results are given below.

3.1. Surface Roughness Analysis

Surface quality is considered an important machinability performance criterion in machining processes. It is necessary to perform R_a evaluation after machining and to observe the effects of different cutting parameters [31]. This portion of the study included conducting tests to assess the impact of various characteristics on surface quality. Figure 4 displays the experimental findings visually. When considering cooling fluids, nanofluid is shown to be the optimal choice. When the V_c was set at 75 m/min, using a nanofluid environment resulted in R_a improvements of about 36.7% and 34% at an f_n of 0.075 and 0.100 mm/rev, respectively, compared to the dry environment. At a V_c of 100 m/min, the use of nanofluid resulted in R_a improvements of about 27.7% and 35.4% at an f_n of 0.075 and 0.100 mm/rev, respectively, compared to the dry environment. The minimum R_a , measuring 0.684 μm , was achieved when the V_c was set at 100 m/min, the f_n was set at 0.075, and the cutting process was conducted in a nanofluid environment. The superiority of the nanofluid cooling fluid compared to other environments is related to the lubrication quality of the nanofluid. Nanofluid cutting fluids exhibit better wettability properties compared to other cutting fluids. This creates a film layer that helps reduce friction in the cutting area [37]. In the Mo-containing nanofluid cutting fluid, oil-coated nanoparticles are transferred from the nozzle to the cutting zone as a fine mist cloud. Thus, the mist cloud that easily enters the cutting zone protects the form of a thin film layer, increasing the wear performance and therefore increasing the surface quality.

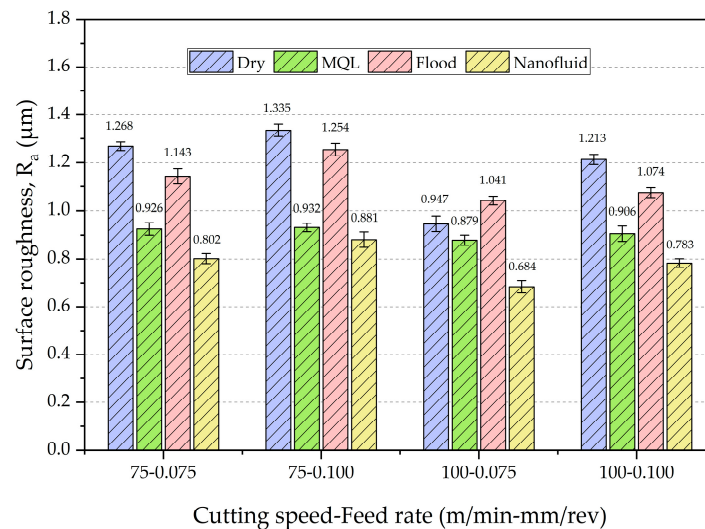


Figure 4. Effects of different cutting parameters and cutting environments on surface roughness (Ra).

The graph clearly demonstrates that there is a direct correlation between feed speed and Ra, indicating that as the feed speed rises, the Ra also increases. According to the literature, the f_n is the most influential factor in determining surface quality. It has been shown that increasing the feed speed leads to an increase in Ra [38]. Khalilpourazary and Meshkat [39] reported that nanoparticle-added coolant showed better c/l performance, thus reducing Ra. Hegab et al. [40] reported in a study that the surface quality increased thanks to the wettability, convection, and conduction advantages of nanofluids.

Surface topography is a very important argument in terms of understanding surface quality. Because it has a direct effect on parameters such as wear and fatigue [41,42]. Figure 5 analyzes surface topographies under various cutting conditions, namely a Vc of 75 m/min and an f_n of 0.075 mm/rev. The Ra in the dry environment was measured to be 1.268 μm . In the MQL, flood, and nanofluid conditions, the recorded Ra values were 0.926 μm , 1.143 μm , and 0.802 μm , respectively. The nanofluid environment yielded the lowest Ra rating. The surface roughness in the nanofluid environment exhibits a higher degree of regularity in comparison to other environments.

