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Machinability Investigations Based on Tool Wear, Surface Roughness, Cutting Temperature, Chip Morphology and Material Removal Rate during Dry and MQL-Assisted Milling of Nimax Mold Steel

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Abstract: Using cutting fluids is considered in industrial applications and academia due to their increased influence over many aspects such as machinability, sustainability and manufacturing costs. This paper addresses the machinability perspective by examining indicators such as roughness, cutting temperature, tool wear and chip morphology during the milling of mold steel. A special type of steel is Nimaxm which is a difficult-to-cut material because of its high strength, toughness, hardness and wear resistance. Since mold steels have the reverse geometry of the components produced by this technology, their surface quality and dimensional accuracy are highly important. Therefore, two different strategies, i.e., dry and minimum quantity lubrication (MQL), were chosen to conduct an in-depth analysis of the milling performance during cutting at different cutting speeds, feed rates and cutting depths. Without exception, MQL technology showed a better performance than the dry condition in obtaining better surface roughnesses under different cutting parameters. Despite that only a small improvement was achieved in terms of cutting temperature, MQL was found to be successful in protecting the cutting tool from excessive amounts of wear and chips. This paper is anticipated to be a guide for manufacturers and researchers in the area of mold steels by presenting an analysis of the capabilities of sustainable machining methods.

Keywords: Nimax; machinability; milling

Citation: Binali, R.; Demirpolat, H.; Kuntoğlu, M.; Sağlam, H. Machinability Investigations Based on Tool Wear, Surface Roughness, Cutting Temperature, Chip Morphology and Material Removal Rate during Dry and MQL-Assisted Milling of Nimax Mold Steel. *Lubricants* **2023**, *11*, 101. https://doi.org/10.3390/lubricants11030101

Received: 2 February 2023
Revised: 21 February 2023
Accepted: 24 February 2023
Published: 26 February 2023

1. Introduction

Plastic mold steel is an essential material in industry and is generally machined under harsh cutting conditions used for forming plastic materials [1]. Unlike other types, this steel tool has a high corrosion resistance, hardness, polishability and patterning ability [2]. Nowadays, a steel named Nimax is used as an extrusion die, an injection die, a blow mold, a forging mold and a go/no go gauge, and contains alloying elements such as chromium, manganese, molybdenum, nickel, vanadium and aluminum [3]. On the other hand, pre-hardened mold steels can endure harsh working conditions thanks to their high hardness and toughness which are related to their microstructure [4]. In addition, heat treatment processes have beneficial effects on the microstructure and mechanical properties. These properties can be enhanced by controlling the heat treatment conditions [5]. The heat treatment process generally consists of quenching and tempering or continuous cooling during working [6]. Quenching and tempering processes have been accepted to improve the combination of strength, mechanical properties, and machinability [7,8]. The pre-hardened plastic mold steel Nimax is commercially available at about 40 Rockwell C hardness [9]. Low-carbon Nimax, which is a mold steel, has a high toughness and shock resistance. It is among a new generation of plastic mold steels that have been pre-hardened by replacing the P20 steel. Tempering is not recommended because it decreases the hardness and toughness. Another feature is that it has good weldability due to its low carbon content [10]. The materials produced to be used as molds generally require additional machining operations to reach the final dimensional accuracy and surface quality. As known, the quality of samples manufactured by molding technologies is directly related to the mold properties. Therefore, machinability improvement is an important goal for such steels to achieve high strength and develop the mechanical and physical characteristics [11]. Mainly plastic mold steels are machined by milling. One of the most popular and effective ways to achieve better machinability criteria is by using cooling and lubricating strategies, which will be the focus of this paper. In a literature survey, it was observed that milling with asymmetrical tools provides versatility due to the high feed rates and efficiency of the AISI P20 mold steel milling process. Asymmetrical cutting tool inserts have paved the way to productive high-feed milling operations in P20 mold steels [12]. To date, different types of steels and high strength alloys have been used to enhance the machinability index via modern lubri-cooling techniques. Among them, minimum quantity lubrication has gained acceleration in recent years as part of the sustainable machining of hard-to-cut metals such as mold steels [13,14]. Despite the importance and popularity of traditional methods such as dry cutting and flooding, their performance has been questioned due to the increasing geometrical and material-based requirements of the produced parts [15]. Prior to the investigation of the potential role of this newly developed approach, it will be useful to understand the tribological mechanisms in modern metal cutting [16]. Since cutting materials, especially those with high hardness and strength, cause excessive temperatures in the machining area, accelerated tool wear and its promoting mechanisms act on the rake, flank and nose surfaces of the edge [17]. Such events weaken the cutting capability of the tool with time and increase the cutting forces, decreasing the surface quality and chip breakability [18]. A solution to be considered is supporting the tribological performance of the tool, which directly reduces the frictional forces, unexpected wear patterns and early breakage possibility [19]. One of the important challenges here is the millimeter squared area of contact between the cutting edge and the workpiece [20]. Due to this phenomenon, high levels of heat accumulate in this zone and randomly dissipate to the work material and cutting tool. However, the main goal in machining operations is to regulate the heat distribution by designing the chip breakage mechanism and eliminating the surplus energy by chip removal. Therefore, a thermal simulation was performed by Krahmer et al. to verify the relationship between material properties, machinability and the thermal field. The results showed that free cutting additives, such as Mn, S and Pb, lead to self-lubrication of free cutting steels [21]. Krahmer et al. reported the presence of Mn and S elements in the rake face of the cutting tools in dry machining. These microstructural components can interpose between the workpiece and the cutting tool surface and act as tribofilms. This phenomenon supports the machining process by reducing friction and helping chip breakage [22]. Free cutting additives can improve the machining characteristics of mold steels without significant changes to the mechanical properties. Consequently, oil and air particles are excellent additives in the contact zones between the tool, workpiece and chip. Regarding lubrication methods, MQL-based cutting seems to be the perfect alternative to conventional flooding for many reasons [23]. Firstly, near dry machining is the basic function of this strategy and allows the use of a minimum quantity of cutting fluid, which reduces the cost, storage zone, transportation effort and time [24]. Secondly, this method is more sustainable, as it uses fewer natural resources. Finally, one can say that the technological aspect of this method is extraordinary from the perspective of the machinability criteria. MQL technology provides some environmental advantages such as clean chips, ease of recycling and better lubrication in the cutting zone [25]. On the other hand, the MQL-based cutting strategy can eliminate the shortcomings of dry machining such as droughts, which cause poor machinability according to several examples in the literature [26]. However, dry cutting is still relevant in today's industrial world due to its simplicity and it not requiring any additional equipment. There is a debate about the place and necessity of the cutting fluids due to the mentioned reasons. In summary, this paper focuses on the cutting performances of MQL and dry machining for a special material.

