

Experimental Comparison of Flood Cooling, Canola Oil-Based MQL, and Dry Hard Milling of 9CrSi Steel

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Abstract—

Surface roughness is an important indicator of machining quality, particularly in the hard milling of hardened tool steels. This study experimentally compares the surface roughness of 9CrSi steel with a hardness of 50 HRC under three machining conditions: flood cooling with an emulsion, minimum quantity lubrication (MQL) using canola oil, and dry milling. The experiments were conducted on a MAZAK VCS-530C machining center using a 10 mm TiAlN-coated milling cutter. The cutting speed, feed per tooth, and depth of cut were maintained at 80 m/min, 0.02 mm/tooth, and 0.4 mm, respectively. The measured surface roughness values were 0.245 μm under flood cooling, 0.260 μm under MQL, and 0.310 μm under dry milling. Compared with dry milling, the surface roughness was reduced by approximately 21.0% with flood cooling and 16.1% with canola oil-based MQL. Flood cooling produced the lowest measured surface roughness, while MQL also improved the surface finish compared with dry milling. These findings provide an experimental comparison of three cooling and lubrication strategies for hard milling of 9CrSi steel under the investigated cutting conditions

Keywords—9CrSi steel; hard milling; surface roughness; minimum quantity lubrication; canola oil; flood cooling; dry machining.

I. INTRODUCTION

Hard milling is an important machining process for manufacturing components from hardened tool steels used in molds, dies, and other industrial applications. Compared with conventional milling of softer materials, hard milling presents greater challenges due to the high hardness of the workpiece, increased cutting resistance, and potential tool wear[1], [2]. Surface roughness is one of the key indicators of machining quality because it affects the functional performance and surface integrity of the machined components. Therefore, improving surface finish while maintaining stable machining conditions remains an important objective in hard milling[3], [4], [5].

Cooling and lubrication conditions play an important role in machining performance. Flood cooling is widely used to provide cooling and lubrication at the cutting zone, while dry machining eliminates the use of cutting fluids during the machining process. However, these two approaches have different advantages and limitations in terms of heat removal, friction reduction, fluid consumption, and environmental considerations[6], [7], [8]. Minimum quantity lubrication (MQL) has attracted considerable attention as an alternative approach because it delivers a small amount of lubricant, usually in the form of an aerosol, to the cutting zone[9], [10], [11]. Previous studies have discussed the principles, benefits, and limitations of MQL in machining. Research has also demonstrated that MQL can influence cutting temperature, chip formation, and dimensional accuracy, indicating its potential to improve machining performance under suitable conditions.

Several studies have investigated the application of MQL in hard milling and the machining of hardened steels. Do and Hsu[12] optimized MQL conditions and cutting parameters in the hard milling of AISI H13 steel. Nguyen and Hsu[13] investigated cutting forces and material removal rate during the hard milling of SKD61 alloy steel. Other studies have focused on surface roughness and the optimization of

machining parameters in hardened SKD11 and SKD61 steels under MQL or nanofluid-MQL conditions[9], [10], [14]. In addition, Nguyen et al[15]. investigated the effects of nanofluid-MQL parameters on surface roughness during the milling of hardened 9CrSi steel. These studies provide a useful basis for understanding the role of lubrication conditions and process parameters in hard milling. Nevertheless, the use of nanoparticle-enhanced lubricants and parameter optimization represents a different approach from a direct comparison of conventional flood cooling, vegetable-oil-based MQL, and dry machining under identical cutting conditions.

Vegetable oils have potential as machining lubricants because of their lubricating properties and their potential environmental advantages[16], [17], [18]. Canola oil can therefore be considered as a base lubricant for MQL applications. Comparing canola oil-based MQL with flood cooling and dry machining under the same cutting conditions can provide practical information about their relative performance in terms of surface roughness. Such a comparison is particularly relevant to hardened 9CrSi steel, for which the surface finish obtained under different cooling and lubrication conditions is of interest in industrial machining. To make the comparison meaningful, the cutting speed, feed per tooth, depth of cut, workpiece hardness, and cutting tool should be maintained consistently across the three machining conditions.

