Influence of MQL Lubricant Type on Surface Roughness in Hard Milling of 9CrSi Steel

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Abstract

The selection of lubricant medium in minimum quantity lubrication (MQL) can affect the surface quality achieved when machining hardened steels. This work examines the surface roughness produced during hard milling of 9CrSi steel (50 HRC) when three different MQL media are applied: canola oil, water-based emulsion, and mineral oil. Milling was performed on a MAZAK VCS-530C machining center using a 10 mm diameter TiAlN-coated end mill. The cutting speed, feed per tooth, and axial depth of cut were maintained at 100 m/min, 0.02 mm/tooth, and 0.3 mm, respectively. Surface roughness was measured using a Mitutoyo SJ-210 tester, with three Ra readings recorded for each lubricant medium. The mean Ra values were 0.2363 µm for canola oil, 0.3160 µm for emulsion, and 0.3610 µm for mineral oil. Under the tested conditions, canola oil produced the lowest mean roughness, corresponding to reductions of 25.2% and 34.5% relative to emulsion and mineral oil, respectively. The findings indicate that lubricant-medium selection is an important consideration in MQL-assisted hard milling of 9CrSi steel.

*Keywords—**9CrSi steel; hard milling; minimum quantity lubrication; canola oil; mineral oil; emulsion; surface roughness.***

I. INTRODUCTION

Machining hardened tool steels is often required when producing dies, molds, and components that must retain dimensional accuracy and surface integrity. In hard milling, the high workpiece hardness and intermittent nature of the cutting process place demanding conditions on the cutting edge. The resulting surface texture is influenced not only by cutting speed, feed, tool geometry, and tool condition, but also by the way heat and friction are managed in the cutting zone [1], [2], [3], [4], [5].

Minimum quantity lubrication is one approach to supplying lubricant during machining while limiting fluid consumption. In MQL, a small quantity of liquid is carried by compressed air and directed toward the cutting region. Its performance therefore depends on both the delivery conditions and the physical and chemical properties of the selected fluid [6], [7], [8]. Previous work has examined MQL in hard milling, including studies on hardened AISI H13, SKD11, and SKD61 steels, and has considered surface roughness, cutting forces, material removal rate, and parameter optimization[5], [9], [10], [11].

The lubricant itself may be particularly important when the amount of fluid delivered is small. Vegetable oils contain triglyceride molecules with polar ester groups and fatty-acid chains, properties that may promote interaction with metallic surfaces and support boundary lubrication. Mineral oils have a different hydrocarbon-based composition, while water-based emulsions combine a water phase with dispersed oil and, depending on formulation, other additives. The potential benefits and limitations of vegetable-oil lubricants and MQL systems have been discussed in previous machining studies [12], [13], [14].

Although these lubricant families are used in machining, their relative surface-finish performance cannot be inferred from fluid category alone. It depends on the actual formulations, delivery settings, tool–workpiece system, and cutting conditions. A direct experimental assessment under a common MQL delivery approach is therefore useful. In this study, the arithmetic mean roughness obtained when milling 9CrSi steel at 50 HRC is evaluated using canola oil, emulsion, and mineral oil as the MQL media. The cutting parameters and machine-tool arrangement are held constant so that the observed differences can be discussed in relation to the tested lubricant media.

II. EXPERIMENTAL PROCEDURE

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 end mill was employed. The cutting speed (Vc), feed per tooth (fz), and axial depth of cut (ap) were fixed at 100 m/min, 0.02 mm/tooth, and 0.3 mm, respectively. Three MQL media were investigated: canola oil, water-based emulsion, and mineral oil. Each medium was delivered to the cutting zone using the MQL system; hence, the study compares lubricant media under MQL application rather than comparing MQL with flood cooling. The MQL delivery settings, including liquid flow rate, compressed-air pressure, nozzle orientation, and nozzle-to-cutting-zone distance, should be reported from the actual experimental records because these values were not specified in the information provided for this manuscript. For the emulsion, its concentration and product formulation should also be stated. Surface roughness was measured with a Mitutoyo SJ-210 tester. Three Ra readings were supplied for each MQL medium. The mean and sample standard deviation were calculated from these three recorded values. The present study focuses on Ra; cutting temperature, cutting force, and tool wear were not measured or included in the supplied dataset.

