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Original Article

The effect of vibration and cutting zone temperature on surface roughness and tool wear in eco-friendly MQL turning of AISI D2

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ABSTRACT

Today, developments in technology have gained momentum more than ever, and the need for efficiency in production as well as in the ecological domain has increased significantly. Studies examining dry machining and coolant removal have been superseded by those presenting new cooling and lubrication techniques. The effects on surface roughness directly related to final product quality are being investigated in terms of tool life and employee health. This has resulted in more frequent use of the eco-friendly minimum quantity lubrication (MQL) technique, which has now become a major competitor to dry and coolant machining. In this study, AISI D2 cold work tool steel, a material widely used in the mold industry, was used as the workpiece. Tests were carried out under dry and MQL conditions and the temperature, cutting tool vibration amplitude, tool wear, surface roughness and tool life were evaluated. The experiments were carried out using two different cutting tool coating types (CVD-chemical vapor deposition and PVD-physical vapor deposition) and three different cutting speeds (60, 90 and 120 m/min) at a constant cutting depth (1 mm) and feed rate (0.09 mm/rev). Results revealed that tool wear, cutting temperature and cutting tool vibration amplitude were lower by 23, 25, and 45%, respectively, compared to dry cutting. Because of these improvements, the surface roughness of the workpiece was improved by 89% and tool life was increased by up to 267%.

Abbreviations: MQL, Minimum quantity lubrication; CVD, Chemical vapor deposition and; PVD, Physical vapor deposition; BUE, Built-up edge; Ra, Arithmetic mean of surface roughness; Rz, Mean of 5 recesses and 5 projections surface roughness.

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1. Introduction

In the early 20th century, cutting fluid use became widespread because dry processing conditions yielded very low performance in terms of accurate dimensions, surface roughness and tool life [1–3]. Although it improves the quality of the final product, the use of cutting fluids is known to be uneconomical as well as hazardous to human health. These negative features have been examined in many studies [4–8]. Furthermore, after completion of its service life, cutting fluid must be disposed of, and its disposal costs twice as much as the price of the cutting fluid [9]. For these reasons, by the end of the 20th century, new cooling and lubrication methods were being proposed and studied [10–13]. Especially in the context of green manufacturing, the MQL technique has become prominent in recent years and its usage is becoming widespread. Among the main features of the MQL technique are that it reduces the cutting zone temperature and the amount of lubrication needed to reduce friction in the cutting zone. The heat generated by the friction at the cutting tool-workpiece interface during chip removal causes the temperature to rise in the cutting zone and this temperature reduces the hardness of the cutting tool material [14]. Many researchers have reported that with this lowered hardness, the cutting tool wears faster and that the changed cutting edge and form of the broken chip due to this wear adversely affect surface roughness and dimensional accuracy [15,16]. Therefore, it is important to avoid very high cutting temperatures. In drilling, milling and turning, 30–38% improvement in surface roughness [17,18], 17.07–59% reduction in cutting forces [17–19], 6.72–51% reduction in cutting temperature/tool tip temperature [17,19–21], and 27.5–409% increase in tool life [20,22,23] have been reported with MQL machining compared to dry machining.

The application of hard cutting tool coatings was a turning point in the development of cutting tools [24]. These hard coatings provide a significant increase in wear resistance and cutting tool life. They also reduce the effects of cutting temperatures and cutting forces on the cutting tools. Today, more than 70% of tungsten carbide tools are coated [25,26]. Carbide tools are usually coated using two methods: CVD and PVD. The CVD coatings exhibit very good adhesion to carbide tools and increase their wear resistance. With PVD coatings, an additional toughness is provided to the cutting edge, as well as an increase in wear resistance of the tools. The resistance of the carbide tools against diffusion and oxidation wear along with hot hardness properties can be increased by TiC, TiN, Al_2O_3, TiCN, TiAlN, TiZrN, TiB_2, and diamond coatings [27]. The TiN, which is generally used in the top layer of hard-coated tools, prevents the formation of built-up edge (BUE) because it provides better chip control compared to other coating types and it provides dry lubrication [28].

The vibration effective on cutting tools has been examined in a number of studies, and can be divided into three categories: free vibration, forced vibration and self-excited vibration [29]. Free vibration due to the immediate impact forces acting on the cutting tool is an unanticipated type of vibration that is not expected to occur in the normal stock removal process. This type of vibration is ignored in studies because it has a shorter and transient effect compared to the other two types of vibration. Forced vibration is directly proportional to the cutting force acting on the cutting tool at regular intervals. Self-excited vibration results from the dynamic imbalance of the turning process. The frequency of the self-excited vibration is close to or greater than the natural frequency of the cutting tool [30]. The accurate interpretation of the vibration occurring in the cutting tool is particularly important as it is directly related to surface roughness and tool life. Several studies have been conducted on the factors and variables that increase the tool vibration amplitude such as cutting speed, feed rate, cutting depth, and cutting forces [31,32].

In this study, AISI D2 cold work tool steel was used as the workpiece, along with CVD- and PVD-coated tungsten carbide cutting tools The main purpose of this study investigated the effects of cutting tool vibration and cutting zone temperature during machining on the cutting tool coating type, surface roughness (Ra and Rz), tool wear, and tool life.

2. Material and methods

Because of its high carbon and chromium content, AISI D2 cold work tool steel with high strength, hardness (50 HRC) and abrasion resistance was used in the study. For the turning tests, tailstock holes, 250 mm in depth and 100 mm in diameter, were drilled to reduce vibration in the workpieces. The chemical components of the AISI D2 cold work tool steel workpiece material are given in Table 1.