Seemingly, MQL-assisted machining can improve the surface finish quality and tool life even under high temperature cutting conditions [27]. Machinability is an index that can be evaluated in terms of many parameters, namely surface roughness, chip formation, tool wear, dimension stability, tool life, cutting force, etc. Therefore, it is important to research the machinability of different types of materials, including mold steels, to understand the performance criteria of lubrication and cooling media. In this way, the gaps in the current literature can be detected easily to further investigate new materials. Wojciechowski et al. [28] conducted an experimental analysis to evaluate the surface roughness of Nimax during the ball end milling process. It was stated that the surface finish is strictly dependent on the dynamical stability. Bayraktar and Uzun [29] conducted a comparative analysis on the machinability of pre-hardened Nimax and Toolox 44 steels. The results showed that the cutting force and surface roughness decreased for Nimax, whereas the cutting force and surface roughness increased for Toolox 44 with an increase in the cutting speed. However, the cutting force and surface roughness showed an increasing trend for Toolox 44 and Nimax with an increased feed rate. Another significant outcome was that the optimum cutting speed of Nimax was higher than Toolox 44.

Machinability investigations of mold steels are important in terms of their accuracy and reflect the quality of the parts produced with these components. It can be said that mold steels have barely been studied by researchers under different conditions which makes them an interesting, novel subject from the perspective of sustainable machining. This paper focuses on the milling operations of Nimax steel during cutting under different cutting and lubrication conditions. In this regard, two different cutting parameters in addition to the dry and MQL-assisted media were evaluated to obtain the best operational conditions. The main aim is to analyze the contribution of the milling parameters and the effect of the lubrication mechanism.

2. Materials and Methods

2.1. Experimental Materials and Their Details

In this study, Nimax was used as the material, which has low carbon ratio, high toughness and shock resistance, and is among the new generation of pre-hardened die steels [29]. This material was obtained by cooling to the required hardness with air. The material, which had a hardness of approximately 40 HRC, was supplied in 80 × 40 × 50 mm dimensions. Inspection of the material is mandatory so that the chemical composition of the material shown in Table 1 can be verified. To obtain more precise results in the experiments (dry and MQL), a TiAl-coated carbide insert was used. PVD coating technology was used for these tools. A cutting tool with the code BDMT11T308ER-JT was used, produced by Kyocera (Kyoto, Japan). The diameter of the cutting tool holder was 16 mm and the radial cutting width was 16 mm. Additionally, the cutting tool tip radius was 0.8 mm. The processing parameters in the experiments are given in Table 2. Two different cutting depths of 0.2 mm and 0.4 mm, two different feed rates per tooth of 0.1 mm/tooth and 0.2 mm/tooth and two cutting speeds (150 m/min and 200 m/min), for both dry and MQL environments, were used and a total of 16 physical experiments were carried out. These machining parameters were selected due to the characteristics of the material and from the recommendations of the cutting tool company. The cutting conditions were selected according to the data obtained as a result of dry experiments. The duration time varied between 0.62 and 1.50 min. Figure 1 outlines the general overview of the study.

Table 1. Chemical composition of Nimax steel.

wt.%	%C	%Si	%Mn	%Cr	%Mo	%Ni
Nimax Sample	0.1	0.3	2.5	3.0	0.3	1.0

Table 2. Machining parameters used in this study.

Machining Parameters	Level 1	Level 2	Units
Cutting speed	150	200	m/min
Feed	0.1	0.2	mm/tooth
Cutting depth	0.2	0.4	mm
Regime	Dry	MQL	-

