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Effect of the Various Cooling Conditions on Surface Quality and Cutting Tool Performance in Turning Processes of Tool Steel

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تأثير ظروف التبريد المختلفة على جودة السطح وأداء أداة القطع في عمليات تحويل فولاذ الأدوات

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Abstract:
This study investigates the effects of various cutting fluids, including dry, wet flood, and Minimum Quantity Lubrication (MQL), on the surface quality of cold work steel during turning operations. The research focuses on key performance indicators such as surface roughness, tool wear rate, and both surface and subsurface integrity. Conducted at the Libyan Centre for Advanced Technology, the study concludes that the use of MQL cutting coolant significantly improves outcomes concerning tool wear, microhardness, and surface and chip morphology. The findings attribute the reduced tool wear to the effective cooling and lubrication provided by the MQL regime, which maintains cutting temperatures at manageable levels.

Keywords: Cutting Conditions, MQL, Surface Quality, Tool Wear.

الملخص
تتناول هذه الورقة تأثير ظروف القطع المختلفة، بما في ذلك سوائل القطع التقليدية، القطع الجاف، القطع باستخدام الهواء المضغوط، وتقنية قطع الحد الأدنى للتزييت(MQL) ، على جودة السطح عند خراطة الفولاذ المستخدم في تصنيع العدد والقوالب. تم التركيز على خشونة السطح، معدل تآكل أداة القطع، وسلامة السطح وما تحت السطح كنتائج لعمليات الخراطة. أجريت هذه الدراسة في المركز الليبي المتقدم للتقنية، وخلصت إلى أن استخدام نظام تبريد القطع MQL أدى إلى نتائج أفضل من حيث تآكل الأداة، الصلادة السطحية، وخشونة السطح. كما أظهرت النتائج أن نظام التبريد MQL يحافظ على درجة حرارة القطع عند مستوى مقبول، مما أدى إلى تقليل قيم تآكل أداة القطع.

الكلمات المفتاحية: ظروف القطع، MQL، جودة السطح، تآكل الأداة.

Introduction
To keep pace with the increasing need for high productivity in the machining industry, cutting and feed speeds must be increased. Cutting naturally produces high temperatures, which not only shorten the life of the tool but also reduce product quality. The use of cutting fluids characterized by advantageous machining, lubricating, and cooling properties contributes positively to overall machining performance [1]. However, a disadvantage of cutting fluids is that their quality degrades over time as they become contaminated with foreign matter. When the fluid loses its functionality, it turns into waste [2]. As a result, the expenses for cooling lubricants in companies constitute a significant portion of the total processing costs. Fluid costs account for between 7% and 17% of total production costs, while tooling costs account for only 4% [3]. This inequality has recently begun to shift. Examples of fluid-related costs include installing a fluid delivery system, purchasing fluids, maintaining the system, and treating fluid waste. Reducing the amount of fluid used can result in significant cost and waste savings, as high-production facilities often use multiple cutting fluid tanks, each containing thousands of gallons. When

quality issues arise, it is not uncommon for an entire container to be flushed to clean the system [4]. Cutting fluid consumption is minimized by employing three strategies. Specifically, high-speed cutting (also known as high-speed machining) and methods with minimal quantity lubrication (MQL) are part of dry cutting, which avoids the use of cutting fluid. Although dry cutting is currently a successful, environmentally friendly manufacturing technique, it may be less effective in situations requiring high machining efficiency, superior surface quality, and challenging cutting conditions. A method known as near-dry machining, or MQL, was created specifically for these situations [5].

