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Machining of Hard-to-cut AISI 4462 Duplex Stainless Steel with an Environmentally Friendly Approach with Vortex Tube

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Machining is a manufacturing process that can be used to produce precision machine parts and has many advantages. The first is the ability to achieve superior surface quality. Tool wear is an inevitable phenomenon that occurs during machining. It is affected by many machining conditions; therefore, this process needs to be monitored and controlled. In this study, tool wear and surface roughness tests were carried out on AISI 4462 duplex stainless-steel materials, known to be a hard-to-cut material. For this purpose, tool wear and surface roughness analyses were implemented by using the environmentally friendly vortex tube cooling system in addition to wet turning conditions for the first time. For both methods, experiments were conducted at a 1 mm depth of cut, 120 m/min cutting speed, and 0.1 mm/rev feed with a 90 mm cutting length for each pass. Both tool wear and surface roughness were examined at the end of each pass. The analysis showed that wet turning gave better results in terms of tool life (19.8 minutes of tool life) compared to 11.1 minutes of tool life in vortex turning. In contrast, the surface roughness values differed up to two times in some experiments, and the vortex tube experiments gave better surface roughness values in all passes. In addition, the vortex tube experiments showed less built-up-edge (BUE) formation than the wet-turning experiments.
Keywords: vortex tube, machining, duplex stainless steel, tool life, surface roughness

Highlights
- *Tool wear is one of the most important outputs of the machining process.*
- *Estimating tool wear and modifying machining conditions based on it are important.*
- *Tool wear is directly dependent on cutting conditions, and unsuitable conditions dramatically increase wear.*
- *It is possible to reduce the surface roughness values by using a vortex tube.*
- *The surface roughness worsens due to the increase in tool wear.*

0 INTRODUCTION

Machining has many advantages over many other manufacturing methods. It is possible to achieve low surface roughness with machining, produce machine parts with high dimensional accuracy, and ensure the repeatability of the manufacturing process [1]. It is also known that machining processes are influenced by many factors, especially cutting speed, feed, and depth of cut [2] and [3]. During machining, friction occurs between the tool and the workpiece [4]. Due to this friction, the cutting tool wears out over time [5]. Tool wear is inevitable, although it is possible to reduce tool wear by choosing the right machining conditions. Machine parts can be machined with dry and wet machining methods [1]. In addition, the machining process can also be carried out using an environmentally friendly vortex tube. It is possible to transmit air cooled down to –50 °C to the contact area between the cutting tool and the workpiece by using a vortex tube. The vortex tube, also known as the Ranque-Hilsch vortex tube, is a piece of equipment that separates compressed air into two swirling streams, one hot and the other cold [6]. In addition, different cooling temperatures can be obtained by using various pressures and gases [7] and [8]. Thus, it may be possible to improve tool life and surface roughness. Machining can be used to produce parts for a wide variety of needs from many different materials. However, the machinability of some materials is more difficult compared to other materials. Stainless steel is one such material. Stainless steel materials are hard-to-cut due to their low thermal conductivity and high hardening tendency [9]. Duplex (ferritic-austenitic) stainless steels are one of the toughest stainless steels [1] and [10]. Stainless steel is one of the essential materials used by many sectors, despite being a hard-to-cut material. In addition, the development of these materials by various methods may increase the use of stainless steel [11] and [12]. Therefore, numerous researchers have attempted to investigate this material group in detail.

Szczotkarz et al. [13] analysed the values of flank wear and crater wear on AISI 316 stainless steel under different machining conditions. The researchers use dry, minimum quantity lubrication (MQL) and minimum quantity cooling lubrication (MQCL) with the addition of extreme pressure and anti-wear (EP/AW) cooling methods. The researchers emphasized that tool wear is accelerated under inappropriate cooling conditions. They also highlighted that wear is intense and tool life is completed quickly,