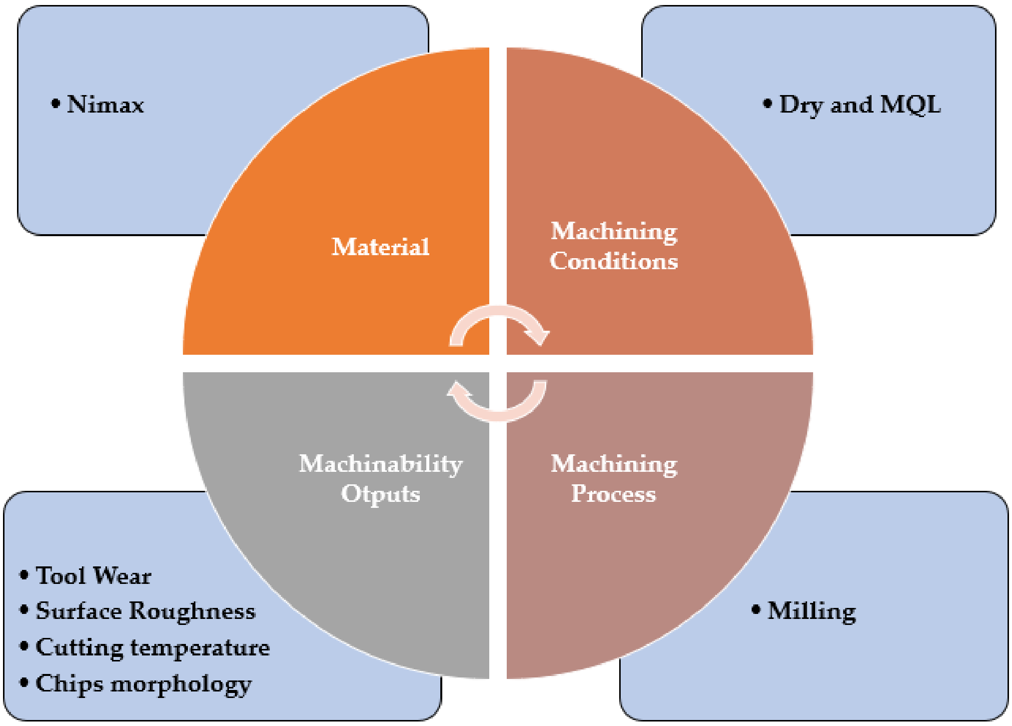

Figure 1. General overview of the selected methodology in this study.

2.2. Experimental Setup of Machining Conditions

In this study, the effect of two different conditions, dry and MQL, were examined. Material formation under dry conditions is covered in this study by not using cutting fluid, as it is the cleanest and cheapest method of cutting. In addition to dry machining, the MQL process was applied from a nozzle with a diameter of 2 mm, which was set at a distance of about 20 mm to achieve a better surface quality, lower tool wear and more efficient machining. A mineral oil-based (olive oil) cutting fluid was preferred during lubrication-assisted experiments. Neat MQL was utilized without adding any reinforcement material. The MQL process was chosen because it fulfills environmental, sustainability and social requirements. The performance of machining with MQL is affected by many parameters such as the nozzle distance and diameter, the oil type and the flow rate. It has been stated that the MQL efficiency decreases at distances greater than 50 mm [30]. The compressor pressure was adjusted to 6 bar and spraying was performed at an angle of 45°. In Figure 2, images including the experimental setup, the MQL unit, and the machinability output measurements are shown.

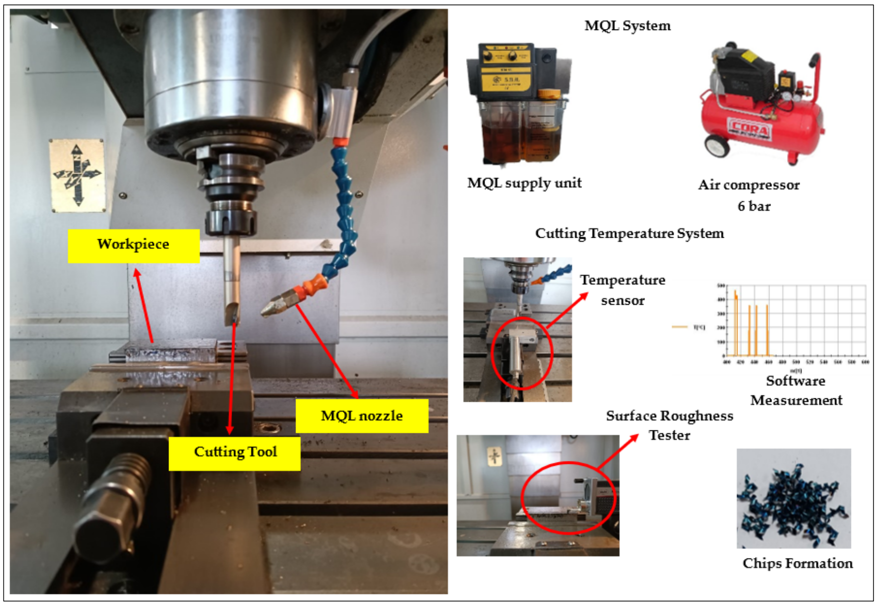

Figure 2. Experimental scheme of the study.

2.3. Detailed Description of Machinability Outputs

In the study, the tool wear, temperature, roughness, surface topology and chip formation were evaluated. Images of tool wear were taken with the aid of a scanning electron microscope (SEM) device (Make: Zeiss Co. Ltd, Jena, Germany). In addition, EDX was used to show the regional, mapping and line analysis obtained. In addition, the formation of chips during the experimental studies was examined with the SEM device. After the process, the material surface roughness was measured with a perthometer (Brand: Mahr Co. Ltd., Goettingen, Germany). This instrument could detect deviations up to 150 µm. Five measurements were taken from the surface after each experiment. To determine the roughness values to be used, the cutting length was 0.8 mm and the tracing length was 5.6 mm. The roughness value was obtained by subtracting the highest and lowest values from the measurements and taking the average of the three values. The cutting temperature of each experiment during the process was measured with a temperature measurement sensor (Telc, Frankfurt, Germany). The sensor works with the InGaAs radiation principle. The sensor was placed at 80 mm from the cutting tool. The material removal rate (MRR) value is considered in this work as a quality indicator to investigate the effect of chip removal speed under different lubricating conditions. The calculation of the MRR is given in below with Equation (1), where V_C is the cutting speed, a_P is the cutting depth and a_e is the feed rate.