Workpieces suitable for hard turning were turned on an Accuway JT-150 CNC lathe. The experiments were carried out at three different cutting speeds (60, 90, 120 m/min) with a constant feed rate (0.09 mm/rev) and constant cutting depth (1 mm) under dry and MQL processing conditions. The experimental setup is shown in Fig. 1. The study used the CNMG 120408 form TiAlN-TiN PVD-coated and TiCN-Al_2O_3-TiN CVD-coated tungsten carbide cutting tools.

Table 1 – Chemical components of AISI D2 cold work tool steel.

Element	C	Si	Mn	P	Cr	Mo	V
%	1.575	0.32	0.3	0.024	11.7	0.74	0.96

Fig. 1 – CNC lathe and MQL system experimental setup.

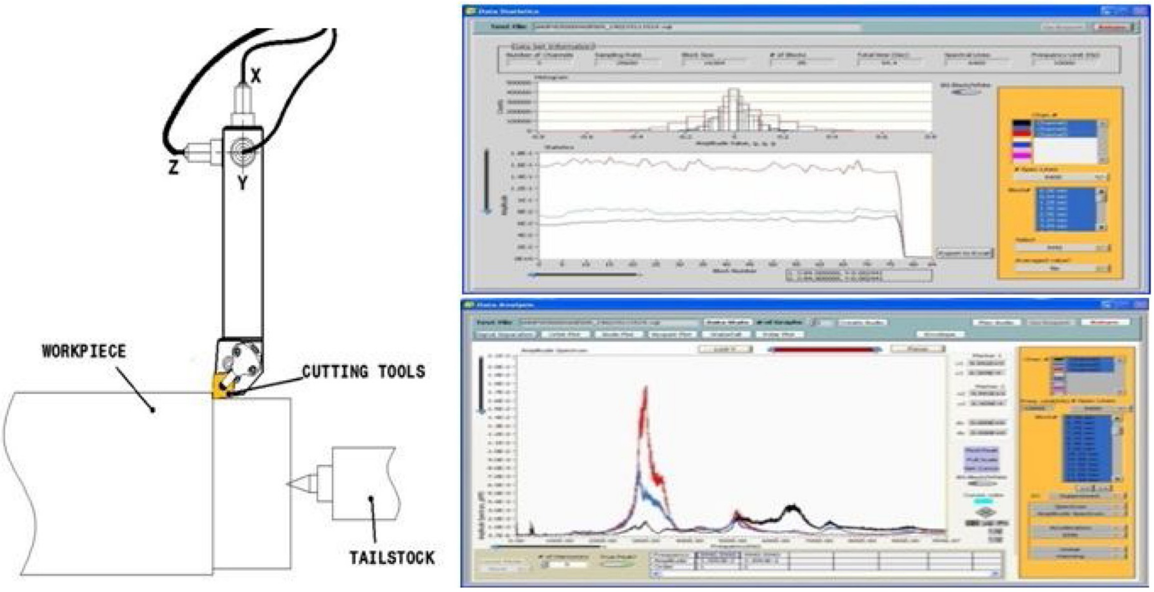

Fig. 2 – Accelerometers mounted on the tool holder at three axes (X, Y and Z) and vibration data.

The B1-210 model MQL system produced by Bielomatik was used. In the experiments, the lubricant used was the ca. 100% biodegradable, vegetable-based SAMNOS ZM-22W cutting oil with a density of 1 g/cm^3 (20 °C) and viscosity of 1.7 mm^2/s (20 °C). This oil was delivered to the cutting zone at a flow rate of 150 mL/h at a distance of 25 mm with a 1-mm diameter nozzle at a pressure of 6 bar. The vibration data generated during cutting were measured using the SpectraQuest software and hardware device accelerometer mounted on the tool holder at the three axes of X, Y and Z, as shown in Fig. 2. After the vibration data collected by the SpectraQuest software were analyzed using VibraQuest, the average of each axis was taken and the amplitude values of the X, Y and Z axes vibration of the tool holder were plotted.

The temperature at the cutting zone was measured using the Optris PI 450 infrared camera. The emissivity value of the thermal camera was taken as 0.81 for the AISI D2 cold work tool steel workpiece material. The thermal camera was fixed to the turret at a distance of 250 mm from the cutting zone so that it moved with the cutting tool during cutting.

In order to determine the surface quality of the material, after each experiment, Ra (arithmetic mean of surface roughness) and Rz (mean of 5 recesses and 5 projections) measurements were carried out from five different points using a Mahr PS10 profilometer. The amount of flank wear on the cutting tools was measured via a DINO LITE 2.0 microscope. In order to better understand the wear types and wear mechanisms, photographs were taken via a FEI Quanta FEG 250 scanning electron microscope (SEM).

3. Results and discussion

3.1. Cutting temperature

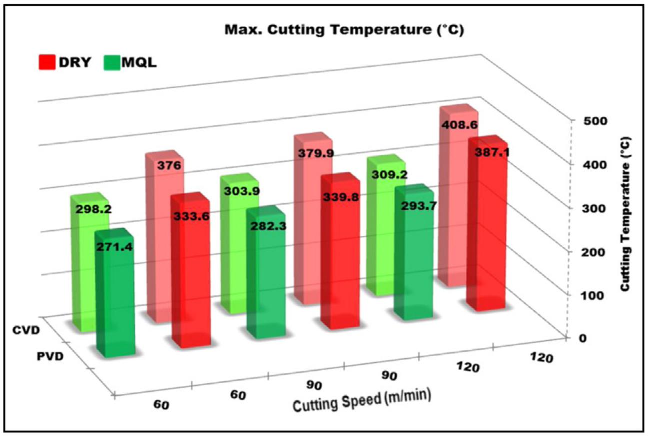

Fig. 3 – Cutting zone temperatures of CVD and PVD cutting tools.