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especially in dry machining conditions. Chen et al. [14] investigated the machinability performance of stainless-steel materials under different cutting parameters, specifically, cutting speed, feed, and depth of cut under dry cutting conditions. In their study, they inspected tool wear and surface roughness values. In the 18-minute tool life experiments, the researchers found that the tool wear first increased rapidly, then progressed at a constant speed, and then increased rapidly again. They also stated that increased tool wear had a negative effect on surface roughness. Derani et al. [15] performed tool wear and surface roughness tests on AISI 316 (austenitic) stainless steel under dry-cutting conditions. The researchers examined both nose wear and flank wear in the experiments and emphasized that nose wear accelerates faster than flank wear initially. They found that these two types of wear gradually increased, and finally, nose wear increased significantly. However, they also emphasized that despite an increase in tool wear, the surface roughness remained largely constant. Singh Bedi et al. [16] investigated tool wear on AISI 304 stainless steel under dry cutting conditions. They emphasized the increase in tool wear values over time. The researchers found flank wear, crater wear, built-up-edge (BUE), abrasion wear, and adhesion wear on the cutting tool in their investigation. The researchers also emphasized that the coating of the cutting tool is lost over time due to wear. Pekşen and Kalyon [17] carried out a tool wear analysis on AISI 430 stainless steel. Three different feeds and cutting speeds were used in these analyses. As a result of the analysis, the researchers suggested that the cutting speed and feed directly affect the tool life. The researchers also determined notch wear, crater wear, and flank wear on the cutting tool.

Yağmur [18] carried out analyses of tool wear and surface roughness using dry machining, MQL, and vortex tube cooling methods. The analyses were carried out using different cutting speeds and feeds. It has been observed that the results are close to each other in the experiments with the vortex tube and the experiments with the MQL. Therefore, in this study, it was understood that the vortex tube could be an alternative option to wet machining for machining. In their experiments with the vortex tube, Cukor et al. [6] pointed out that in some machining experiments, vortex machining may offer better tool life than wet machining. The researchers also discovered that overall production costs could be minimized using this environmentally friendly method. Pinar et al. [19] emphasized that similar results can be obtained with these two cooling methods in their experiments in which they compared vortex tube and wet machining processes. Thus, the researchers stated that it is possible to perform wet machining processes using the vortex tube method. Valic et al. [3] used different cutting speeds, feeds, and depth-of-cut parameters in their studies on X20Cr13 martensitic stainless steels. The researchers combined the vortex tube and MQL system and proposed an alternative method for machining stainless steel. In this proposed method, the air-oil mixture (vortex tube + MQL) resulted in an additional temperature reduction of -38.1 °C at the tool-work interface compared to the use of MQL alone.

The number of studies in the field of sustainable machining has been increasing. Korkmaz et al. [20] adopted dry, MQL, and nano-MQL methods for machining hard-to-cut nickel-based superalloys. As a result of the experiments, the researchers concluded that tool wear could be reduced by up to 60 % using sustainable methods. Airao et al. [21] used ultrasonic-assisted turning under dry, wet, MQL, and LCO_2 methods on hard-to-cut Ti-6Al-4V material. As a result of the experiments, the researchers proposed that LCO_2 and ultrasonic vibration could considerably reduce the specific cutting energy without sacrificing surface roughness or tool life. Shah et al. [22] used environmentally friendly lubrication techniques in their study. Electrostatic minimum quantity lubrication (EMQL), hybrid nanoparticles immersed in EMQL (HNEMQL), and electrostatic lubrication (EL) techniques were used in experiments with precipitation-hardened stainless steel. As a result, it is comprehended that the HNEMQL method provides up to 10 % lower power consumption compared to other methods. In contrast, the EL technique has the lowest tool wear. In addition, the researchers proposed that it is possible to reduce the *Ra* value by approximately 30 % with the EL technique.

In the examination of the existing literature, it is seen that while there are numerous studies on stainless steel, the number of studies on duplex stainless steel is limited. In addition, the number of studies using the vortex tube cooling method used in this study is very limited. Also, no study was found in which tool wear and surface roughness values were analysed over time.

In this study, tool wear analysis was carried out using AISI 4462 duplex stainless steel (a hard-to-cut material). Time-dependent analyses of tool wear and surface roughness values were also conducted. Furthermore, the effect of tool wear on the change in surface roughness of the machined part was thoroughly investigated.

1 MATERIALS AND METHODS

1.1 Materials

In this study, AISI 4462 (X2CrNiMoN2253) duplex stainless steel materials with a diameter of 75 mm and a length of 110 mm were used in the experiments. The chemical and mechanical properties of this material are shown in Table 1.