$$\text{MRR} = V_C \times a_P \times a_e \quad (1)$$

3. Results

3.1. Tool Wear Mechanism and Its Promoting Type of Wear

Wear on the cutting tools in machining is a natural result of actions such as the intense plastic deformation and the high coefficient of friction around the contact zones between the cutting tool and the workpiece. Such developments produce different shaped chips which not only manufacture new surfaces but also help to carry the heat from the medium. The effects of several parameters contribute to the interaction during cutting: (i) material properties such as hardness, toughness, heat treatment and manufacturing type; (ii) cutting mechanism, namely intermittent or continuous; and (iii) descriptors of the tool geometry, i.e., the radius, approaching angle, chip breaker, coatings, etc. [31]. During this stage, micro-scale alterations play a role depending on the thermal, mechanical, chemical and fatigue properties, which are called load factors [32]. As a result of these effects, primary wear mechanisms act on the cutting tools. In time, these micro-scale alterations become wear types located on the different surfaces of the cutting edge. Abrasive, adhesive, diffusive and oxidative wear mechanisms are the main contributors which create wear textures [33].

In the light of the previous knowledge on wear developments on the cutting edges, SEM images taken of different cutting tools that are exposed to various cutting conditions, Figure 3, were examined. First, it should be noted that no important changes or developing wear were observed with the change in feed rate and depth of cut under milling Nimax steel with MQL or dry media. Therefore, SEM images were taken of the cutting tools machined with different cutting speeds and lubricating media, as the labels located above and to the left of Figure 3 show. As can be clearly seen, nose wear is the principal wear type irrespective of the cutting conditions. However, the level and footprint of this wear show a change with the shift in the cutting speed and media. No wear traces were observed on the rake and flank faces. A high cutting speed combined with the maximum material remove rate (MRR) and a dry medium caused significant nose wear and partial breakage in this area. Even under these conditions, clean rake and flank faces are observed; however, this kind of breakage was observed at the maximum wear rate during milling of Nimax steel. As known, the abrasive wear mechanism is the main reason for improved nose wear. During machining of hardened steel such as Nimax steel, hard particles rupture from the cutting tool and strike the tool edge, creating such a situation. As seen, MQL conditions provide excellent results, which include slight nose wear and no wear on the flank and rake faces. In summary, Nimax mold steel can be seen as a material with good machinability in terms of tool wear if the cutting conditions are appropriate. Figure 4 demonstrates the mapping results of each cutting tool, similar to Figure 3. Four columns, including a general view of the insert, a zoomed-in view of the nose, mapping view and an elemental analysis based on percentages, are shown in the figure. As can be seen, the coating of the cutting tool can be protected much better under MQL conditions; however, with dry machining, a percentage of the elements are reduced. In addition, when applying a higher cutting speed, the coating elements are lost much more when compared with a lower cutting speed. It should also be noted that Mn and Cr are the main elements that were transferred to the cutting tool from the workpiece material. It can be said that MQL application is successful in protecting the cutting tool during machining of Nimax steel.

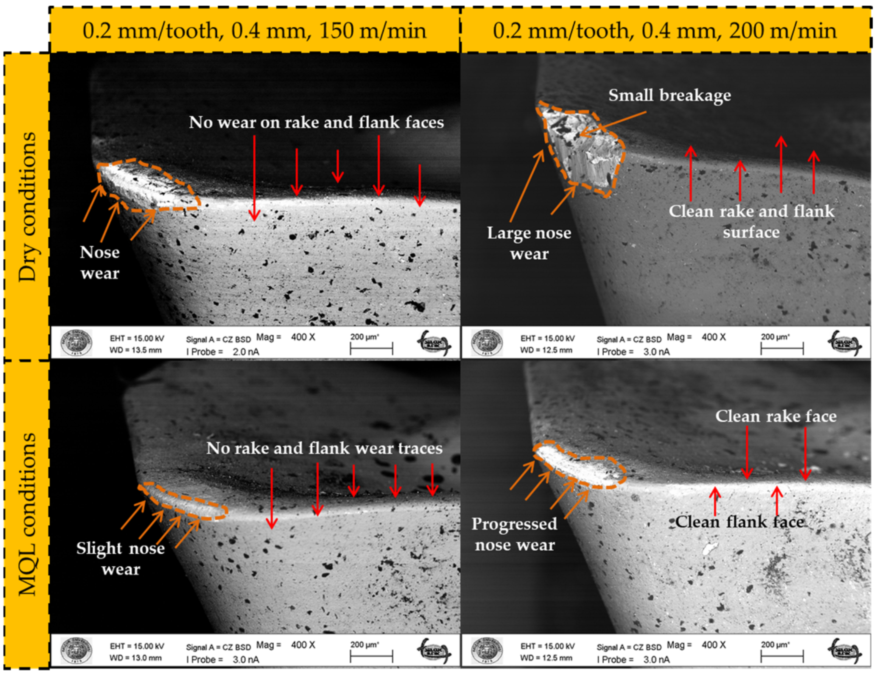

Figure 3. SEM images of the tools under MQL and dry conditions with the change in cutting parameters.