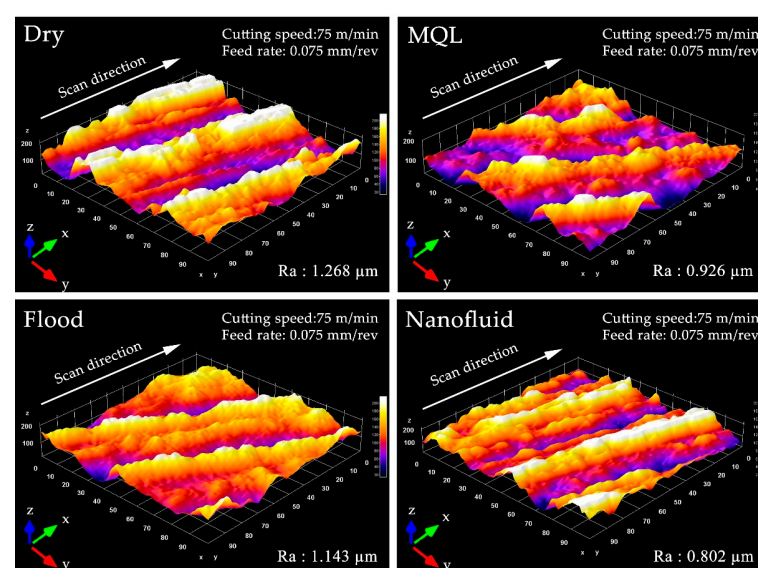


Figure 5. Surface topographies under various cutting conditions, including a Vc of 75 m/min and an f_n of 0.075 mm/rev.

3.2. Flank Wear Analysis

Tool wear is a feature that has a significant impact on all machinability parameters. Therefore, a detailed examination of tool wear analysis is very important [43,44]. Extended tool lifespan decreases both the cost of cutting tools and the duration required for tool replacement. This research study examined the impact of two different V_c s, two f_n s, and four cooling conditions on the amount of wear experienced on the flank of the tool. A grand total of 16 tests were conducted, with a distinct state-of-the-art cutting edge being used for each individual experiment. The degree of erosion on the cutting tool edge was quantified and documented using an optical microscope. Figure 6 illustrates the impact of various cutting settings and cutting circumstances on V_b . The nanofluid environment is shown to decrease V_b in comparison to other settings. When the V_c was set at 75 m/min, using a nanofluid environment resulted in a reduction in V_b of roughly 24% and 27% at an f_n of 0.075 and 0.100 mm/rev, respectively, compared to the dry environment. When the V_c was adjusted to 100 m/min, substituting a nanofluid environment for a dry environment led to a decrease in V_b of about 26% and 22% at an f_n of 0.075 and 0.100 mm/rev, respectively. A V_c of 75 m/min, an f_n of 0.100, and a nanofluid environment resulted in a minimum V_b measurement of 0.301 mm. Wear may be directly attributed to elevated temperatures and heightened friction in the cutting area. The cooling liquids used in this study were effective in reducing temperatures. However, in this study, minimum wear values were obtained with the nanofluid cooling method. Additionally, it was observed that V_b increased with increasing V_c , and V_b decreased with increasing feed speed. It was determined that these results are compatible with the literature [45–47].