Table 1. *The chemical and mechanical properties of AISI 4462*

Element	C	Cr	Mo	Ni	Mn
wt.%	0.015	22.69	3.11	4.84	1.40

Mechanical properties	Yield strength [MPa]	Tensile strength [MPa]	Hardness [HBW]
Values	488	692	218

In the machining experiments, TNMG 160404-M3 (Grade TP2500) cutting inserts supplied by SECO, which were developed for P-class materials (steels), were used to clearly observe the tool wear. The utilized insert was suitable for average cutting conditions (designated as the P25 class). In addition, this insert was coated with Ti (C, N) + Al_2O_3 layers by CVD (chemical vapour deposition) method.

Moreover, a PTGNR 2020K16 tool holder with a 90° approach angle is preferred. It is crucial to determine the cutting speed, which has a prominent effect on tool wear. Depending on the material used (AISI 4462 duplex stainless steel), the cutting speed recommended by the tool manufacturer (SECO) is used as a reference. However, to observe the effect of wear more clearly, the cutting speed was preferred as 120 m/min. ISO 3685 [23], the primary standard for tool wear testing, was used to determine the cutting parameters other than the cutting speed. For this purpose, the parameters recommended by ISO 3685 were used, i.e., a depth of cut of 1 mm, a feed of 0.1 mm/rev, and a cutting-edge radius of 0.4 mm.

1.2 Methods

In the experiments, in addition to the conventional cooling approach of wet turning (5 % concentration), an environmentally friendly vortex cooling approach was also used. A vortex tube (Ranque-Hilsch vortex tube) was used to achieve a temperature of –23 °C at 5 bar pressure and measured using a K-type thermocouple and a Fluke 179 multimeter (Fig. 1).

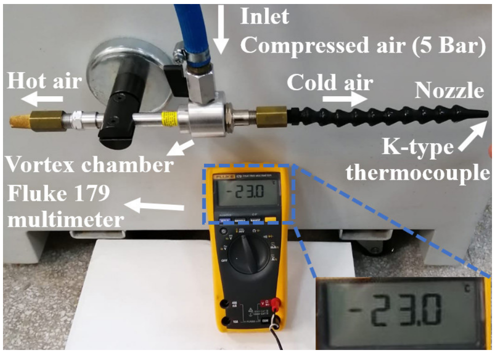

Fig. 1. *Vortex tube*

Turning experiments were carried out with a cutting length of 90 mm in each pass. After each