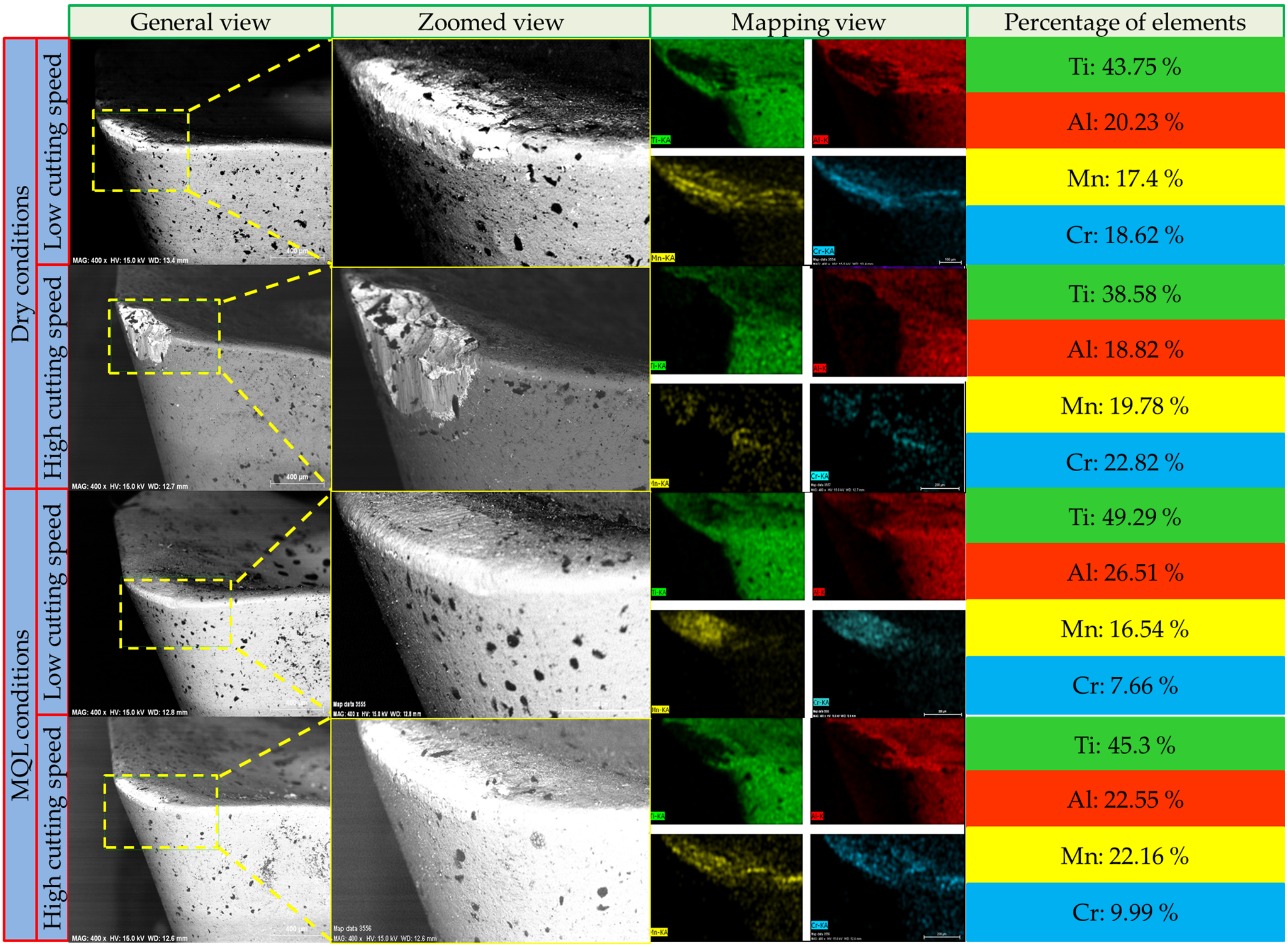

Figure 4. EDX and mapping results of the cutting tools.

3.2. Surface Roughness

The surface condition of a part is a critical outcome not only for machining operations but also for all manufacturing procedures. Therefore, examination of the surface parameters is quite important to understand the quality of the process, to determine the operational parameters and to assess whether the material demands have been met or not. In this regard, expressing the surface condition with a value gives an indication of the quality to the producers and consumers. Surface roughness is the best candidate for this value thanks to its qualities such as ease of measurement, repeatability and reliability [34]. Moreover, this variable can be represented by many indicators such as maximum roughness, average roughness, etc. Due to all these reasons, determination of the surface roughness after a machining operation is highly feasible [35]. On the other hand, the mold steels used in this study require good surface quality due to it directly affecting the parts produced by casting technologies. Thus, this study aims to measure the impact of milling and cooling conditions on the surface roughness of Nimax steel. As the most preferred parameter for analyzing the surface roughness, the average roughness, Ra, was selected in this paper. The measurement strategy is based on the calculation of average surface heights and depths across the surface.

As a result, Figure 5 demonstrates the surface roughness variations with the change in milling and lubrication parameters. As seen, the basic cutting parameters have no significant influence on the surface faults, deviation and waviness. On the other hand, when a comparative analysis is carried out for dry and MQL environments, the negative impact of the droughts of the dry medium on the surface roughness can be clearly seen. An approximate two-fold increase is observable from the minimum to the maximum values of roughness, belonging to MQL and dry media, respectively. This was explained by previous researchers as the decreasing support of the tribological mechanism on the contact surfaces between the tool and the workpiece. Since events around the cutting zone are affected by friction, wear and lubricating factors, the chip formation, tool wear and surface condition of the workpiece are affected by these factors. These results are in line with the papers in the literature and other machining characteristics addressed in this study.