III. RESULTS AND DISCUSSION

A. Measured Surface Roughness

The individual Ra readings and the corresponding group means are presented in Table 1. The three readings for each condition are retained in the table to show the spread of the measured

values; the mean and sample standard deviation are also reported.

TABLE I. SURFACE ROUGHNESS RESULTS FOR THE THREE MQL MEDIA

MQL medium	Ra readings (µm)	Mean ± SD (µm)
Canola oil	0.225; 0.238; 0.246	0.2363 ± 0.0106
Emulsion	0.310; 0.305; 0.333	0.3160 ± 0.0149
Mineral oil	0.352; 0.350; 0.381	0.3610 ± 0.0173

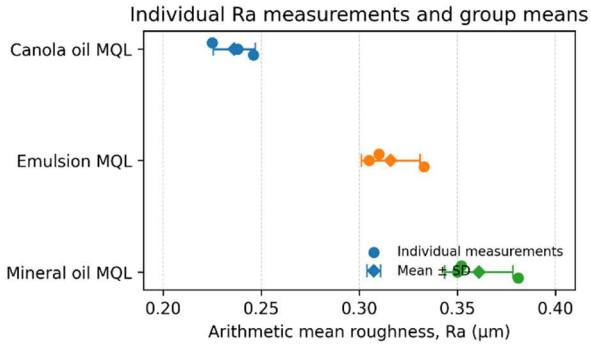

Fig. 1. Individual Ra readings are shown as circles; diamonds indicate the mean, and whiskers indicate ±1 sample standard deviation.

The mean Ra was lowest with canola oil MQL (0.2363 µm), followed by emulsion MQL (0.3160 µm) and mineral-oil MQL (0.3610 µm). The canola-oil condition therefore yielded a mean Ra 25.2% lower than the emulsion condition and 34.5% lower than the mineral-oil condition. The emulsion condition yielded a mean Ra 12.5% lower than mineral oil. The individual readings follow the same overall ordering, although the small number of readings limits the strength of any population-level inference.

B. Interpretation of the Results

The surface-finish advantage observed with canola oil may be related to its molecular structure. Canola oil is composed mainly of triglycerides containing fatty-acid chains and ester groups. The polar character of these molecules may encourage adsorption or interaction at metallic surfaces and support the formation of a boundary lubricating layer. Such a layer could reduce friction and adhesive interaction near the cutting interface, which may contribute to lower Ra. Vegetable oils have been investigated for their lubrication potential in machining and related processes [16]–[18]. Nevertheless, the present work did not directly characterize the lubricating film, friction coefficient, or tool wear; the proposed mechanism should therefore be treated as an interpretation rather than a directly verified finding.

The emulsion-based MQL condition produced an intermediate surface roughness. Its water phase may contribute to heat absorption, while the dispersed oil phase and any formulation additives may provide lubrication. The balance between these functions depends on emulsion concentration, formulation, droplet formation, and the ability of the aerosol to reach the cutting interface. Since the emulsion was supplied by MQL, its behavior should be discussed as emulsion delivered in an MQL stream, not as conventional high-volume flood cooling.

Mineral-oil MQL produced the highest mean Ra among the three tested media. This result may reflect the particular properties of the mineral-oil product used, including its viscosity and additive package, together with its interaction with the cutting zone under the selected MQL settings. It would be too broad to conclude that mineral oils are intrinsically less effective than vegetable oils, because commercial mineral lubricants differ in formulation and may contain additives intended to improve boundary or extreme-pressure performance. The conclusion supported by the current dataset is limited to the three media and the cutting conditions examined.

IV. CONCLUSIONS

This work investigated surface roughness during hard milling of 9CrSi steel (50 HRC) using three MQL media. Within the limits of the tested cutting conditions and the measurements supplied, the following findings were obtained:

- Canola oil MQL produced the lowest mean Ra (0.2363 µm), compared with 0.3160 µm for emulsion MQL and 0.3610 µm for mineral-oil MQL.
- The mean Ra obtained with canola oil was 25.2% lower than that obtained with emulsion and 34.5% lower than that obtained with mineral oil.
- Emulsion MQL gave an intermediate mean Ra, while mineral-oil MQL produced the highest mean Ra in the present tests.

These results identify canola oil as the most favorable of the three tested media in terms of measured surface roughness. Further experiments should document and control the MQL delivery parameters and should include additional responses, such as tool wear and cutting temperature, to clarify the mechanisms responsible for the observed differences.

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