Lecturer review

The surface quality during the finishing processes of a workpiece is crucial for product quality. The use of cutting fluids, such as coolants or Minimum Quantity Lubrication (MQL), when turning hard steel can significantly impact surface roughness and tool life. Studies have demonstrated that MQL, which utilizes a small amount of cutting fluid, can improve surface roughness compared to dry and flooded lubrication conditions [6]. Additionally, the application of cutting fluid using the MQL technique, particularly between the flank surface and the workpiece, has shown superior results in terms of surface roughness and roundness error compared to dry machining [7]. Furthermore, the incorporation of water into MQL has been found to enhance surface roughness and reduce roundness defects, making the results comparable to those achieved with coolant flooding [8]. Finally, the use of nitrogen gas as a cooling technique in the hard turning of stainless steel has been shown to result in a better surface finish and longer tool life compared to dry cutting [9].

Another study compared the performance of dry, flooded, and MQL conditions in turning Ti-6Al-4V alloys. It was found that MQL showed better performance in reducing surface roughness compared to dry and flooded lubrication conditions [10]. Another study investigated the impact of PVD multilayer coatings and cutting fluids (MQL and flood) on surface integrity during the machining of Nimonic C-263. It was observed that MQL and flood environments provided superior surface quality at low and medium cutting speeds and feeds. However, at high cutting speeds and feeds, surface integrity deteriorated due to increased tool wear and reduced cooling and lubrication efficiency [11]. In the micro-milling of aluminum alloy 1100, the application of MQL was found to improve surface roughness by reducing friction between the tool and the workpiece. The spindle speed did not significantly influence surface roughness in the presence of MQL [12]. In ultrasonic-assisted machining of multi-directional CFRP laminates, flood coolants provided better results than MQL. However, MQL still showed comparable performance to flood coolant and can be used for near-dry cutting requirements [13]. Electrostatic Minimum Quantity Lubrication (EMQL) was investigated as a cost-effective and environmentally friendly alternative to conventional flood cooling and MQL. The effectiveness of EMQL was influenced by cutting speed and voltage, as well as factors such as air pressure, nozzle position, and distance [14]. Previous research has established that using cutting fluids, such as Minimum Quantity Lubrication (MQL) and cryogenic machining, can improve surface integrity and reduce heat generation during machining [15]. MQL machining with varying speeds, feeds, and cutting depths has been shown to improve the surface quality of steel materials [16]. Other studies have concluded that the addition of graphene layers to cutting fluids used in MQL has been found to improve lubrication properties and reduce wear mechanisms on cutting tools [17]. Vegetable-based cutting fluids applied using the MQL method have been shown to reduce cutting temperatures and increase tool life in steel end milling. They have also been found to provide a better surface finish and reduce cutting forces compared to traditional wet machining [18][19].

Regardless of whether it involves dry lubrication, wet flood lubrication, or minimal quantity lubrication (MQL), several studies have compared the performance of MQL with flood lubrication in turning steel. The results show that MQL, combined with a low feed rate, can achieve surface roughness values comparable to those of conventional cutting fluids, while also reducing costs and social and environmental impacts [20]. Additionally, the effects of lubrication mode (dry and wet) and the chip removal process on machining characteristics were investigated. It has been found that MQL, as a near-dry machining method with micro lubrication, can improve surface finish and reduce chip thickness in machining aluminum alloys [21]. Furthermore, minimum quantity electrostatic lubrication (EMQL), which combines electrostatic spraying and MQL, has shown potential in turning stainless steels. Machining parameters and oil mist parameters such as cutting speed, voltage, air pressure, and nozzle position influence the effectiveness of EMQL [22]. In terms of tool wear and surface roughness, the use of plant-based cutting fluids with the MQL technique has shown better performance compared to flood cooling and dry machining in turning hardened steel [23]. Finally, the addition of water to MQL was investigated to minimize thermal damage during steel grinding. The results suggest that incorporating water in MQL can improve surface quality and serves as a viable alternative to traditional cutting fluids [24].