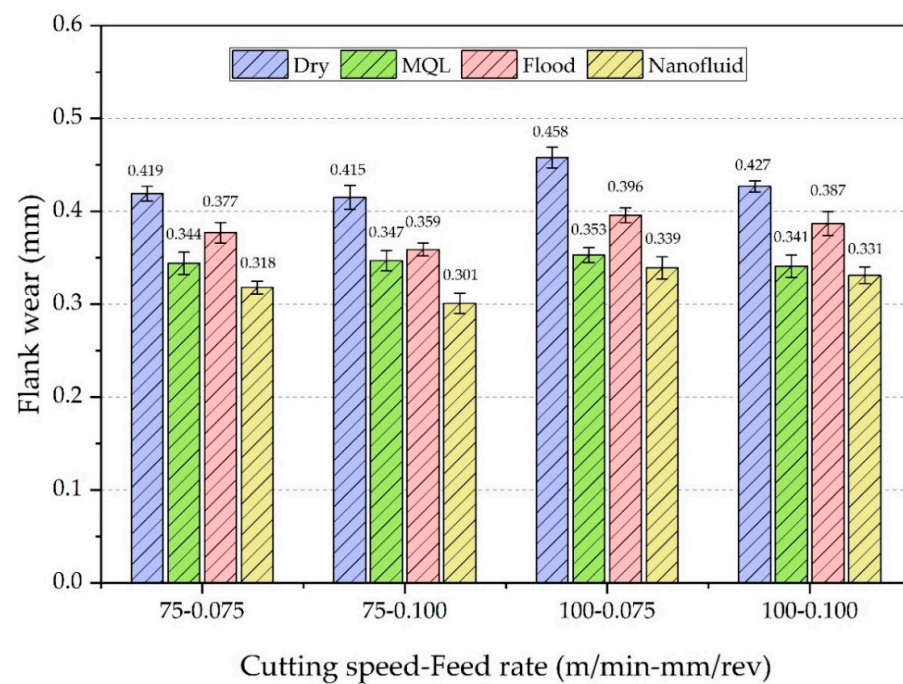


Figure 6. The impact of various cutting settings and cutting conditions on the development of V_b .

Tool wear arises during the process of machining as a result of plastic deformation and high levels of friction between the cutting tool and the material [48]. At this stage, different loads affect wear mechanisms depending on thermal, mechanical, and chemical properties. These loads cause wear mechanisms to occur in different parts of the cutting tool over time [49]. The wear mechanisms occurring in this study can be listed as nose wear, cutting tool peeling, and adhesion. SEM pictures of the cutting tool under various cutting settings are shown in Figure 7, with a V_c of 75 m/min and an f_n of 0.075 mm/rev. The forms of wear that manifest on the cutting tool are observed under identical cutting and feed velocities. Notch wear and flank wear were seen in dry circumstances. Additionally,

flank wear was detected in the MQL, flood, and nanofluid environments. The nanofluid environment yielded the lowest flank wear value when the V_c and f_n were kept constant. In addition, as shown in Figure 8, an EDS analysis of the cutting tool used in the MQL environment was performed and the materials contaminated by the workpiece on the tool were detected as adhesion.

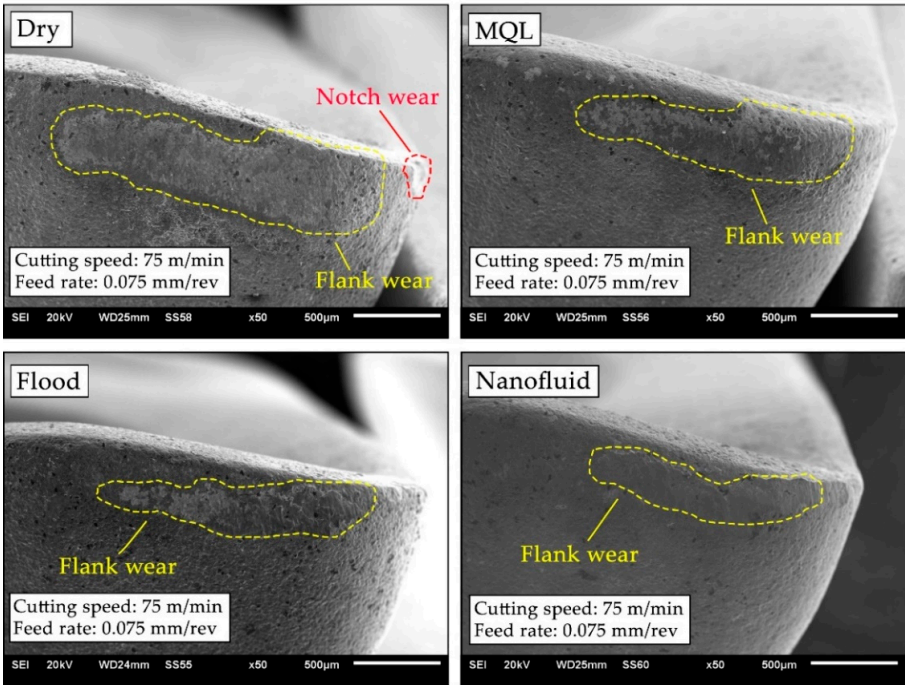


Figure 7. SEM pictures of cutting tools at 75 m/min V_c , 0.075 mm/rev f_n , and different cutting environments.