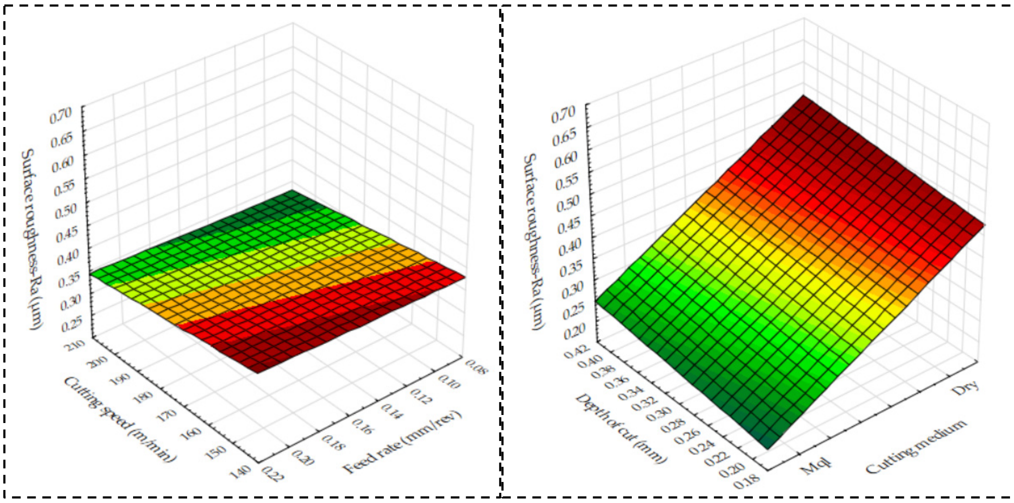

Figure 5. Surface roughness variations according to the combined effects of cutting and cooling parameters.

The combined effect of the cutting parameters versus the cooling medium can be seen in Figure 6. As seen, when applying higher cutting speeds, the surface roughness shows a decreasing trend, as observable in the last four experiments. This explains the positive contribution of the higher cutting speed on the roughness. Significant differences can be seen at lower material removal rates. Not only is the minimum surface roughness obtained under these conditions, but the dry medium also exhibits the highest surface roughnesses. This trend continues at higher levels of feed rate and depth of cut. In summary, it is critical to mention that a good MRR and the lowest surface roughness value can be obtained at a low cutting speed, a high feed rate and a high depth of cut under MQL-assisted milling.

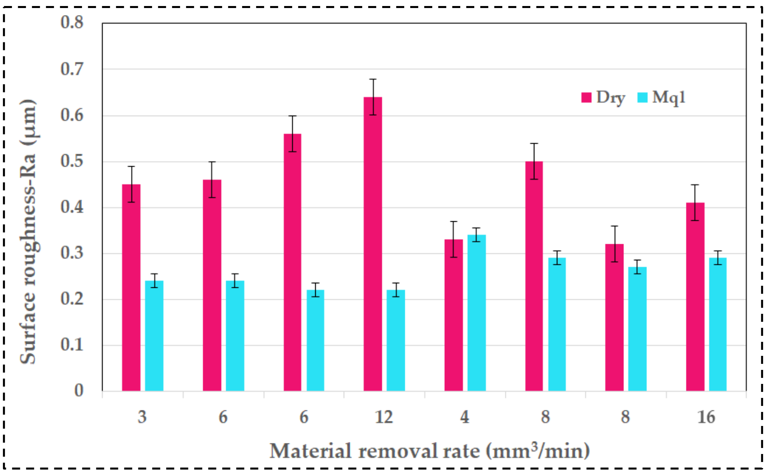

Figure 6. Surface roughness variations according to material removal rate.

3.3. Cutting Temperatures

Cutting temperatures show momentary alterations during machining operations which can be detected in the workpiece material or on the tool surfaces. Since most of the energy transferred to the machine tool is transformed into heat energy, temperatures increase on the contact surfaces because of the coefficient of friction [36]. Overheating during cutting operations lowers the quality of the material properties which affects the service life of the elements, i.e., accelerates the degradation of the cutting tool and/or causes poor mechanical and physical properties of the workpiece material. Ideally, chips are expected to remove most of the heat from the cutting zone during cutting. Considering the milling operation was used in this study, it is easier to remove the chips via the cutting mechanism. However, hardened materials such as Nimax may cause instant loads on the cutting tool which produce abnormal cutting temperatures and reduce the fatigue life [37]. Therefore, we intended to examine the impact of the cutting parameters and the lubrication medium on the cutting temperatures in the milling of mold steel. Figure 7 shows the cutting temperature variations during milling operations according to the combinations of different cutting parameters and cutting media. On the left side, the feed rate and cutting speed versus cutting temperature can be seen. Increasing the cutting speed and feed rate strongly increases the cutting temperature, linked to high levels of plastic deformation. Additionally, it is critical that high levels of frictional force produce more heat around the cutting zone, which also shows an increase with feed and speed. Therefore, no surprising results are observed at this point. On the right side of the figure, the depth of cut also plays a small role in the change in cutting temperature; however, this can be ignored while comparing the other contributors. When looking at the effects of the cutting medium, including MQL, on the operation, a direct reduction in the cutting temperature is observed. This is an expected result knowing that the lubrication improves the tribological mechanism and reduces the coefficient of friction. In summary, it can be said that lower cutting parameters, along with the MQL medium, are the ideal operational conditions during milling of hardened mold steel.

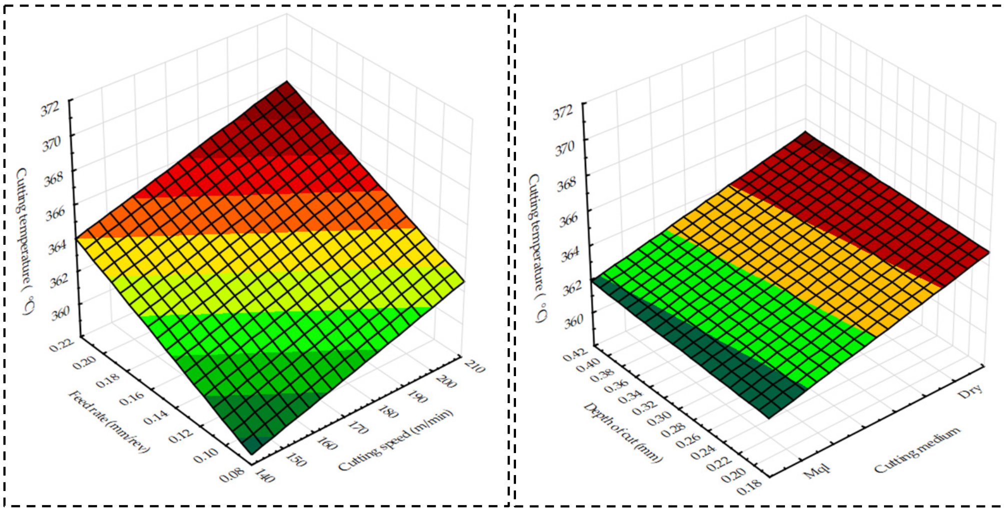

Figure 7. Cutting temperature variations according to combined effects of cutting and cooling parameters.