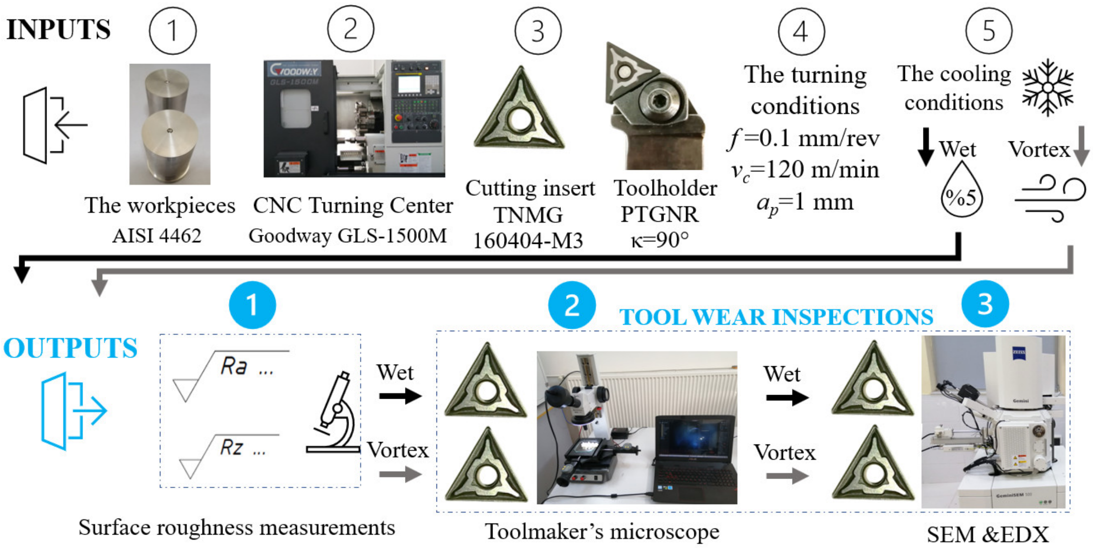

Fig. 2. *Experimental setup*

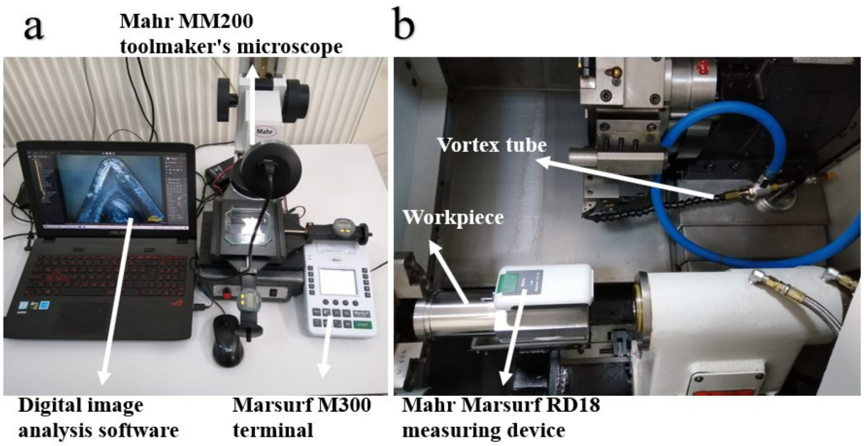

Fig. 3. *Measurement setup; a) tool wear measurement, and b) surface roughness measurement*

turning pass, the surface roughness values of the workpieces were measured according to the ISO 21920-3:2021 (formerly ISO 4288) standard [24]. The tool wear was measured by removing the cutting tool from the tool holder. Both flank wear values and notch wear values were observed in tool wear examinations. In addition, the cutting tools were examined by scanning electron microscope (SEM) and SEM energy dispersive X-ray (SEM&EDX) analysis at the end of all the experiments (Fig. 2).

The surface roughness values were measured with a Mahr M300 terminal and a Mahr Marsurf RD18 measuring device via Bluetooth connection. The tool wear measurements were performed using a Mahr MM200 toolmaker's microscope equipped with an M-shot MD30 camera via digital image analysis software (Fig. 3).

2 RESULTS AND DISCUSSION

2.1 Tool wear

Tool wear is one of the principal factors to monitor in machining. During the experiments, the cutting tool was removed from the tool holder after each pass, and the tool wear was measured, as shown in Fig. 3. The tool wear inspections performed at each pass are shown in Fig. 4.

In Fig. 4, time-dependent tool wear (flank and notch) can be clearly seen. Time-dependent tool

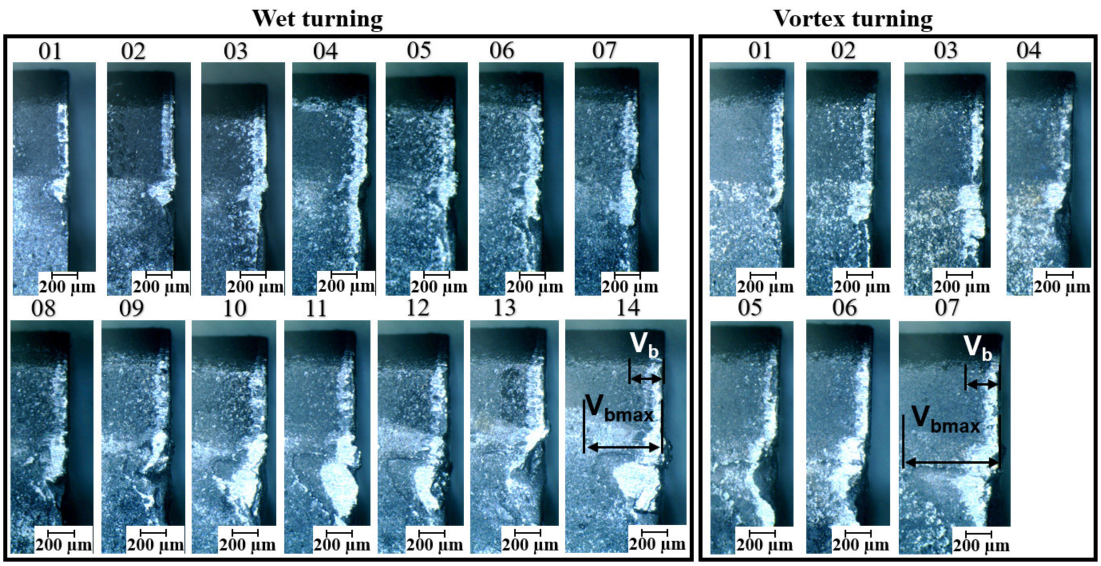

Fig. 4. *The tool wear (flank wear) inspections at each pass*

wear analysis according to tool wear inspections and measurements shown in Fig. 4 is shown in Fig. 5.