Cutting fluids are widely used in machining operations to enhance tribological properties and dissipate heat [25]. However, conventional cutting fluids have raised concerns regarding cost, environmental impact, and human health [26]. As an alternative to flooded coolant, Minimum Quantity Lubrication (MQL), which uses a small amount of cutting fluid, has been studied [27]. Research indicates that MQL improves surface roughness and reduces tool wear compared to dry and flooded lubrication conditions [28]. Additionally, variables such as feed rate, cutting speed, and tool coating type can affect MQL performance [29]. Electrostatic Minimum Quantity Lubrication (EMQL), which combines electrostatic spraying and MQL, has emerged as an alternative to conventional cutting fluids. EMQL has demonstrated its ability to enhance cutting efficiency while reducing adhesion and friction between workpiece materials.

Experimental Procedure

A conventional lathe (manufacturer: Biglia; model: B131/52) was used to carry out the experiments on DIN1.2714 and ST37 under all machining conditions. Before conducting the actual experiments, the workpiece was fixed on the headstock, and facing operations and center drilling were performed to solve the overhang problem. The obtained material exhibited microcracks on the surface and wobbles, which could severely affect processing quality. Therefore, to eliminate these effects, 1 mm of the top layer was removed from the material. The cutting tool was selected based on the manufacturer's recommendation (SNMG120408 MP). For each experiment, a new cutting edge was used to observe tool wear over a constant period of approximately 5 minutes. Table 1 lists the experimental details considered for the present study.

Preliminary experiments were conducted to determine the appropriate range for each process parameter. In this study, machinability assessments were performed under various cooling environments, including dry, compressed air, MQL, wet, and refrigerated conditions. The rotational performance characteristics at different speeds were compared while maintaining constant other input parameters. Speed is a critical parameter as it is directly related to surface quality and material removal rate. Therefore, the machinability properties were examined under different speed conditions. Table 2 presents the experimental results. Similar experimental designs have been utilized in the literature to investigate machinability properties. Compressed air was supplied from the tank and directed to the machining process in a jet form via an external nozzle. In MQL experiments, an air coolant mist was delivered to the tool tip-workpiece interface using a nozzle. Figure 1 depicts the machining zone under different cutting cooling techniques.

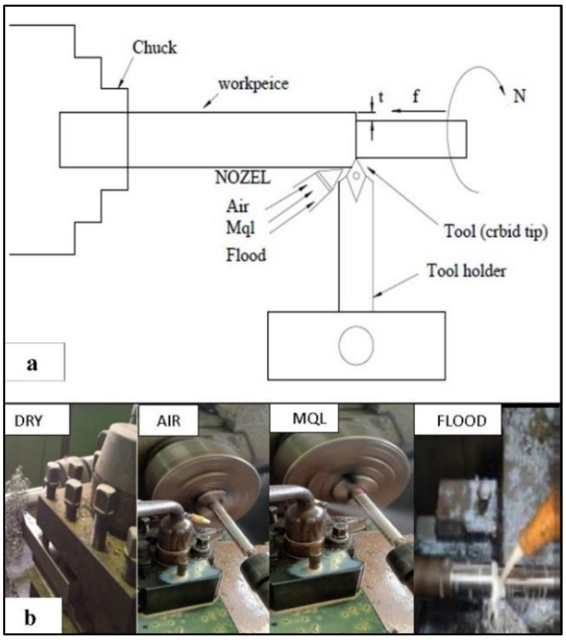
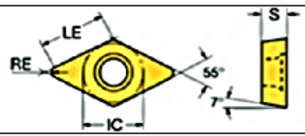


Figure 1: a) Schematic turning process, and b) machining processes and cooling techniques.

For tool wear analysis, each experiment was conducted for a constant duration of 5 minutes. Tool wear was measured using an optical microscope. The average surface roughness (Ra) was considered a key surface quality characteristic and was measured using a surface tester. For each machined sample, five Ra values were recorded over a cutting length (λc) of 4 mm, and the average of these values was considered the actual surface roughness parameter. Additionally, surface morphology and tool wear mechanisms were investigated.

Table 1: Experimental conditions.