With the effect of friction during cutting, a high amount of heat is produced in the cutting zone. This heat, up to a certain value, facilitates the cutting as it allows for easy separation of the chip from the workpiece. However, the increased heat adversely affects the hardness of the cutting tool, thus accelerating the wear of the tool [14,33]. Fig. 3 shows that MQL reduced the cutting zone temperature by approximately 100 °C at all cutting speeds in both CVD and PVD coated tools. The MQL system provides some lubrication and reduces friction on the machined surface [34,35]. This results in a lower cutting zone temperature. Increasing the cutting speed causes the friction to increase, thus increasing the cutting zone temperature [36–38]. Under all cutting conditions, lower cutting zone temperatures were observed with PVD tools than with CVD-coated tools. This is thought to be due to the thermal conductivity of the Al_2O_3 coating material in the middle layer of the CVD-coated tool. The Al_2O_3 material exhibits low thermal conductivity at high temperatures. This makes it difficult for the temperature at the cutting tool tip to exit the cutting

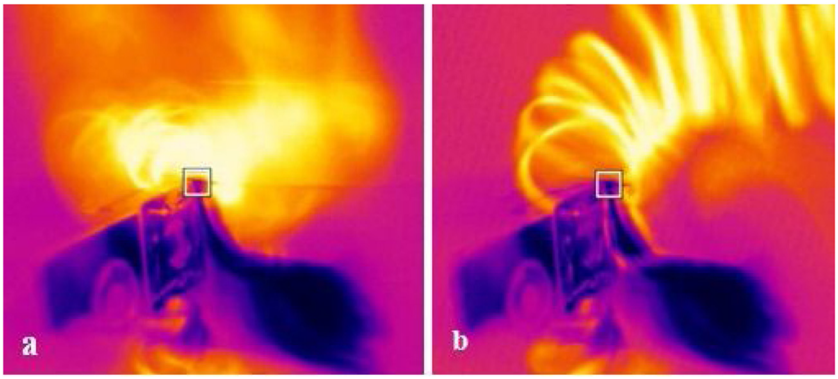

Fig. 4 – Thermal images of chip flow under different cutting conditions: a) Dry; b) MQL.

zone [28,39,40]. One of the reasons that the cutting temperature of the cutting zone is low during MQL is that the chip is moved away from the cutting zone due to the high pressure of the MQL system. In Fig. 4, this is clearly seen in the thermal images of the chip emerging from the cutting zone under dry and MQL conditions.

3.2. *Cutting tool vibrations*

Shown in Fig. 5 are the variations of vibration amplitude values for the CVD and PVD tools according to the frequencies measured at three axes under dry and MQL cutting conditions at 120 m/min cutting speed. The averages of the vibration amplitudes collected at all cutting speeds according to the X, Y and Z axes are given in Fig. 6. The highest vibration amplitudes were measured on the Z axis. This arose from the fact that more movement occurred in the Z axis, which was the direction of cutting where the tool impacted the workpiece [41]. Lower vibration amplitude values were measured with MQL machining than with dry machining. This was explained by the lubrication provided by MQL in the cutting zone that reduced friction at the cutting tool-workpiece interface [34,42], lowered the cutting zone temperature [17,19], and reduced tool wear [43].

The vibration amplitude values of the cutting tools coated via both CVD and PVD methods rose at all three axes with increasing cutting speed. This increase is thought to have been due to the increase in cutting tool wear and the increased centrifugal force. Increased temperature in the cutting zone accelerates cutting tool wear. As a result of losses due to wear on the cutting tool tip, the tip radius of the cutting tool and the broken chip form deteriorate as the chip is removed. Continuous shape and area changes occur at the cutting tool-workpiece contact zone. Wear on the cutting tool and surface roughness on the workpiece increased because of BUE formed on the cutting tool. All these changes resulted in changes in cutting forces, surface roughness and cutting tool vibration values [31].

The vibration amplitude values of the PVD-coated tool were lower than those of the CVD-coated tool. It is thought that the increased heat accelerated the wear due to the Al_2O_3 coating in the middle layer of the CVD-coated tool, keeping the temperature in the cutting zone, while the excessive vibration when removing the chip with the CVD-coated tool is thought to have been due to changes in the cutting force on the cutting tool.

3.3. *Surface roughness*

Fig. 7 shows changes in the surface roughness depending on the cutting speed of the cutting tools. In the experiments, Ra values were measured as 0.32–3.26 μm and Rz values as 2.22–11.13 μm. The graphs show a significant reduction in both Ra and Rz values for both cutting tool types under MQL machining compared to dry machining. Processing with MQL yielded an improvement of up to 88% in Ra and 91% in Rz compared to dry processing. This was associated with the lower cutting zone temperature, vibration amplitude values and cutting tool wear with the MQL machining. Cutting tool wear [44–46] and cutting tool vibration [47] directly affect the surface roughness. In the experiments, the PVD-coated tools exhibited lower surface roughness values than the CVD-coated tools under all cutting conditions. This was attributed to less wear on the PVD-coated tools than on the CVD-coated tools. There is a direct relationship between cutting tool wear and surface roughness [44].

The graphs show that the increasing cutting speed affected both surface roughness values (Ra and Rz). This was attributed to the increases in the cutting speed, cutting zone temperature and cutting tool wear resulting from increased cutting tool vibration amplitudes.

3.4. *Tool wear*

The graph in Fig. 8 shows the differences in the CVD and PVD tools under dry and MQL conditions depending on the cutting speed. The flank wear in the cutting tools was lower in experiments performed with MQL than under dry cutting. Because the MQL system provides some lubrication in the cutting zone, it lowers the cutting zone temperature, thus reducing wear on the cutting tool. The flank wear values of the cutting tools increased with both dry and MQL machining conditions as cutting speed was increased. Cutting forces increased due to the increased friction and cutting zone temperature resulting from the faster cutting speed and consequently, tool wear was adversely affected [48,49].