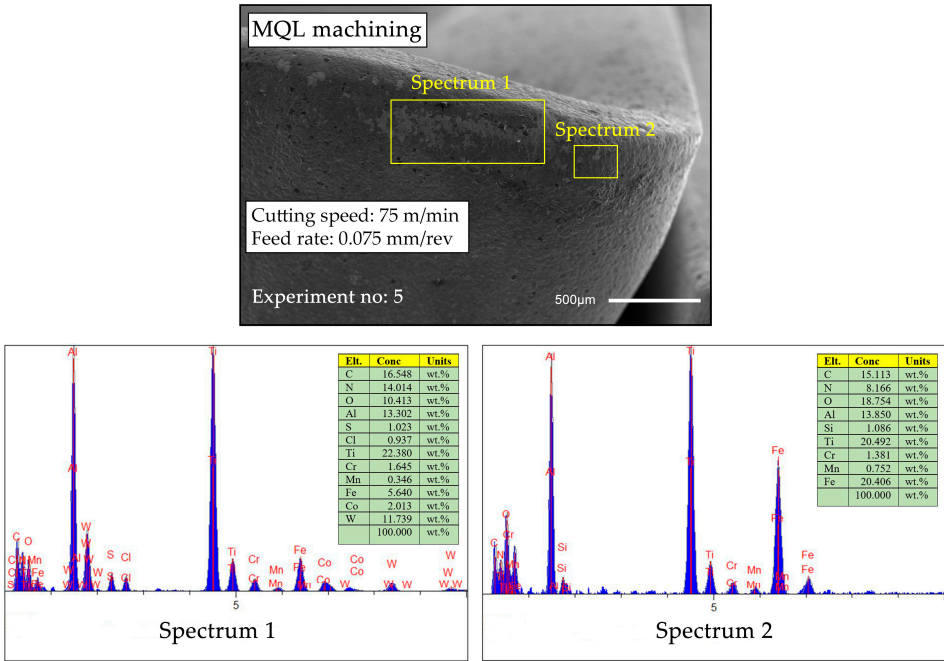


Figure 8. EDS analysis of cutting tools used in MQL environment.

Figure 9 shows the cutting tool mapping analysis and backscattered images obtained as a result of machining in a dry environment. The figure shows an overview of the cutting tool, mapping, and element analysis in percentages. As understood from the EDS analysis,

it was observed that the coating was peeled off from the cutting tool in dry machining and the presence of the main elements of the cutting tool was observed in the peeled parts.