Figure 8 shows the cutting temperature variations according to the MRR, comparing MQL and dry environments. Since the MRR is an indicator based on the basic cutting variables, the stress level of the cutting tool, the plastic deformation rate and the frictional forces can be correlated with this value. The graph was created based on the experimental results of the calculation of the MRR. In the first four experiments, MQL and dry conditions produced similar temperatures. Meanwhile, with the increase in the cutting speed, the difference between these two media increases. On the other hand, the feed rate also has an important impact on the cutting temperature, while the influence of the depth of cut can be ignored. This graph demonstrates a critical point, which is that using suitable lubrication strategies make a small difference in terms of the temperature variations for faster manufacturing in the machining of hardened materials.

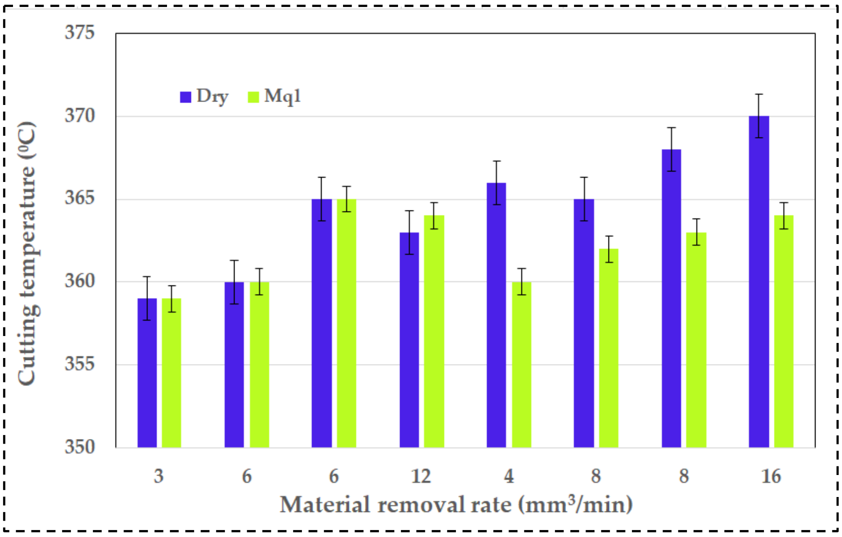

Figure 8. Cutting temperature variations according to the material removal rate.

3.4. Morphology of Chips

Chips generated during machining are small particles ruptured from the workpiece material and allows obtaining new surfaces with better properties and shape than before the manufacturing process. A high pressure and temperature are induced at the contact surfaces between the chip and the cutting tool as a result of the intense friction. The energy accumulated at these points mostly spreads out through the materials and a large part of the heat is taken away by the removed chips. This rate has been calculated as 80% in some work; however, it is important to understand that a large part of the heat should be transferred by the chips. The chip shape is heavily dependent on the cutting mechanism and material properties. Regarding the classification of the removed chip, the shape, color and serration pattern are the primary indicators that reflect the quality and condition of the chips. The chips can indicate the underlying mechanism of the machining operation.

Figure 9 shows the general and an enlarged SEM view of the chips collected after the experiments using dry and MQL media. Additionally, for a better comparison with the previous sections, a change in cutting speed was considered while keeping the feed rate and the depth of cut constant. When comparing the lubrication methods, the upper surface of the chips appear completely different. Material agglomeration is seen on the surface of the chips which is thought to be due to the existence of oil particles around the cutting zone. A surface with less damage and roughness is obtained. Looking at the general shape of the chips, c-type chips were obtained with a low cutting speed and a dry medium. Shifting the conditions from a low to a high cutting speed, comma-type chips were observed, rather than the c-type chips obtained under dry cutting. Additionally, for both dry and MQL conditions, the serrations become deeper at higher cutting speeds. Irregularity in the serrations appears much more with low cutting speeds under dry media conditions; however, under MQL conditions, the opposite is true. Under MQL conditions, curled- and c-type chips were mostly seen. In total, comma-, c-, and short curled-type chips are the main chip types observed during milling of Nimax steel, which are the ideal chip shapes in machining. It should be noted that in terms of chip morphology, Nimax steel has good machinability. On the other hand, it is clear that MQL conditions are much more effective regarding the reduction in the serrations, which improves the quality of the machined surface and reduces tool wear as outlined in the previous sections.