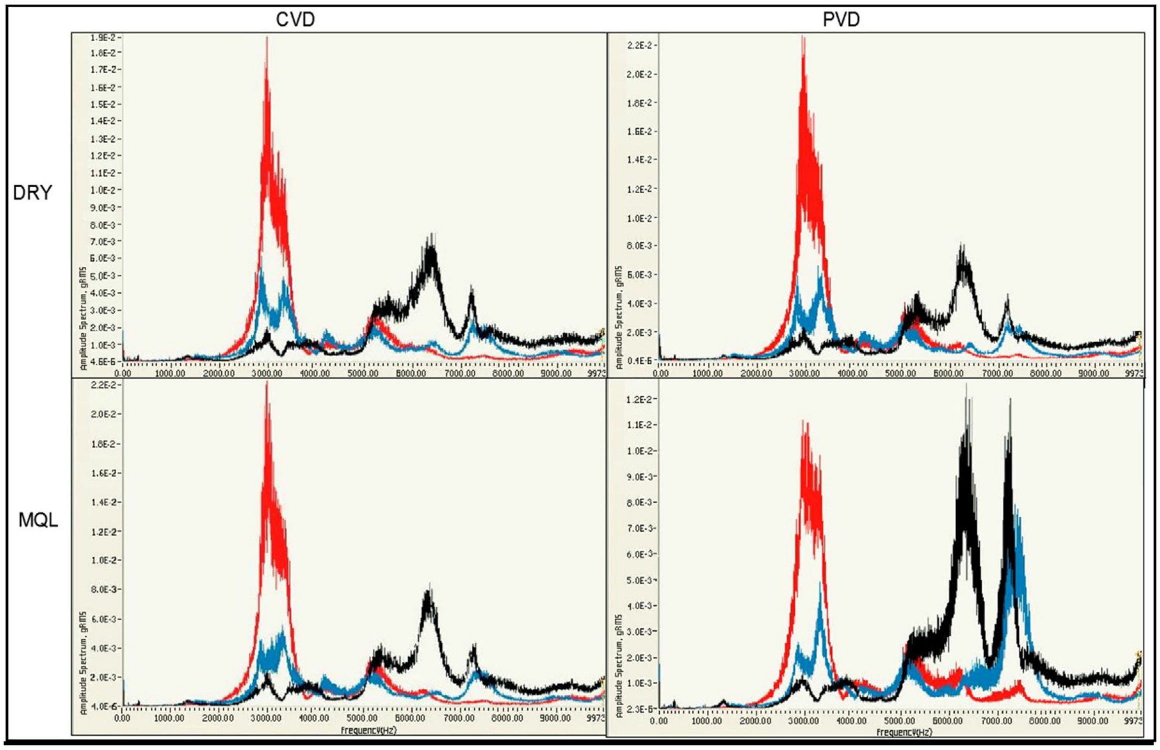

Fig. 5 – Variation of vibration amplitude values for CVD and PVD coated tools according to frequencies under dry and MQL cutting conditions at 120 m/min cutting speed.