<table>
<tr><td>Workpiece material and size</td><td colspan="9">Din1.2714 &st37 round bar and (Ø 30 mm × 250 mm)</td></tr>
<tr><td rowspan="2">Chemical composition of DIN 1.2714 AISI L6</td><td>C</td><td>Si</td><td>Mn</td><td>P</td><td>S</td><td>Cr</td><td>Ni</td><td>Mo</td><td>V</td></tr>
<tr><td>0.50-0.60</td><td>0.10-0.40</td><td>0.65-0.95</td><td>0.03</td><td>0.03</td><td>1.00-1.20</td><td>1.50-1.80</td><td>0.45-0.55</td><td>0.07-0.12</td></tr>
<tr><td>Hardness</td><td colspan="9">50-55 HRC</td></tr>
<tr><td rowspan="2">Chemical composition of DIN 2391 ST37</td><td>C</td><td colspan="2">Si</td><td colspan="2">Mn</td><td colspan="2">P max</td><td colspan="2">S max</td></tr>
<tr><td>≤0.17</td><td colspan="2">≤0.35</td><td colspan="2">≥0.35</td><td colspan="2">0.04</td><td colspan="2">0.04</td></tr>
<tr><td>Hardness</td><td colspan="9">10≤ HRC</td></tr>
<tr><td>Cutting inserts: VBMT 16 04 04-UM 525
VBMT 331-UM</td><td colspan="9"> </td></tr>
<tr><td>Turning process parameters</td><td colspan="9">Cutting velocity (v): 1600/300 rpm; feed rate (f): 0.035 mm/rev; depth of cut (d): .5 mm</td></tr>
<tr><td>Environments and coolants used</td><td colspan="9">Dry (no coolant); pressed air, MQL and wet (emulsion-based flood cooling: 1:20 soluble oil)</td></tr>
<tr><td>Cutting fluid supply</td><td colspan="9">- Dry
- Compressed air: 4 bar, flow rate
- MQL cooling—compressed air: 4 bar, flow rate: 50 ml/h (through external nozzle)
- Wet cooling—flow rate: 50/min (through external nozzle)</td></tr>
<tr><td>Nozzle diameters used to spray coolant for different environments</td><td colspan="9">Compressed air and MQL: Ø5 mm, wet: Ø 10 mm</td></tr>
</table>

Evaluation of Performance Measures of Tool Wear:

The performance metrics of tool wear, such as Tool Wear Rate (TWR) and Relative Wear Ratio (RWR), were identified in this experiment and evaluated as follows.

Evaluation of tool wear rate (TWR):

The tool wear rate is a critical parameter for turning operations involved in surface modification. The dimensional accuracy and surface quality of the turned product largely depend on electrode wear. Excessive tool wear negatively impacts machining performance due to arcing. Therefore, achieving an optimal tool wear rate is essential for effective surface modification. The cutting insert is cleaned with acetone before and after processing. The following formula is then used to calculate the Tool Wear Rate (TWR):

$$TWR = Wtb - Wta \ gm \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (=)$$

Were,
TWR = tool wear rate gm/min.
Wtb = weight of tool before machining in gm.
Wta = weight of tool after machining in gm.

An electronic balance (KERN) was used to weigh the tool before and after machining. The balance has a capacity of 200 grams and can accurately measure weights to 0.0001 grams, as shown in Figure 2.

Figure 2: Electronic balance.

Surface morphology

Microscopic images were captured based on the cross-sectional area of the sample. The samples were cut using a water-cooled abrasive blade, then cleaned with ethanol and acetone, and mounted under pressure. The samples were ground with silicon carbide abrasives, polished with a diamond suspension, and finely polished with colloidal silicon dioxide. Titanium samples were micro-etched with Kroll's reagent, while Co-Cr samples were etched accordingly. The micrographs, shown in Figure 3, were captured using an optical microscope (NIKON) at 100x magnification.

Figure 3: Optical Microscope.

