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A review on the hard turning process under Minimum Quantity Lubrication condition

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Abstract
In this paper, a comprehensive review was made on the application of Minimum Quantity Lubrication (MQL) condition on the efficiency of the hard turning process. The main findings on the improvement in turning of unheat-treated materials and hard turning are specified. The results of the hard turning process are evaluated through surface quality, cutting forces, cutting temperature, and tool wear. These experimental results indicate that high cutting forces and cutting temperatures are still the major issues in hard turning under dry condition. The application of MQL technique provides the higher lubrication performance compared to dry, wet, and compressed air assisted conditions. The work also pointed out the necessity of using appropriate technology to improve the cooling effect of MQL, leading to enhance the hard turning efficiency.
Keywords: *hard turning; Minimum Quantity Lubrication; surface quality; cutting force; cutting temperature, tool wear*

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I. Introduction

Recently, hard machining technology has been widely studied and developed in the production practice. It is the precision machining process of materials with a hardness greater than 45 HRC, typically after they have undergone heat treatment [1]. This technique is used as an alternative or supplementary solution to the grinding process, particularly in the final stages of production, to achieve tight tolerances and excellent surface finishes. It includes operations such as hard turning, milling, and drilling performed on hardened materials like tool steels, bearing steels (e.g., AISI 52100), and superalloys such as Inconel or titanium alloys. The cutting tools used in hard machining are required to withstand extreme conditions and include such the materials as coated carbides, ceramics, cubic boron nitride (CBN), polycrystalline cubic boron nitride (PCBN), and so on [2].

One of the major advantages of the hard machining technique is its ability to support or replace the grinding, leading to shorten the set-up time, production cycles, improve the flexibility, and lower manufacturing costs. This technology also allows to be carried out under dry condition in many cases, reducing the environmental impact and dependency on coolants. Hard machining can achieve excellent surface finishes, sometimes comparable to grinding, with roughness values as low as R_a=0.2µm or smaller. However, the elimination of cutting fluids also presents challenges, such as rapid tool wear, the risk of surface damage (including micro-cracks or white layers), and difficulty maintaining dimensional accuracy under high cutting forces and temperatures [3].

Hard machining is widely used in industries such as automotive (for gears, shafts, and transmission components), aerospace (for engine and structural parts), tool and die making, and medical manufacturing. Recent developments in this field include the supplement of hard machining methods to grinding to improve the productivity and flexibility [4]. Despite its challenges, hard machining continues to grow in popularity as a flexible, efficient, and sustainable solution for manufacturing high-precision components from hard materials.

Among hard cutting processes, hard turning has been widely applied for finishing the hardened steels and tool steels. This method is performed on lathes using specialized cutting tools made from materials like cubic boron nitride (CBN), ceramics, or coated carbides. Hard turning is often employed as a cost-effective and efficient alternative to traditional grinding, especially for producing precision components like gears, bearings, and shafts. It offers several advantages, including faster processing times, the ability to perform dry machining (eliminating the need for coolant), and lower equipment costs. Additionally, it allows for flexibility in handling complex geometries [1]. However, hard turning also presents certain challenges, such as increased tool wear and the need for precise control to achieve high-quality surface finishes and tight tolerances. It is not suitable for all applications, particularly those requiring intricate internal features or extremely fine finishes [3]. Despite these limitations, hard turning has become a valuable technique in modern manufacturing, particularly in the automotive and aerospace industries.

In order to improve the hard turning performance while ensuring the sustainable characteristic of dry condition, Minimum Quantity Lubrication (MQL) is a lubrication technique that uses a very small amount of cutting fluid, typically just a few milliliters per hour, delivered directly to the cutting zone as the oil mist form [5]. Unlike traditional flood cooling methods that use large volumes of coolant, MQL aims to reduce both environmental impact and treatment costs of the used cutting fluids while still providing effective lubrication and cooling at the tool-workpiece interface. MQL is especially effective in high-speed and precision machining operations such as drilling, milling, and turning. It helps reduce friction and heat generation, which prolongs tool life and improves surface finish. The mist is usually a biodegradable oil or oil-water emulsion, delivered through specially designed nozzles or through the spindle in more advanced systems. Hence, the application of MQL technique for the hard turning process is an attractive research topic, and in this paper, a comprehensive review is made on the hard turning process under MQL condition.

II. Application of Minimum Quantity Lubrication in the turning process

Due to the high lubricating performance, Minimum Quantity Lubrication method is widely applied in turning the different types of materials before heat treatment. There have been many studies to prove the positive results. Hwang and Lee [5] investigated the turning process of AISI 1045 steel under wet and MQL conditions. They claimed that MQL technique exhibits the superior advantages over wet condition in lubrication efficiency and environmental issues. Lohar and Nanavaty [6] concluded that the cutting force reduced by 40%, cutting heat reduced by 36% and surface quality improved by 30% were reported under MQL condition when compared to dry and wet modes. Hadad and Sadeghi [7] also found the better surface quality and cutting force reduction under MQL environment when compared with dry and wet conditions in turning AISI 4140 steel. Stephenson et al. [8] studied the turning performance of Inconel 750. They pointed out that the improvement of tool life and material removal productivity by nearly 40% was noted with MQL condition when compared to wet cutting. Saini et al. [9] compared the dry and MQL turning processes of AISI 4340 steel. Based on the experimental results, MQL machining show beneficial effects compared to dry machining with the reduction of cutting forces by 17.07% and cutting heat by 6.72% at the tool tip. Table 1 summarized the study results on the influences of cooling lubrication conditions and workpiece material in the turning process.