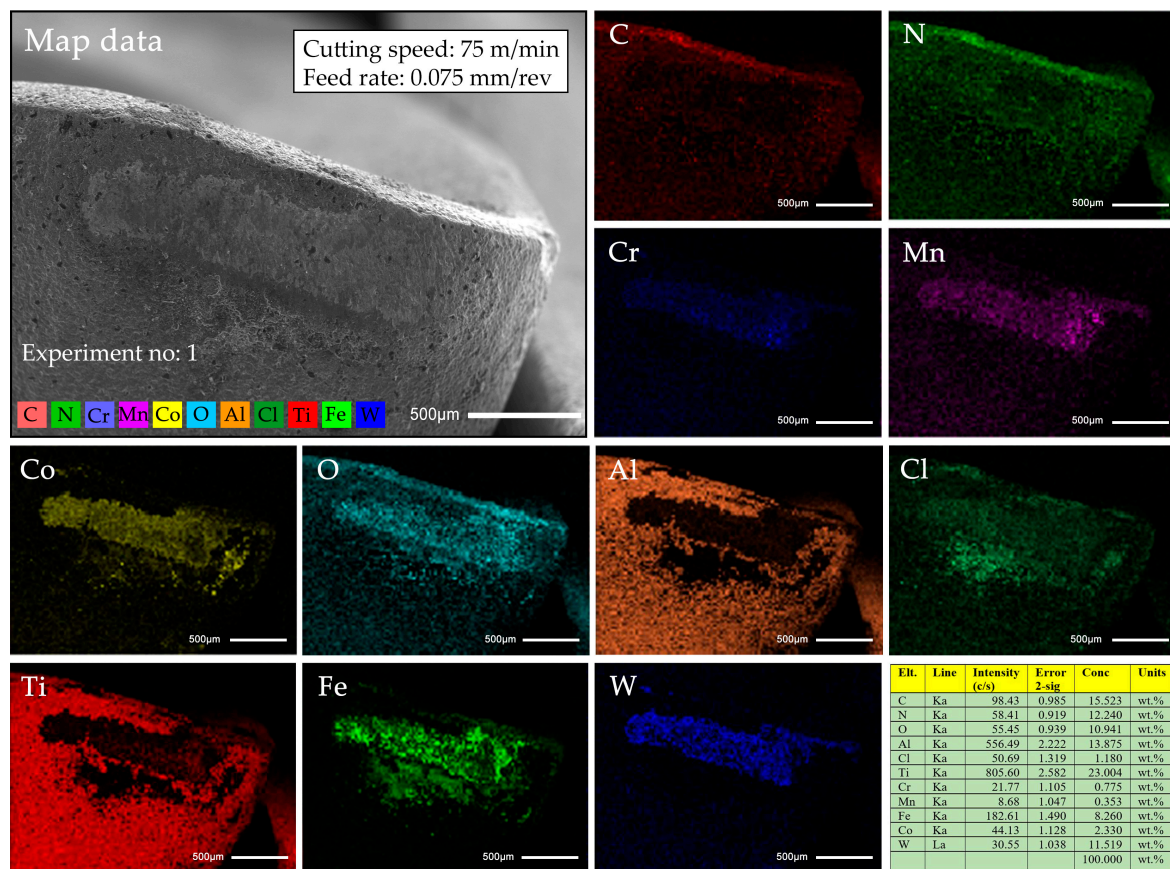


Figure 9. Cutting tool mapping analysis in dry environment.

3.3. Cutting Temperature Analysis

The temperatures in the cutting zone play a vital role in determining the tribological performance and dimensional accuracy of the cutting tool. Furthermore, the temperatures in the cutting zone possess the capability to influence the surface integrity of the workpiece [50]. In other words, the temperatures formed between the cutting tool and the chip surface are important for quality machining and productivity. For this reason, the analysis of temperatures occurring during cutting should be considered in detail [51]. Figure 10 demonstrates the influence of different cutting settings and cutting circumstances on the temperature during cutting. Based on the trials, it was concluded that the flood environment demonstrated superior cooling in comparison to other cutting settings. It has been noted that the flood environment yields superior outcomes in all cutting parameters. According to the average temperatures, it was found that temperatures in the flood environment decreased by around 56.5% compared to the dry environment. This condition may be attributed to the fact that the cutting fluid, when used as flood cooling, delivers enhanced cooling to the cutting zone. The flood cooling strategy can affect T_c depending on many parameters such as V_c , f_n , tool geometry, and the workpiece. When evaluated in terms of V_c , it was seen that it gives better results at low speeds compared to high speeds. In terms of f_n , lower T_c s were obtained at high feed speeds compared to low feed speeds. Optimal cooling may be achieved by regulating the temperatures between the cutting tool and the surface of the chip [52]. The T_c reached its lowest point of 61.4 °C when the V_c was set to 75 m/min, the f_n was 0.100 mm/rev, and the cutting operation was conducted in a flood environment. Figure 11 shows thermal images taken during processing.

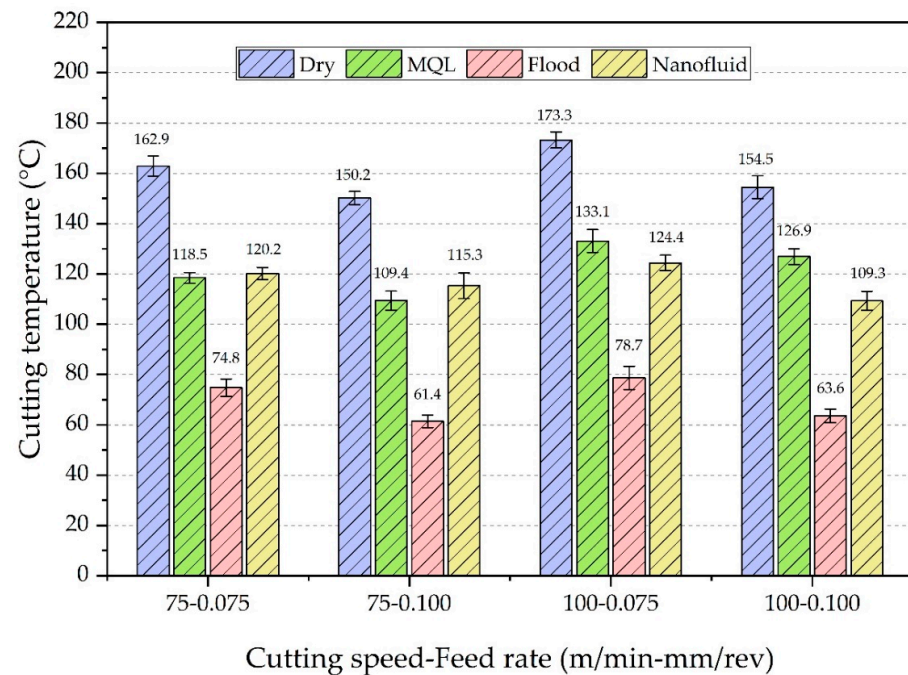


Figure 10. The influence of different cutting parameters and cutting circumstances on the temperature during cutting.