Surface roughness (SR)

The rough surface of technical components acts as a stress concentrator, leading to the formation of cracks and corrosion, ultimately resulting in early component failure. Surface irregularities arising during processing are classified as rough surfaces. Surface roughness is defined as the deviation of a surface from its geometric mean. Higher deviations indicate a rough surface, while lower deviations signify a finished surface. The Ra value of the processed sample was measured using the “TIME®3221 Roughness Tester” shown in Figure 4. The cutting lengths were 0.08 mm, 0.25 mm, 0.8 mm, and 2.5 mm, chosen to measure average deviations. The final result for further analysis is the average of three measurements taken in different directions.

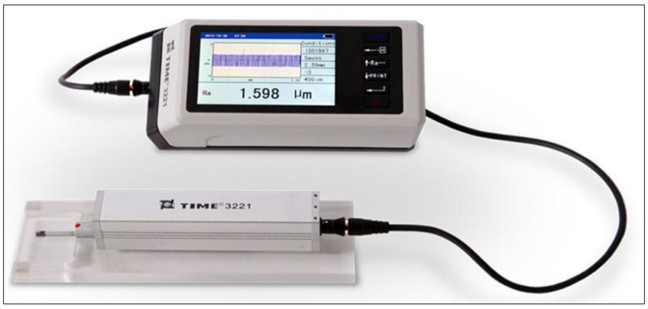


Figure 4: Surface Roughness Tester.

Microhardness (MH)
An increase in the microhardness of the work surface during machining is desired compared to the base material. The microhardness of the work material was measured before and after the experiment. Three measurements were taken at different locations, and the average was considered the final microhardness. The microhardness of the work surface was measured using a digital microhardness tester (Model No. 005 LEICA), as shown in Figure 5, under a load of 500 gf and a dwell time of 10 seconds. The sample processed with P/M electrodes exhibited higher microhardness compared to the electrolytic copper electrode.

Figure 5: LEICA Vickers Microhardness Tester.

Results and Discussion

Topography and Surface Roughness
The surface integrity of machined workpieces is crucial for ensuring machining efficiency and overall quality, as it is influenced by various factors during the machining process, with surface roughness (Ra) serving as a key indicator.

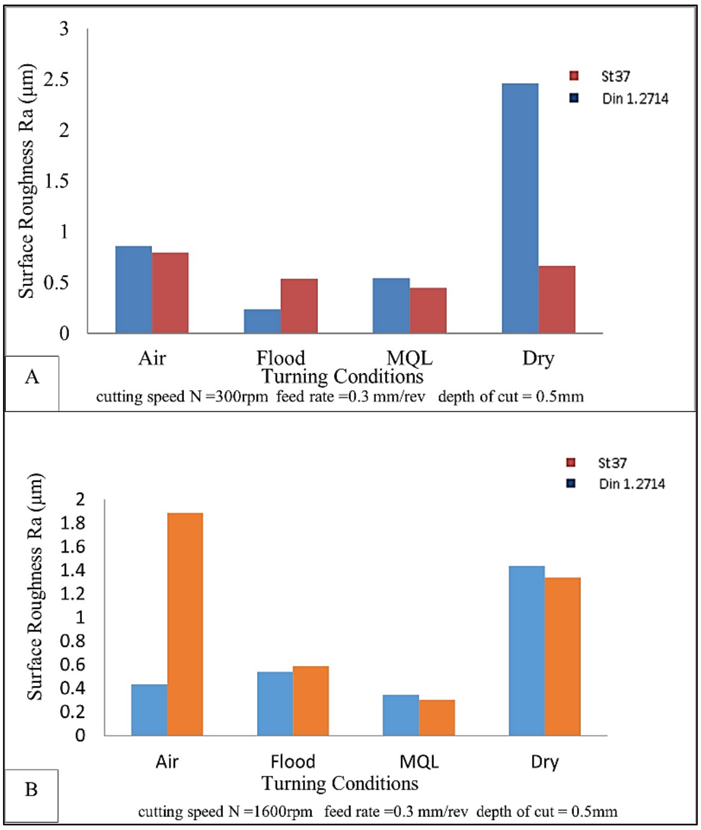


Figure 6: Variation in surface roughness under dry, flood cooling, MQL, and compressed air conditions a) at 300 rpm and b) at 1600 rpm.