Single-point cutting tools are typically used in lathes. The tool life control of these cutting tools is carried out according to ISO 3685 [23], which specifies certain limits for tool wear. If the tool wear is regular, the flank wear limit value (V_b) is 300 µm, and if the wear is irregular, the notch wear limit value (V_{bmax}) is 600 µm. Therefore, both flank and notch wear values were measured in the tool wear measurements. The experiments were terminated when the flank wear or notch wear value reached the limit value.

Both flank wear and notch wear increased rapidly in both wet turning and vortex cooling conditions (Fig. 5). In both cooling conditions, notch wear increased faster than flank wear; this is a known situation. Derani et al. [15] found that notch wear is more than twice as high as flank wear in the first phase of tool wear. The flank wear, in contrast, increased rapidly and then continued to do so at a constant rate almost to the end of the experiments. Acceleration of flank wear towards the end of tool life is a known fact [15] and [25]. However, in this study, an acceleration zone of the flank wear value was not detected. Notch wear is directly influenced by cooling conditions. The wear rate of the notch wear decreased with the wet turning. In the experiments performed with the vortex tube, it was determined that the value of notch wear increased dramatically at the end of the 6th pass.

In the experiments, flank wear and notch wear, which are the tool life criteria, were reached almost simultaneously. As a result of 19.8 minutes of tool life under the wet turning conditions (14th pass), the tool life was completed according to both flank wear and

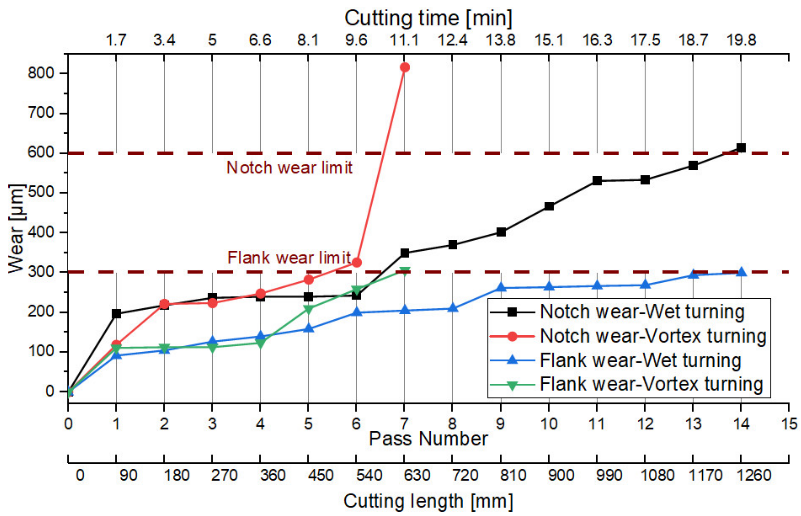

Fig. 5. *Tool wear*

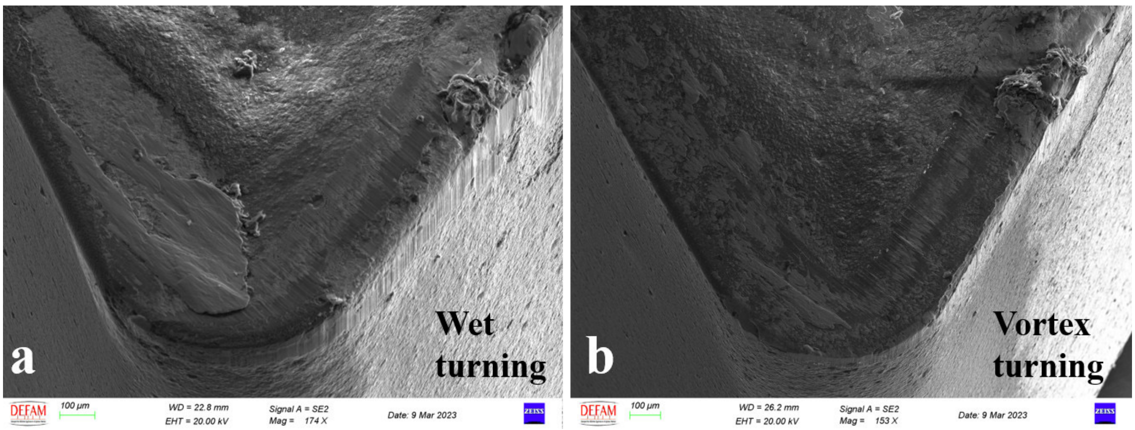

Fig. 6. *The SEM images of the cutting tools SEM images of cutting tools; a) wet turning after 19.8 minutes of cutting time, and b) vortex turning after 11.8 minutes of cutting time*