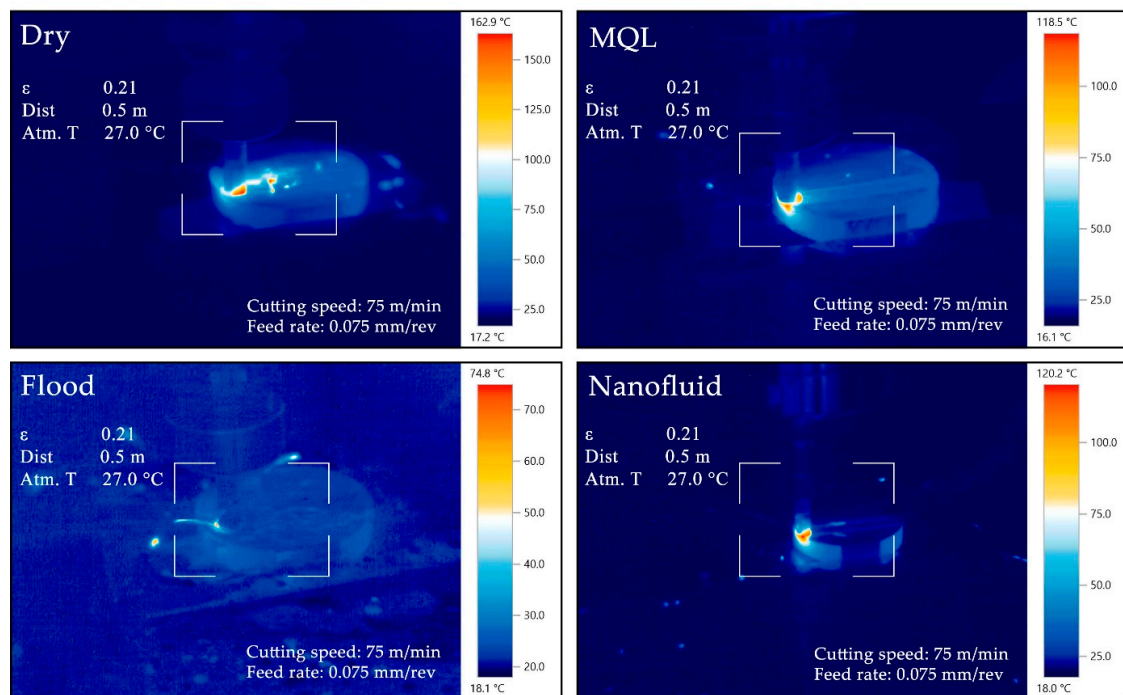


Figure 11. Thermal camera images taken during processing.

3.4. Power Consumption Analysis

Energy consumption occurs in machining processes during basic manufacturing operations [53]. Machining, one of the most important technologies in the manufacturing sector, has made significant contributions to the development of the economy. Research has been conducted on many factors in the machining industry, such as cutting tools, c/l techniques, and cutting parameters [54,55]. During the course of this study, significant efforts were undertaken to develop a procedure that is both cost-effective and ecologically sustainable. Concurrently with technological advancements, V_c in cutting instruments is