Figure 6 shows that the Ra value remains relatively stable across various machining conditions. However, average values indicate that flood cooling and emulsion MQL conditions yield lower Ra values compared to other methods, with emulsion MQL achieving the lowest Ra value of 0.3 µm. Additionally, the average Ra values for the 1.2714 material at 1600 rpm are lower than those at 300 rpm, approximately 0.3 µm and 0.5 µm, respectively. Compressed air and dry conditions exhibit higher roughness levels. The superior surface quality obtained with emulsion MQL can be attributed to its effective lubrication, which reduces friction during the challenging chip-tool and tool-workpiece interactions. Figure 7 presents the surface topography of the machined workpiece under different machining conditions. The variation in surface texture is evident and corresponds to the Ra values shown in Figure 6. Emulsion MQL's effective lubrication reduces tool wear, resulting in a smoother surface. The surface topography achieved with emulsion MQL surpasses that of dry, flood, and air conditions.

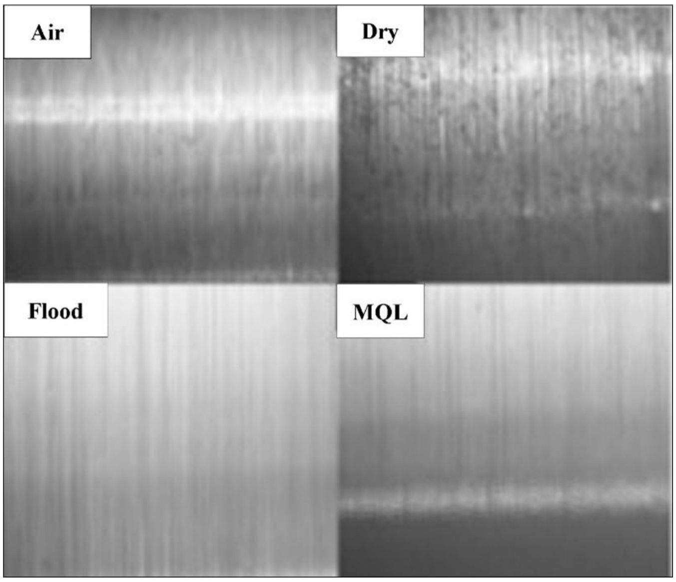


Figure 7: Surface topography of the machined workpiece under pressed air, dry, flood, and MQL conditions.

This study underscores the importance of coolant characteristics in the lubricant blend when combined with solid lubricants. Enhanced tribological properties at the tool-work and chip-tool interfaces help maintain the cutting-edge geometry and are associated with minimal flank wear when using MQL, as shown in Figure 6. Dry machining typically results in increased surface roughness due to excessive tool wear, while MQL can also lead to higher roughness because of insufficient lubrication during the machining process. Previous studies have demonstrated that MQL can create a stable and continuous lubricant film during machining, enhancing performance. Moreover, surface roughness is significantly influenced by the lubrication and cooling effects of fluids. When lubrication is predominant during machining, the material exhibits increased resistance to cutting forces, facilitating easier chip formation and improving surface quality.

Effect of Cutting Conditions on Tool Wear

Table 2 presents the final weight of the tool after machining hard steel (DIN 1.2714) workpieces under various cooling conditions. Figure 8 demonstrates the influence of tool flank wear on machining duration, with cutting speeds ranging from 80 to 260 m/min and feed rates varying between 0.06 and 0.26 mm/rev.

Table 2: Tool Wear Under Different Cutting Conditions.