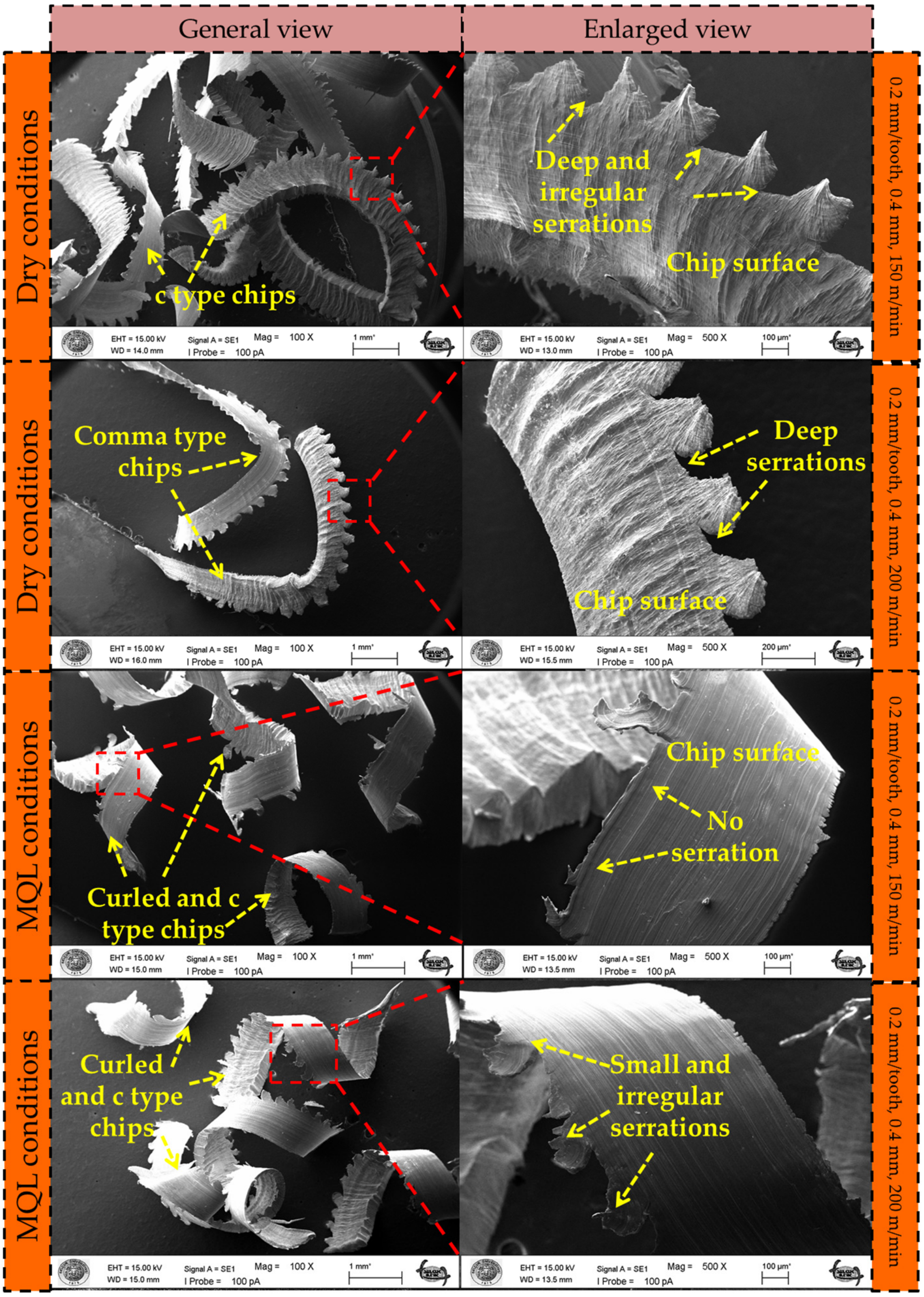

Figure 9. SEM images of chips after experiments with MQL and dry media with the change in cutting parameters.

4. Conclusions

The main aim of this paper is to analyze the effect of cutting parameters and lubrication on the machinability characteristics of Nimax mold steel. Milling experiments were carried out in this study according to full factorial design, altering the parameters of cutting speed, feed rate, depth of cut and lubrication. Evaluations of the experimental results were presented based on graphical drawings and SEM figures. The main outcomes of this paper are listed below:

1. Chip morphology and tool wear conditions were discussed based on SEM observations. Nose wear is the principal wear type observed on the tool edges, irrespective of cutting conditions. It should be noted that the level of the nose wear varies, especially

when the cutting speed and lubrication type are changed. Since nose wear is triggered by the abrasion particles expelled from both the tool and the workpiece, the abrasion mechanism is effective during the cutting of Nimax mold steel.

2. Comma, c, and short curled chips are the main chip types observed during milling of Nimax steel. These types can appear alone or together under different circumstances. The main differences in chip type were seen when varying the cutting speed and lubrication type. Deep and irregular serrations were observed under dry and low cutting speed conditions. Dry cutting produces deeper serrations than when using the MQL-assisted medium.
3. The cutting temperature exhibits slight changes with the different values and types of operational parameters. The cutting speed and the feed rate most significantly affected the cutting temperature. Including the MQL medium into the machining environment dramatically reduces the temperature and increases the MRR. At increased MRR values, the importance of the MQL medium increases, which can be observed by the difference between the effect of the dry medium and the MQL medium.
4. On analysis of the surface roughness, lubrication is the most influential contributor among all variables. Changing the media from dry to MQL media creates a dramatic reduction in the surface roughness value. Additionally, it is clear that with the application of an MQL strategy, it is possible to increase the MRR while retaining a high-quality surface.

Author Contributions: Conceptualization, M.K., R.B.; methodology, M.K., R.B.; validation, H.D., R.B. and H.S.; formal analysis, H.D., R.B. and H.S.; investigation, H.D. and R.B.; resources, M.K. and R.B.; data curation, R.B.; writing—review and editing, M.K., H.D. and R.B.; visualization, M.K.; supervision, M.K., H.D., R.B. and H.S.; project administration, M.K., H.D., R.B. and H.S.; funding acquisition, M.K., H.D., R.B. and H.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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