notch wear criteria. In the experiments with the vortex tube, the tool life was completed after 11.1 minutes (7th pass). When both cooling methods are evaluated together, it is comprehended that the experiments with the vortex tube have an efficiency of 56 % compared to the wet turning.

SEM analyses were carried out to compare the cutting edges concerning each other. Fig. 6 shows both the nose and top surfaces of the cutting tools employed with both cooling conditions.

Similar types of tool wear are observed on the tools in both cooling conditions (wet and vortex tube). The BUE formation is commonly observed in the machining of stainless steels [4]. However, in the wet turning conditions, significant BUE formation was detected on the top surface, whereas in the vortex tube experiments, BUE formation was limited (Fig. 6). The BUE formation observed in the wet turning cutting tool was also investigated using SEM-EDX analysis (Fig. 7).

Fig. 7a presents three selected areas for inspecting the chemical composition of the cutting insert via SEM-EDX. As can be clearly seen in Fig. 7d, the chemical composition includes significant amounts of Cr (21 %), Ni (4 %), and Mo (2 %) as determined by the examination made in the BUE observed area (red rectangle). The composition is consistent with the chemical composition of the AISI 4462 material used in the experiments and directly confirms the formation of BUE. In addition to the high W content seen in Fig. 7b, the presence of many other elements indicates both the loss of the WC insert coating and the apparent BUE formation. A significant Al content was detected in Fig. 7c. It is comprehended that it is an unworn surface since the cutting tool coating had Ti (C, N) + Al_2O_3 layers.

2.2 Surface Roughness Measurements Results

One of the most significant features desired in the mechanical parts manufactured with machining is the achievement of the expected surface roughness values. In this study, the surface roughness measurements were carried out on the computer numerical control (CNC) turning centre without removing the workpiece. Five different surface roughness measurements were taken on the workpiece, and the average of these values was calculated. The average surface roughness values obtained are illustrated in Fig. 8.