seeing substantial increases. Therefore, elevated temperatures at the interface between the tool and the chip decrease the lifespan of expensive cutting tools and impact the quality of the workpiece's surface. This scenario results in the depletion of resources and loss of products in the metal processing sector. Coolants may enhance surface quality and prolong cutting tool lifespan in the metal cutting sector while treating steels. Nevertheless, the use of petroleum-derived cutting fluids, which now predominates, may lead to significant and irreversible issues in terms of both economic impact and human well-being. This section examines the impact of various cutting fluids and cutting settings on energy usage, as shown in Figure 12. Nanofluid was shown to be the most effective cooling medium in terms of power usage across all cutting parameters. When the V_c was set at 75 m/min, using a nanofluid environment resulted in Pd reductions of roughly 2% and 3% at an f_n of 0.075 and 0.100 mm/rev, respectively, compared to the dry environment. Based on a V_c of 100 m/min, an improvement of approximately 4.6% and 1% in Pd was achieved, respectively, at an f_n of 0.075 and 0.100 mm/rev in the nanofluid environment compared to the dry environment. The lowest Pd value (743 W) was obtained at 100 m/min V_c , 0.100 feed speed, and in a nanofluid environment. In terms of V_c , increasing V_c caused a decrease in Pd. Similarly, Pd tends to decrease with increasing feed speed. Makhesana et al. [34] used MoS_2 and graphite-reinforced nanofluids as cutting fluids during the machining of nickel-based superalloys. As a result, they reported that MoS_2 -doped nanofluid reduces Pd. A study by Usca [46] reported that cellulose nanocrystal-based nanofluid cutting fluid was used as a coolant during the machining of Dillimax 690T. According to that report, higher cutting and feed speeds result in decreased power usage.

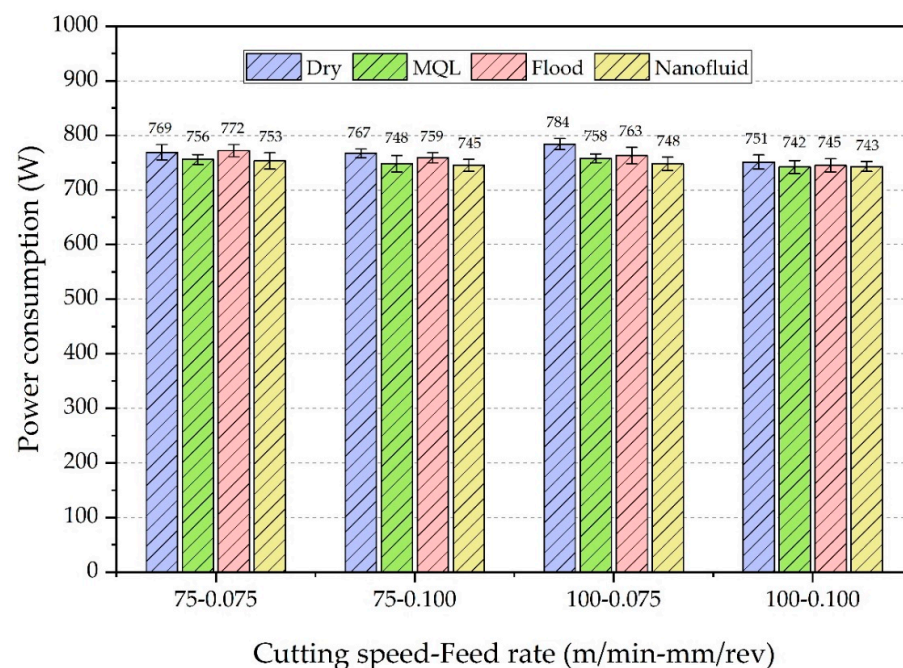


Figure 12. The influence of different cutting parameters and cutting circumstances on Pd.

4. Conclusions

This research study aimed to explore the machinability qualities of AISI 5140 steel, which is often used in the industrial sector. The investigation included analyzing the steel's performance under various cutting settings and cooling procedures. The results are given below.

- Nanofluid was identified as the optimal medium for Ra. The lowest Ra obtained was $0.684 \mu\text{m}$ under the conditions of a V_c of 100 m/min, an f_n of 0.075, and cutting performed in a nanofluid environment.

- It was shown that the presence of nanofluid leads to a decrease in V_b in comparison to other conditions. The minimum V_b measurement (0.301 mm) was achieved by using a V_c of 75 m/min, an f_n of 0.100, and a nanofluid environment.
- Based on the mean temperatures, it was concluded that temperatures decreased by around 56.5% in the flood environment compared to the dry environment. The T_c was minimized to 61.4 °C by using a V_c of 75 m/min, an f_n of 0.100 mm/rev, and a flood environment.
- The best cooling environment for P_d in all cutting parameters was determined to be nanofluid. In terms of V_c , increasing V_c caused a decrease in P_d . Similarly, P_d tended to decrease with increasing feed speed.

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