Condition	Before Work wt.(gm)	Final wt.(gm)	Amount of Wear (gm)
Dry	4.06	4.0231	0.0369
Air	4.06	4.0515	0.0055
MQL	4.06	4.0598	0.0002
Flood	4.06	4.0575	0.0025

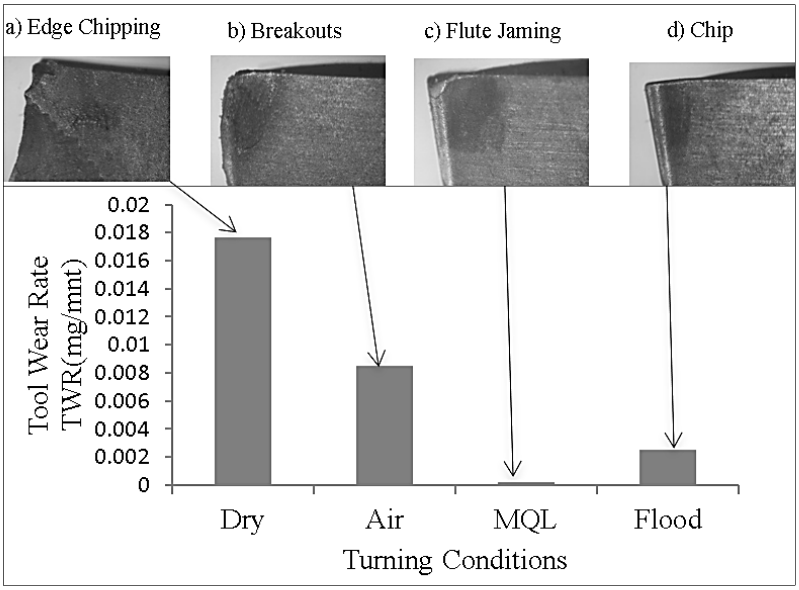


Figure 8: Tool Wear Under Various Conditions: a) Dry Turning, b) Compressed Air Turning, c) MQL Turning, and d) Flood Turning.

Figure 8 illustrates the variations in cutting conditions and recorded tool wear at the end of the processes. The dry machining approach exhibited the most significant tool wear, followed by compressed air machining. As expected, MQL machining resulted in the least tool wear, followed by the wet (oil-in-water) machining test. The dry machining test, which demonstrated considerable flank wear, was stopped after edge chipping occurred (Fig. 3a). Conversely, the compressed air and MQL tests had to be terminated while the lathe was in operation due to chips sticking in the flutes. The provided image shows the removed material (Fig. 3b). Despite ending the experiments, the wear on the tools' edges was quite noticeable.

Effect on chip formation and Chip morphology

Chip formation is a critical aspect of cutting technology. Figure 9 presents the results from the machining tests. Using compressed air and dry cooling, chip breakage occurred due to high friction between the workpiece and tool, as well as the reduced ductility of DIN 1.2714. Chips measuring between 7 and 10 mm in length and approximately 0.5 to 1 mm in diameter were observed, alongside smaller shiny pieces, as shown in Figures 10a and 10b. Traditional flood cooling produced long, yellowish chips due to the increased cutting temperature from the shearing mechanism (Figure 10d). When utilizing Minimum Quantity Lubrication (MQL) with an emulsion, chip breakage significantly improved, with similar chip diameters; however, most chips were longer, and smaller shiny chips were also observed (Figure 10c). In this context, cooling and lubrication work together to reduce friction and enhance chip formation during machining. The MQL cooling reduces friction and the ductility of the workpiece, while the emulsion further decreases friction and facilitates chip separation. These findings suggest that the MQL cooling-lubricating technique is the most effective in reducing chip breakage.