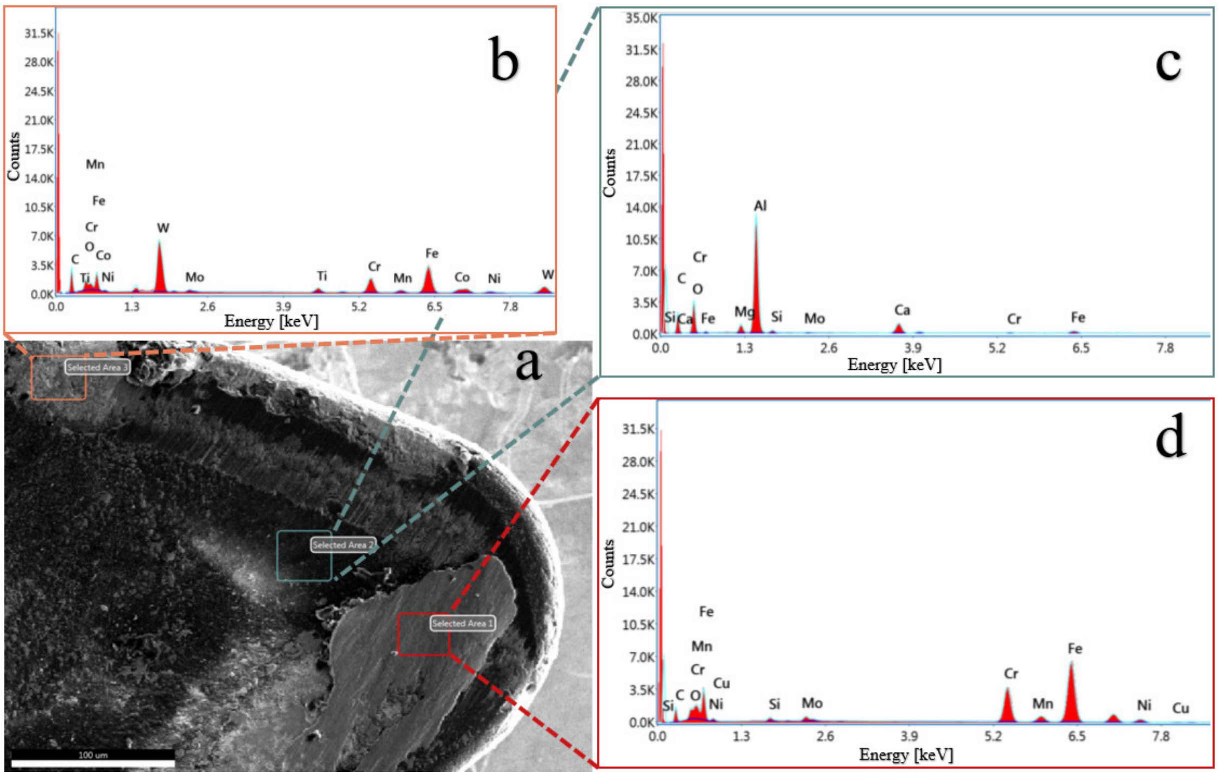

Fig. 7. *The SEM-EDX analysis of the wet turning cutting tool after 19.8 minutes of cutting time; a) top surface of the cutting tool, b) EDX analysis of area 3, c) EDX analysis of area 2, and d) EDX analysis of area 1*

It is known that surface roughness can vary depending on tool wear. In many studies, an increase in tool wear causes the deterioration of surface roughness values [26] and [27]. Selecting the appropriate experiment conditions has an outstanding influence on the surface roughness. Maruda et al. [28] used sustainable MQCL methods in turning steel materials in their study. In addition, MQCL MQCL&EP/AW was also investigated. As a result of the study, it was encountered that the surface roughness could be improved by up to 29 % with MQCL and up to 70 % with MQCL&EP/AW. Therefore, a detailed study of the effect of cooling conditions on surface roughness was conducted.

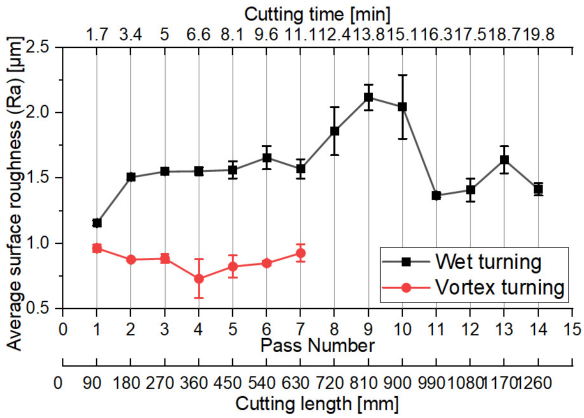

Fig. 8. *The average surface roughness (Ra) values*

Interesting results were obtained in this study. While it would be expected that the surface roughness values would be better under wet turning conditions, better results were acquired in the vortex tube experiments. The feed and cutting speed values used in the experiments and the chip breaker form of the cutting tool directly affect the chip formation. In the examinations, it was comprehended that the cutting tool could not partially perform the chip-breaking function under the current experimental conditions, and the chip could not be removed from the cutting area at some moments. Although the tool life is completed early in the experiments with the vortex tube, it is understood that much better surface quality can be obtained because it helps to remove the chips from the workpiece surface. As a result, much better surface quality was achieved in the experiments with the vortex tube. In addition, this surface quality obtained was not directly affected by tool wear, and superior results were obtained throughout all passes. This is thought to be due to the prominent BUE formation seen in cutting processes using wet turning in tool wear analyses (Fig. 7a).

In the wet turning condition, it is observed that the surface quality deteriorates over time due to tool wear. However, it is comprehended that the surface quality has improved after 15.1 minutes of tool life. This situation is also seen in some literature studies [15]. Cutting tools used in turning can provide better surface quality as a result of wear towards the end of their life [15] and [29].

The most effective parameter in evaluating surface roughness is the average surface roughness (*Ra*) parameter. However, the *Ra* parameter can only provide general information about the surface; therefore, the maximum height of the profile (*Rz*) parameter is also analysed (Fig. 9).