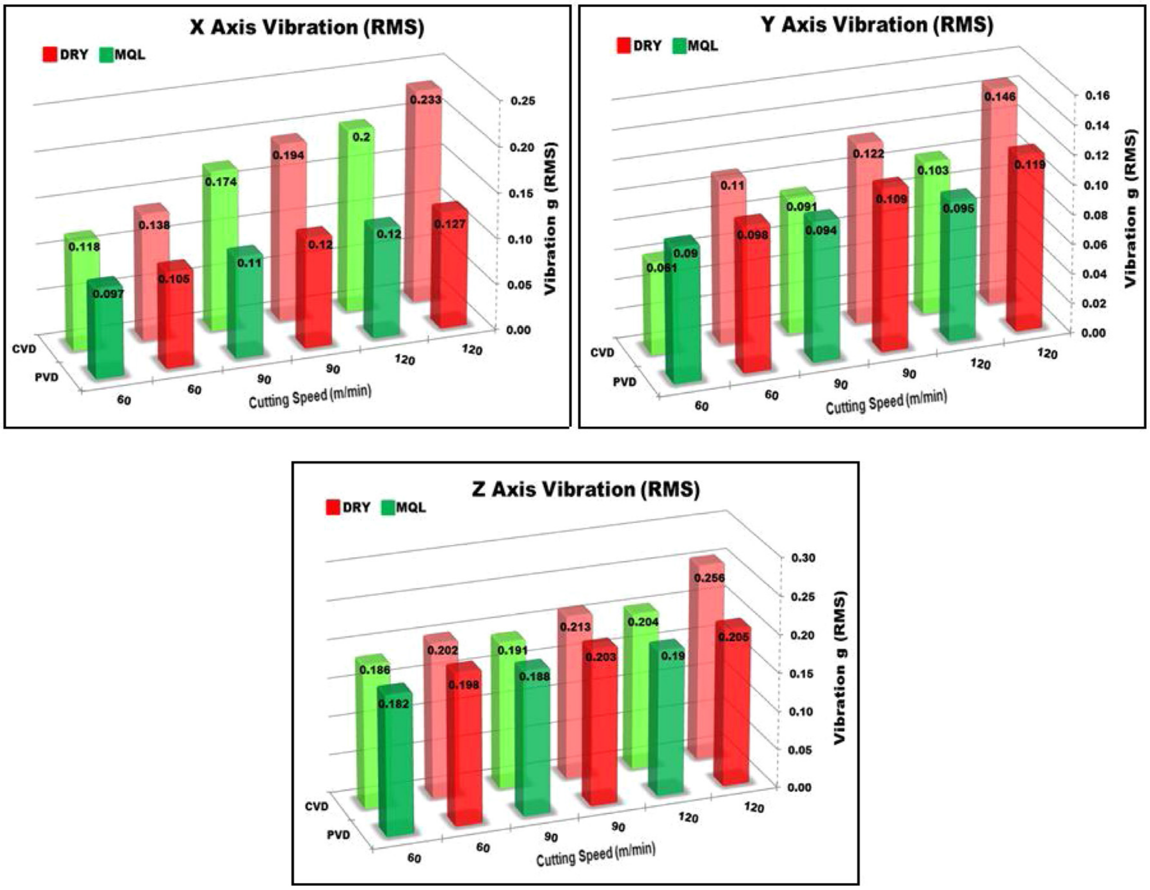

Fig. 6 – Averages of the vibration amplitude values collected at different cutting speeds according to X, Y and Z axes.

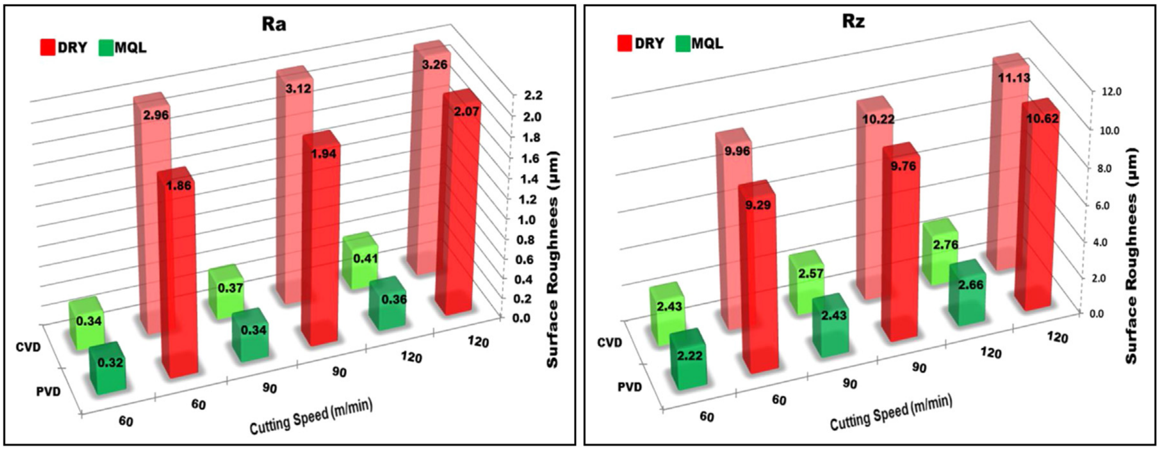

Fig. 7 – Surface roughness changes due to cutting speed of CVD- and PVD-coated cutting tools.

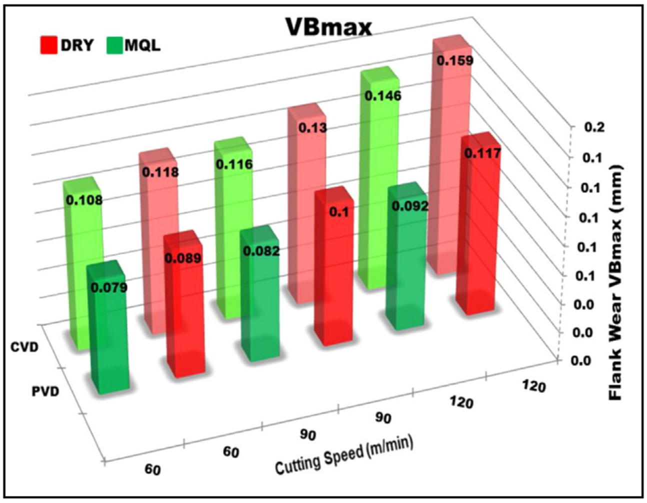

Fig. 8 – CVD and PVD coated tools under dry and MQL conditions depending on different cutting speeds.

The PVD-coated tool was shown to perform better under all cutting conditions than the CVD-coated tool. The wear resistance of the cutting tools increased with greater coating thickness. However, this causes brittleness, and the removal of the coating layer becomes a problem. A thinner coating provides higher toughness [50]. Generally, CVD coatings are thicker than PVD coatings. The CVD coatings are at a minimum 6–9 μm thick, while PVD coatings are 1–3 μm thick [51]. Coatings made via PVD are much smoother than CVD coatings and can be deposited onto sharp edges [52,53].

Images of the wear on the cutting tools taken by optical microscope are shown in Fig. 9. The pictures clearly show that the cutting tools had less wear with MQL machining and that the cutting tool wear increased with increasing cutting speed. On the other hand, BUE, caused by the adhesive wear mechanism, occurred on the cutting tools under all cutting conditions. The BUE dimensions generally decreased with increasing cutting speed. For better understanding of the wear mechanisms, SEM images at different magnifications were taken of the cutting tools for the experiments carried out at a feed rate of 0.09 mm/rev and a cutting speed of 120 m/min (Figs. 10–14). The SEM pictures showed that flank wear and nose wear caused by the abrasive wear mechanism had occurred in all cutting tools. With the CVD-coated cutting tool, the coating layer had been removed in some areas during turning under dry cutting conditions (Fig. 10). Furthermore, as a result of the removal of the TiN coating (the top coating), portions of the Al_2O_3 coating layer (white points) at a depth of 40-μm in a line extending for 400 μm starting from the lower limit of the flank wear can be seen on the CVD-coated tool. The EDS analysis taken from these white points verifies this situation, as shown in Fig. 11. In the SEM picture taken of the PVD-coated tool turned under dry cutting conditions, the flank and nose wear, abrasion marks and BUE formation are clearly seen on the cutting tool (Fig. 12). Fig. 13 shows the SEM image of the CVD-coated tool under MQL machining conditions. Again, flank and nose wear are clearly seen on the cutting tool. In addition, the abrasion marks on the cutting edge and the Al_2O_3 coating material (the middle layer) also stand out. However, the resulting BUE formed at the cutting edge is much less than that formed under the dry cutting condition. Similarly, the SEM picture of the PVD-coated tool under MQL machining shows the BUE formation to be much less than under the dry cutting condition (Fig. 14). Thus, the MQL system greatly reduced the type of BUE that adversely affects surface roughness and tool wear.