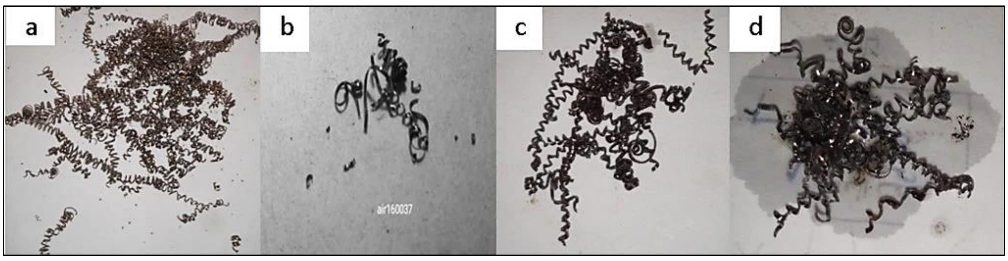


Figure 10: Chip formation under different cooling conditions: a) Dry, b) Compressed Air, c) MQL, and d) Flood.

Surface microhardness

Numerous factors in machining influence microhardness as a response parameter. The functionality of the material is affected by the amount and intensity of heat generated during machining. Therefore, an evaluation was conducted to assess how MQL impacts surface microhardness, with comparisons made to dry and flood cooling. Tests were carried out on DIN 1.2714 alloy steel, maintaining a hardness of 40 ± 5 HRC during the hardening process. Figure 11 illustrates the microhardness trend below the machined surface of the workpiece, under consistent machining parameters and selective lubrication. MQL showed increased microhardness (50 and 100 μm) under the machined surface compared to ductile tool steel. The MQL cutting regime resulted in a peak microhardness of 369.5 Hv.

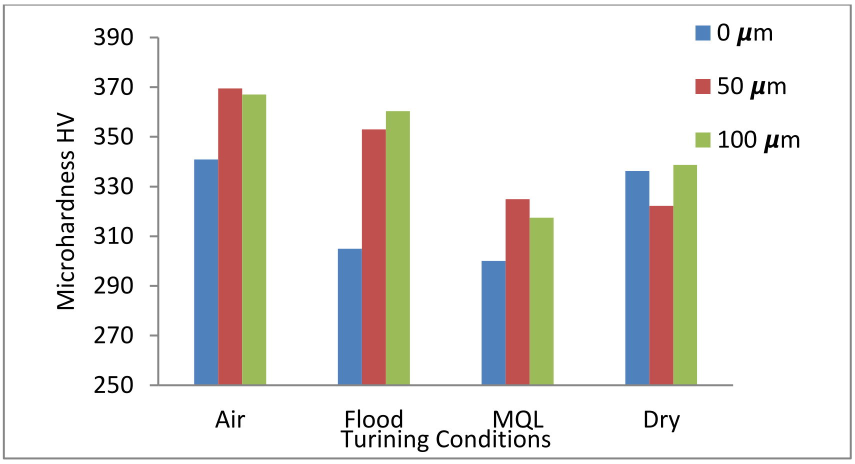


Figure 11: Variations in microhardness values below the machined surface during dry, flood cooling, MQL, and MQSL conditions.

Conclusion

This research evaluates various cutting condition methods in turning operations, comparing their impact on surface quality. Different lubrication methods were tested on cold work tool steel, including minimum quantity lubrication (MQL), compressed air, flood, and dry machining. The study uniquely assesses MQL's ability to improve surface quality, manage cutting temperatures, and predict tool deterioration. The findings show that MQL significantly enhances surface roughness compared to other methods, achieving the lowest Ra value of 0.3 μm. Cutting without coolant resulted in a surface roughness 2 μm higher than other conditions. Flood cooling, while effective in surface roughness, poses environmental concerns. Compressed air provided better surface quality than dry machining. Cooling methods during turning improve machining efficiency of hard tool steel, with MQL notably reducing flank wear. MQL's chilling effect lessened flank wear, while dry conditions showed adhesion and severe wear. MQL reduced wear mechanisms and formed continuous chips due to reduced friction. High cutting temperatures in dry environments prevented coarse-grained structures and hardening, while MQL increased material tensile strength and microhardness due to its chilling and lubrication effects.

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