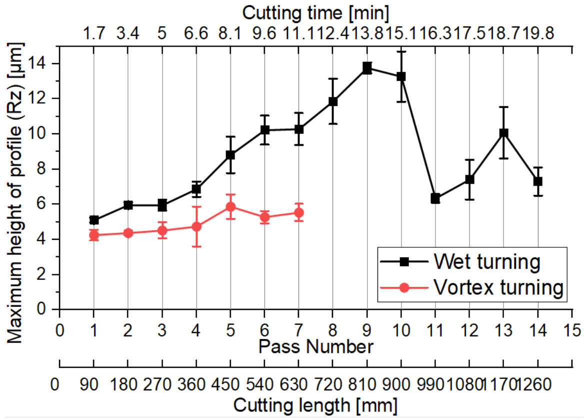

Fig. 9. *Maximum height of profile (Rz) values*

Similar to the *Ra* parameter, which gives principal information about surface roughness, vortex cooling creates better surface quality in the *Rz* parameter (Fig. 9). Under wet machining conditions, the *Rz* parameter is 5.45 times of *Ra* parameter on average, under the vortex turning conditions *Rz* parameter is 5.75 times of *Ra* parameter on average.

Tool life, workpiece surface roughness, and sustainability are the main topics of discussion in industrial machining processes. Within the scope of this study, it was found that the use of the vortex tube, which may contribute to sustainability, could be a satisfactory alternative in industrial practice, especially since it offers better surface quality.

3 CONCLUSIONS

Machining is a complex process influenced by numerous factors. Tool life and surface roughness are of immense importance in controlling this process. In this study, tool wear and surface roughness experiments were carried out on the material AISI 4462 (X2CrNiMoN2253), which is duplex stainless steel and belongs to the class of hard-to-cut materials. The experiments were conducted at a cutting speed of 120 m/min, a depth of cut of 1 mm, and a feed of 0.1 mm/rev. Experiments were conducted with both wet and vortex tube cooling methods for the first time on AISI 4462.

Experiments were carried out with a 90-mm cutting length for each pass, and at the end of each pass, both tool wear and surface roughness were investigated. As a result of these experiments, the following results emerged:

- Tool life under wet turning conditions was completed after 19.8 minutes (14th pass) based on flank wear and notch wear standards. However, in the experiments with the vortex tube, the tool life was completed in 11.1 minutes (7th pass). The BUE formation on cutting tools was observed in both methods.
- In both wet and vortex cooling conditions, both notch and flank wear were rapidly worn within 1.4 minutes of cutting time (first pass). Both types of wear continued to increase at a constant wear rate under wet turning conditions. However, under the vortex cooling conditions, the tool was rapidly worn, especially after 6.6 minutes of cutting time, and the tool life was completed.
- Similar types of wear were observed in both wet and vortex cooling conditions. In particular, abrasion wear and the BUE formation were evident. Interestingly, however, the vortex tube experiments revealed less BUE formation than the wet-turning experiments. The interesting situation was presumably an indication of chip control problems. In vortex cooling conditions, better chip control was achieved in all experiments. In particular, the selected low feed value (0.1 mm/rev) may have caused the insert's chip breaker geometry not to function appropriately. Since the loss of chip control is due to the low feed, further studies may investigate increasing the feed values to analyse the effects of wet and vortex cooling methods.
- Better surface roughness was expected under the wet machining conditions; however, better surface roughness values (*Ra* and *Rz*) were determined in the experiments with the vortex tube. In general, vortex cooling resulted in two times better surface quality, and the lowest surface roughness was obtained with about 0.65 μm for *Ra* and about 3 μm for *Rz*. This could be explained by the fact that the BUE formation was lower in the experiments performed with the vortex tube. In addition, this situation showed that a possible consequence of the chip control problem may be seen in the surface roughness.
- Under wet machining conditions, the surface roughness deteriorated up to two times due to tool wear, reaching approximately 2.2 μm. This deterioration was not observed in the vortex tube experiments. Stable surface roughness values were mostly obtained in the vortex tube experiments, while decreasing surface roughness values were obtained in some experiments. However, it is interesting to note that some improvement in surface roughness values was detected towards the end of the tool life under wet machining conditions.
- The vortex tube, a sustainable approach, could be a suitable alternative in industrial applications, especially because it provides a higher surface quality.

According to the data obtained within the scope of this study, investigating the use of a vortex tube with the MQL system in detail in future works may be of interest. Experiments can be performed by using MQL and a vortex tube together. It would also be interesting to use nanoparticles in MQL applications. In addition, these processes can be investigated using the finite element method.

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