3.5. *Tool life*

Tool wear has a direct impact on surface roughness, production time, and cost. Since tool life and tool wear are considered as machinability measures, they are important issues in machinability studies [54–56]. Fig. 15 shows the tool life differences between the CVD-coated (Fig. 15a) and PVD-coated (Fig. 15b) tools at a cutting speed of 90 m/min and a feed rate of 0.09 mm/rev under dry and MQL machining conditions. Machining with MQL prolonged the tool life of the CVD-coated tool by 267% compared to dry machining, while the tool life of the PVD-coated tool was prolonged by 200%. With the MQL system, the oil reaches the cutting zone under high pressure, reducing the cutting zone temperature and cut-

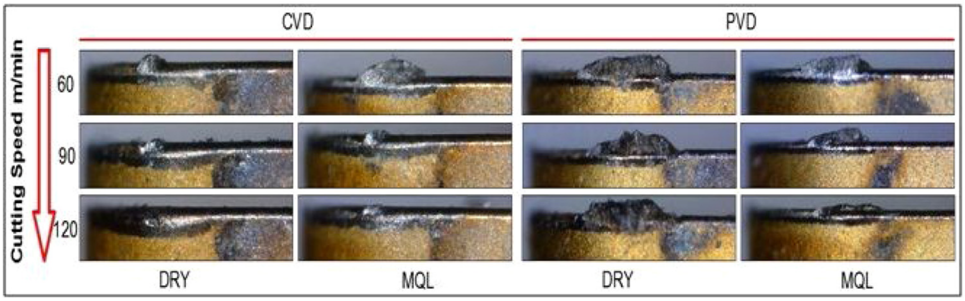

Fig. 9 – Flank wear on CVD and PVD coated tools under dry and MQL conditions according to different cutting speeds.

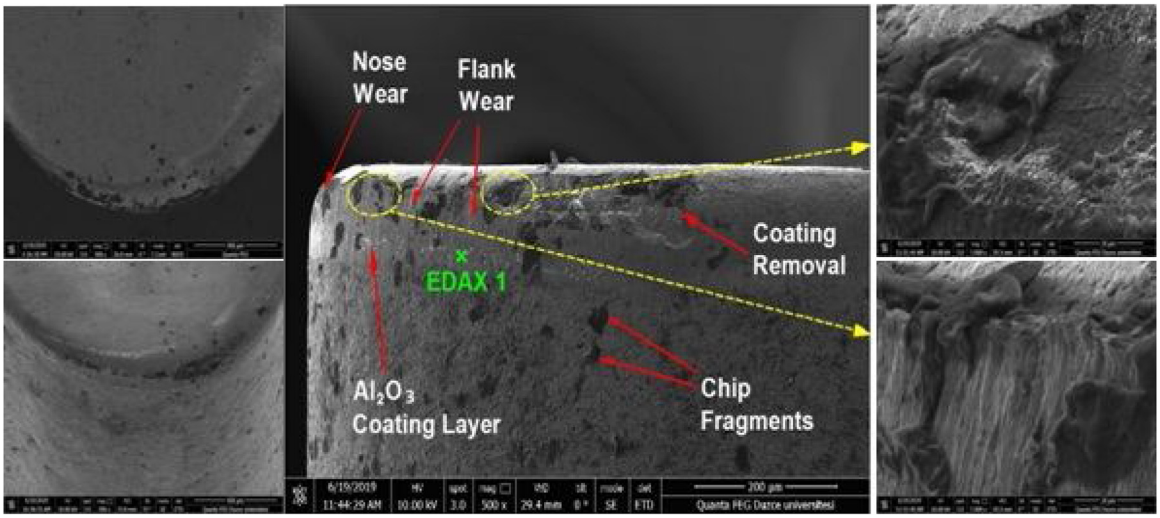

Fig. 10 – SEM images of CVD-coated cutting tool under dry cutting conditions.