***Table 1**. Summary of the results on the influences of cooling lubrication regime and workpiece material in turning process*

Reference and year	Cooling lubrication conditions	Workpiece material	Findings
Hwang and Lee [5] (2010)	Wet, MQL	AISI 1045 steel	MQL technique shows the superior advantages over wet condition in lubrication efficiency and environmental issues
Lohar and Nanavaty [6] (2013)	Dry, wet, and MQL	AISI 4340 alloy steel	Compared to dry and wet modes, cutting force reduced by 40%, cutting heat reduced by 36% and surface quality improved by 30% were reported under MQL condition.
Hadad and Sadeghi [7] (2013)	Dry, wet, and MQL	AISI 4140 steel	Turning with MQL mode gives better surface quality and reduces cutting forces when compared with dry and wet conditions.
Stephenson et al. [8] (2014)	Wet, MQL	Inconel 750	The improvement of tool life and material removal productivity by nearly 40% was noted with MQL condition when compared to wet cutting.
Saini et al. [9] (2014)	Dry, MQL	AISI 4340 steel	MQL machining show beneficial effects compared to dry machining with the reduction of cutting forces by 17.07% and cutting heat by 6.72% at the tool tip.

III. Application of Minimum Quantity Lubrication in the hard turning process

Recently, Minimum Quantity Lubrication method has been used in the hard turning process in order to improve the machining performance. Kumar and Ramamoorthy [10] studied the hard turning process of AISI 1045 hardened steel (45 HRC) under MQL condition. The obtained results indicated that the hard turning performance under MQL condition was better than that in dry turning and conventional wet turning on the basis of parameters such as cutting force, temperature and surface finish. Tasdelen et al. [11] compared the different cooling lubrication conditions (dry, MQL and compressed air assisted cutting) in the hard turning performance of hardened steel. The authors concluded that under MQL and compressed air conditions, the lower contact length was reported when compared to dry cutting. On the other hand, MQL and compressed air contributed to reduce the total natural contact length due to the better cooling lubrication effects. Beatrice et al. [12] conducted the hard turning process of AISI H13 steel (45 HRC) and used Artificial Neural Network (ANN) model to predict the surface roughness and cutting temperature. The obtained results showed the good agreements between the predicted values and the experimental data. The application of MQL technique promoted green environment by minimizing the industrial hazard due to of harmful aerosols and usage of large quantity of cutting fluid. Kumar et al. [13] investigated the effects of dry, wet, and MQL conditions on hard turning of hardened AISI 4340 steel. Based on the results, the MQL environment helps improved the surface quality as compared to dry and wet conditions, thereby enhancing the machining performance. Das et al. [14] made a study on hard turning of AISI 4340 alloy steel under water soluble coolant, compressed air assisted cutting, and MQL conditions. The findings revealed that MQL condition decreased the tool wear rate more effectively than water soluble coolant and compressed air assisted cutting conditions. The generated chips with least serrations were reported in the case of MQL, followed by water soluble coolant and finally the compressed air assisted cutting. Table 2 summarized the study results on the influences of cooling lubrication conditions and workpiece material in MQL hard turning.

Table 2. *Summary of the results on the influences of cooling lubrication regime and workpiece material in MQL hard turning*

Reference and year	Cooling lubrication conditions	Workpiece material	Findings
Kumar and Ramamoorthy [10] (2007)	MQL	AISI 1045 hardened steel (45 HRC)	Hard turning performance under MQL condition was found to be superior to that compared to dry turning and conventional wet turning on the basis of parameters such as cutting force, temperature and surface finish
Tasdelen et al. [11] (2008)	Dry, MQL and compressed air assisted cutting	AISI 1045 steel (45 HRC)	MQL and compressed air decrease the contact length compared to dry cutting. MQL and compressed air lower the total natural contact length due to the better cooling lubrication effects
Beatrice et al. [12] 2014	MQL	AISI H13 steel (45 HRC)	Artificial Neural Network (ANN) model can be used to predict the surface roughness and cutting temperature. MQL technique promoted green environment by minimizing the industrial hazard due to of harmful aerosols and usage of large quantity of cutting fluid
Kumar et al. [13] (2017)	Dry, wet, and MQL	Hardened AISI 4340 steel	MQL condition improves the surface quality as compared to dry and wet conditions in turning
Das et al. [14] (2020)	water soluble coolant, compressed air assisted cutting, and MQL	AISI 4340 alloy steel	MQL condition reduces the tool wear more effectively than water soluble coolant and compressed air assisted cutting conditions. The chips with least serrations were reported in the case of MQL, followed by water soluble coolant and finally the compressed air assisted cutting.

IV. Discussion

In addition to the studies on MQL turning of unheat-treated materials, the work on MQL-assisted hard turning has been growing steadily, driven by the need for sustainable and efficient machining processes. The adoption of biodegradable oils like vegetable oils has been the eco-friendly alternatives to conventional cutting fluids in MQL-assisted hard turning. The summary of the comparative studies on MQL, dry, flood cooling, and compressed air assisted methods was conducted to evaluate performance metrics such as surface roughness, tool wear, cutting forces, and cutting temperature, highlighting the advantages of MQL in certain applications.

V. Conclusion

In this article, the application of Minimum Quantity Lubrication (MQL) condition was studied to specify the effects on the efficiency in turning of unheat-treated materials and hard turning. The higher lubricating effects were reported in turning of unheat-treated materials, leading to achieve the better surface quality and lower cutting forces and cutting heat. Through the comparative studies with dry, wet, and compressed air assisted conditions, the advantages of MQL were determined. Also, the works on the application of Minimum Quantity Lubrication (MQL) for hard turning are still limited, so the necessity of using appropriate technology to improve the cooling effect of MQL technique [15] is needed to develop and study in order to enhance the hard turning efficiency.

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