Accordingly, this study experimentally compares surface roughness in the hard milling of 9CrSi steel with a hardness of 50 HRC under three conditions: flood cooling using an emulsion, minimum quantity lubrication using canola oil, and dry milling. The experiments are performed on a MAZAK VCS-530C machining center using a 10 mm TiAlN-coated milling cutter at a cutting speed of 80 m/min, a feed per tooth of 0.02 mm/tooth, and a depth of cut of 0.4 mm. The surface roughness values obtained under the three conditions are compared to identify the condition associated with the lowest measured roughness and to quantify the differences between the machining strategies. The findings provide a straightforward experimental reference for selecting cooling

and lubrication conditions for hard milling of 9CrSi steel under the investigated cutting parameters.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Experimental Setup

The experiments were conducted on a MAZAK VCS-530C machining center using 9CrSi steel with a hardness of 50 HRC. A 10 mm diameter TiAlN-coated milling cutter was used. The cutting speed, feed per tooth, and depth of cut were fixed at 80 m/min, 0.02 mm/tooth, and 0.4 mm, respectively.

B. Cooling and Lubrication Conditions

Three machining conditions were compared: flood cooling using an emulsion, minimum quantity lubrication (MQL) using canola oil, and dry milling without externally supplied cutting fluid. The workpiece material, cutting tool, and cutting parameters were kept consistent across all conditions. Three independent milling trials were performed for each condition.

C. Surface Roughness Measurement

Surface roughness was evaluated using the arithmetic mean roughness parameter (R_a). Multiple measurements were taken on the machined surface of each trial to obtain a representative value. The results were compared directly to identify the differences in surface roughness among the three machining conditions. The relative reduction in R_a was calculated using dry milling as the reference condition.

III. RESULTS AND DISCUSSION

A. Comparison of Surface Roughness

The surface roughness results obtained under the three machining conditions are presented in Table 1 and Figure 1.

TABLE I. SURFACE ROUGHNESS UNDER DIFFERENT COOLING AND LUBRICATION CONDITIONS

Machining condition	Surface roughness, R_a (μm)
Flood cooling	0.245
Canola oil-based MQL	0.26
Dry milling	0.31

The results show that flood cooling produced the lowest surface roughness, with a R_a value of 0.245 μm . Canola oil-based MQL resulted in a slightly higher value of 0.260 μm , while dry milling produced the highest roughness of 0.310 μm .

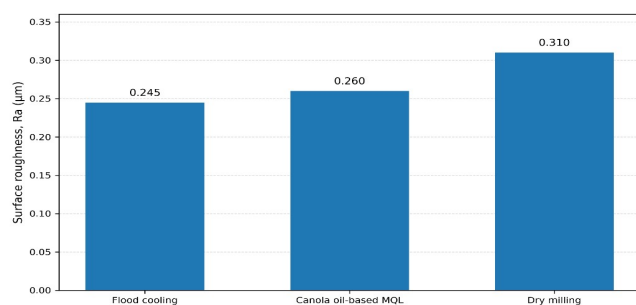


Fig. 1. Comparison of surface roughness under flood cooling, canola oil-based MQL, and dry milling conditions.

Compared with dry milling, flood cooling reduced R_a by approximately 21.0%, whereas canola oil-based MQL reduced R_a by approximately 16.1%. The surface roughness obtained with flood cooling was approximately 5.8% lower than that obtained with MQL.

B. Discussion

The lower surface roughness obtained under flood cooling may be associated with its cooling and lubrication capabilities, which can help reduce friction and limit heat accumulation in the machining zone. Canola oil-based MQL also produced a smoother surface than dry milling, potentially because the supplied lubricant reduced friction at the tool-workpiece interface.

Under dry conditions, the absence of an externally supplied cutting fluid may contribute to increased friction and thermal loading, potentially affecting the machined surface finish. However, these mechanisms were not directly measured in the present study and should therefore be regarded as possible explanations.

Overall, flood cooling provided the best surface finish among the three conditions investigated. Nevertheless, canola oil-based MQL also improved the measured surface roughness compared with dry milling, indicating its potential as an alternative lubrication approach for hard milling of 9CrSi steel under the selected cutting parameters.

IV. CONCLUSIONS

This study experimentally compared surface roughness in the hard milling of 9CrSi steel with a hardness of 50 HRC under flood cooling, canola oil-based MQL, and dry milling. The main conclusions are as follows:

- Flood cooling produced the lowest surface roughness, with a R_a value of 0.245 μm , followed by canola oil-based MQL at 0.260 μm and dry milling at 0.310 μm .
- Compared with dry milling, flood cooling and canola oil-based MQL reduced R_a by approximately 21.0% and 16.1%, respectively.
- Canola oil-based MQL provided a better surface finish than dry milling and may be a practical alternative when reducing lubricant consumption is a consideration. However, further investigation is required to evaluate its overall environmental and economic benefits.

Under the investigated cutting conditions, flood cooling provided the best surface finish, while canola oil-based MQL also demonstrated potential for improving surface quality in hard milling of 9CrSi steel.

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