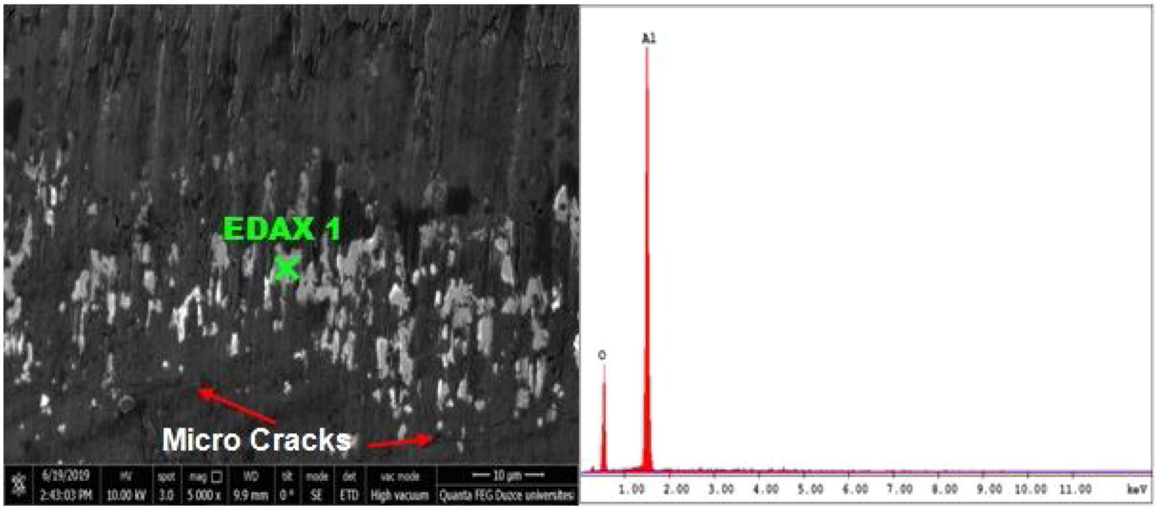

Fig. 11 – SEM image of CVD-coated cutting tool under dry cutting conditions and EDS analysis.

ting tool vibration amplitude. Thus, the tool life was extended with long-term protection of the cutting tool form and reduced tool wear.

With dry machining, the PVD-coated tool life was four times higher than the CVD-coated tool life, and three times higher with MQL. This can be explained by the high temperatures and vibrations generated in the cutting zone of the CVD-coated tool, which increased the wear on the cutting tool, thus reducing its tool life.

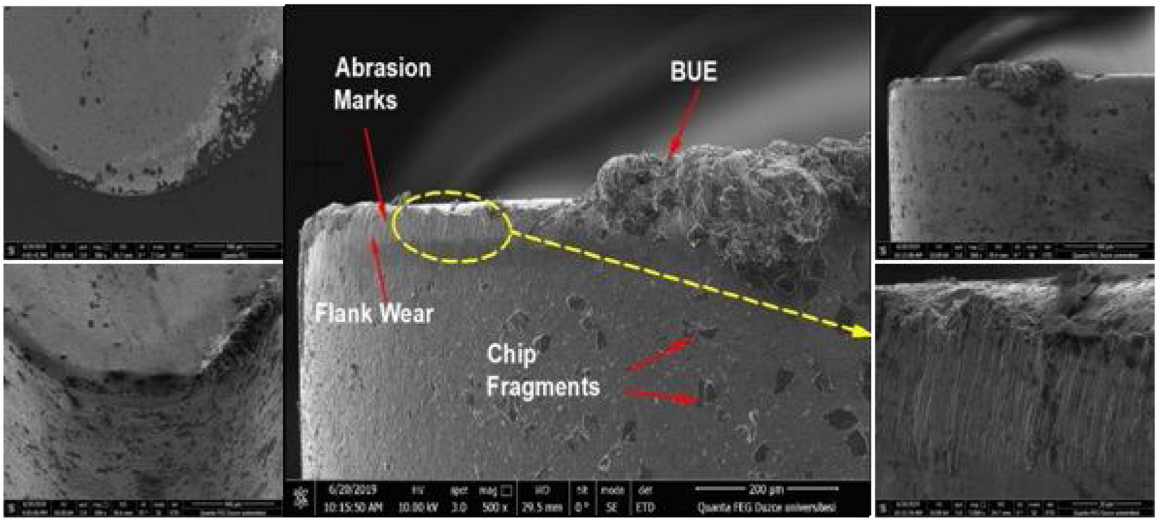

Fig. 12 – SEM images of PVD-coated cutting tool under dry cutting conditions.

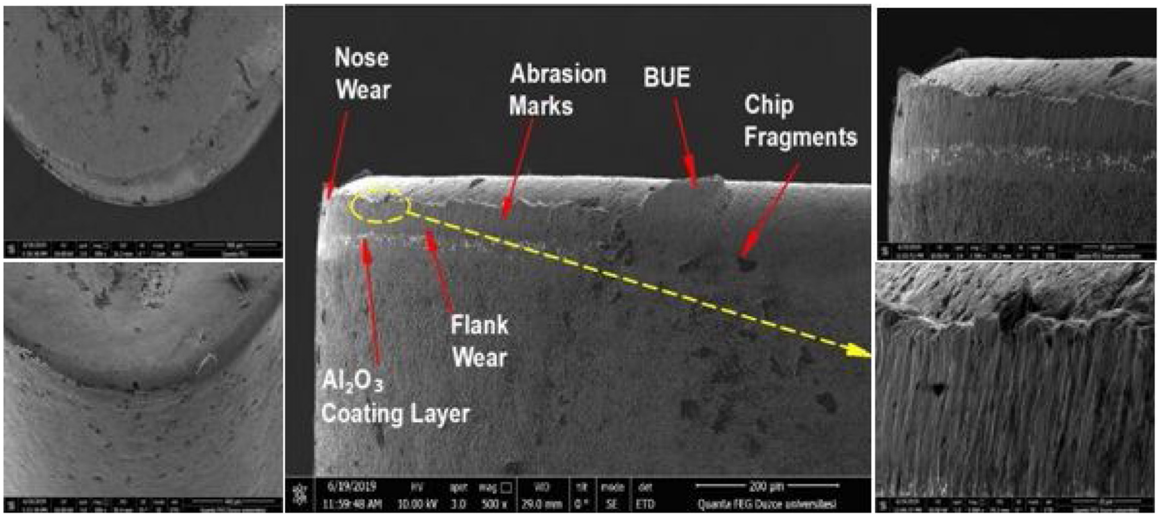

Fig. 13 – SEM images of CVD-coated cutting tool under MQL cutting conditions.

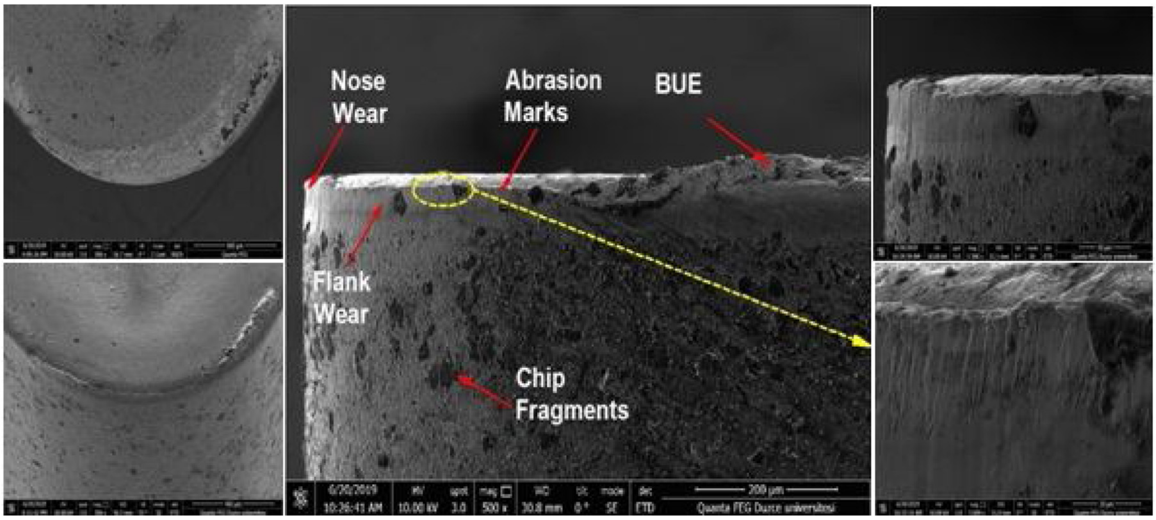

Fig. 14 – SEM images of PVD-coated cutting tool under MQL cutting conditions.

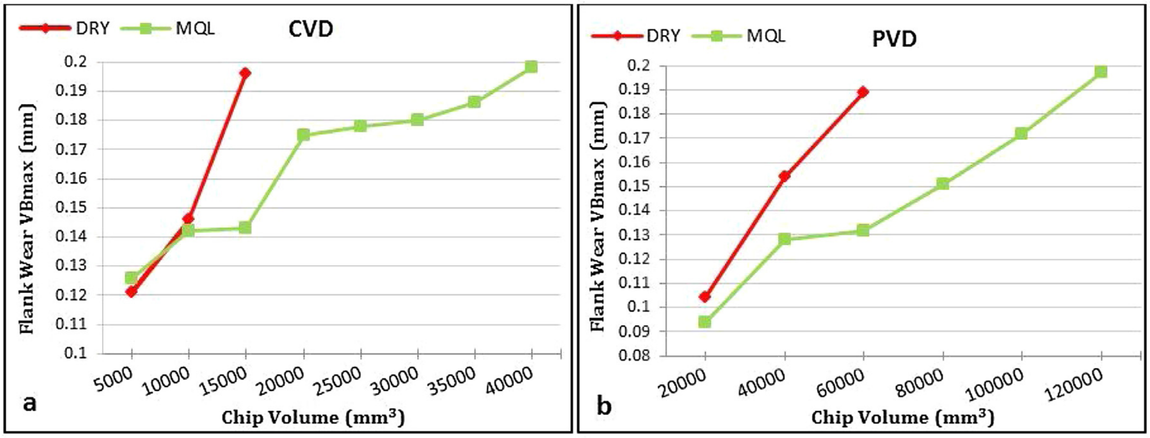

Fig. 15 – Tool life differences at 0.09 mm/rev and 90 m/min cutting parameters under dry and MQL machining conditions: (a) CVD-coated tools; (b) PVD-coated tools.

4. Conclusion

In this study, the effects of the cutting zone of the MQL system on cutting temperature, cutting tool vibration, surface roughness, tool wear and tool life were investigated in the turning of AISI D2 tool steel with PVD and CVD-coated tools. The results obtained from the experiments are given below.

Compared to dry machining, the eco-friendly MQL system was found to reduce the cutting zone temperature by approximately 100 °C at all cutting speeds in both tools (CVD and PVD). Similarly, tool vibration amplitude values decreased with MQL machining. Compared to dry machining, MQL machining demonstrated significant improvements in both Ra and Rz for both cutting tool types. Processing with MQL resulted in 88% improvement in Ra and 91% improvement in Rz. In the experiments carried out with MQL, less tool wear was seen than with dry cutting. Machining with MQL prolonged the tool life of the CVD tools by 267% and the PVD tools by 200% compared to dry machining.

The PVD-coated tools generated lower cutting temperatures than the CVD-coated tools. Moreover, the PVD tool vibration amplitude values were also lower than those of the CVD tools. The highest vibration amplitudes were measured on the Z axis. In terms of both Ra and Rz values, the PVD-coated tools showed better surface roughness values under all cutting conditions. In tool wear, the PVD tool also showed better wear performance at all cutting speeds compared to the CVD tool. Under dry machining, the PVD-coated tool life was four times longer than the CVD-coated tool life. Under MQL machining, the PVD-coated tools had a tool life three times longer than that of the CVD-coated tools.

For both cutting tool types (PVD and CVD) and for both cutting conditions (dry and MQL), with increased cutting speed, the cutting zone temperature, cutting tool vibration amplitude values, surface roughness (Ra and Rz) and tool wear increased as well.

Conflicts of interest

There were no conflicts of interest in the study. I take full responsibility for this.

Acknowledgments

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmrt.2020.01.010.

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