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A study on effects of cutting parameters on surface roughness in hard milling of AISI D2 tool steel under pure and SiC nanofluid MQL environment

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Abstract

The presented work aims to investigatethe influencesof MQL with/without SiC nano cutting oil,cutting speed, and feed rate on the surface roughness R_a in the hard milling process of AISI D2 tool steel (58 ÷ 60 HRC). The influences of input parameters were studied by usingthe factorial experimental design. The obtained experimental results indicated that feed rate has the greatest influence, followed by cooling/lubricating (C/L) mode and cutting speed, and emphasizing the importance of selecting low feed rates and appropriate lubrication conditions to attain the smaller surface roughness values. Additionally, while feed rate is the most influential factor, the combined effects of cutting speed and lubrication conditions must be considered simultaneously to achieve the better machining outputs.

***Keywords:** Hard milling;nanofluid; SiC nanoparticle; MQL; cutting speed; feed rate; surface roughness;*

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I. Introduction

In the last few decades, hard machining has emerged as a critical manufacturing approach in response to the growing demand for high-performance components with superior dimensional accuracy, surface integrity, and reduced production costs [1]. Traditional machining of hardened materials often requires multiple steps, including rough machining, heat treatment, and subsequent grinding or finishing processes. These additional stages increase production time, cost, and complexity [2]. In contrast, hard machining enables the direct cutting of materials with hardness typically above 45 HRC, allowing for the consolidation of processes into a single setup. The increasing use of advanced materials such as hardened steels, superalloys, and tool steels in industries like aerospace, automotive, and die–mold manufacturing has further accelerated the need for efficient hard machining techniques [3]. Manufacturers are continuously seeking methods that can enhance productivity while maintaining or improving product quality. Hard machining offers advantages such as reduced machining time, elimination of coolant in some cases (dry machining), improved flexibility, and the ability to achieve high surface finish comparable to grinding. Moreover, advancements in cutting tool materials, such as coated carbide, cubic boron nitride (CBN) and ceramic tools, along with improved machine tool rigidity and stability, have made hard machining more feasible and reliable. As a result, hard machining is increasingly recognized as a sustainable and cost-effective alternative to conventional finishing processes, driving its adoption in modern manufacturing systems [4].

In recent years, the increasing demand for high-precision and complex-shaped products has significantly raised the requirements for mold manufacturing. Manufacturers are under pressure to reduce production time and cost while maintaining superior quality. This has led to the adoption of advanced technologies such as CAD/CAM systems, high-speed machining (HSM), and hard machining processes, which allow for greater efficiency and reduced reliance on traditional finishing methods like grinding and polishing.

AISI D2 tool steel is widely used in mold manufacturing due to its excellent combination of high hardness, wear resistance, and dimensional stability. As a high-carbon, high-chromium cold work tool steel, AISI D2 typically achieves hardness values in the range of 55–62 HRC after heat treatment, making it particularly suitable for applications that involve severe abrasive wear and high mechanical stress [5]. These properties make it an ideal material for producing molds that require long service life and consistent performance under demanding operating conditions.In mold production, AISI D2 is commonly applied in the fabrication of injection molds, die casting dies, and forming tools where resistance to wear and deformation is critical. Its high chromium content leads to the formation of hard carbide particles, which significantly enhance its wear resistance. This characteristic is especially beneficial in mold cavities and cores that are exposed to repeated friction, high pressure, and contact with hard or abrasive materials such as reinforced plastics or metal powders.Moreover, AISI D2 tool steel exhibits good dimensional stability during heat treatment, minimizing distortion and ensuring that tight tolerances can be maintained in complex mold geometries. This is a crucial factor in precision mold manufacturing, where even slight dimensional deviations can affect the quality of the final product. Additionally, its relatively good compressive strength allows it to withstand high clamping forces and cyclic loading conditions without premature failure.Nevertheless, due to its high hardness and abrasion resistance, AISI D2 is considered a difficult-to-cut material, particularly in the hardened state [5]. High cutting heat and cutting forces often generated in hard machining processes negatively affect the machined surface quality and tool life. It is necessary to adopt the advanced cooling lubrication methods to achieve the required surface finish and dimensional accuracy while maintaining reasonable tool life.Minimum Quantity Lubrication (MQL) techniquehas been considered as a promising method to introduce the superior lubrication effect on the contact zones while the cutting oil is consumed with a very small amount [6,7]. The low cooling effects resulted from MQL method are the main drawback, which makes its effectivenessin hard machining limited, so the additives of nanoparticles in the based oil used for MQL system is the appropriate solution [8]. The improvement in cooling and lubricating performance has been proven, leading to the enhancement of machining efficiency [8,9]. However, there is a little information on the application of SiC nano cutting oil to MQL technique in hard milling of AISI D2 tool steel [11,12]. Accordingly, the authors made a study on the effects of nano cutting oil, cutting speed, and feed rate on the surface roughness in milling AISI D2 tool steel (58÷60HRC).

II. Methodology

The setup of experimental devices is shown in Figure 1.Vertical Center SMART 530C (Mazak, Japan) was used to conduct the hard milling trials. AISI D2 tool steel samples were hardened to reach the hardness values of 58 ÷ 60 HRC. The chemical composition and mechanical properties of AISI D2 tool steel are given in Tables 1, 2.The Mitutoyo SJ-210 surface roughness tester was used to measure the surface roughness $R_a$values after each cut. The factorialexperimental design was used to investigate the effects of input variables (cooling/lubricating mode, cutting speed, and feed rate) on surface roughness R_a. The input factorswith theirlevels are given in Table 3.

Table 1. Chemical composition of AISI D2 tool steel

Element	C		Mn		P	S	Si		Cr		V		Mo	
Weight (%)	1.4	1.6	0.1	0.6	0.03	0.03	0.1	0.6	11	13	0.5	1.1	0.7	1.2

Table 2. Mechanical Properties of AISI D2 tool steel

Mechanical Properties	Metric	Imperial
Hardness, Knoop (converted from Rockwell C hardness)	769	769
Hardness, Rockwell C	62	62
Hardness, Vickers	748	748
Izod impact unnotched	77.0 J	56.8 ft-lb
Poisson's ratio	0.27-0.30	0.27-0.30
Elastic modulus	190-210 GPa	27557-30457 ksi

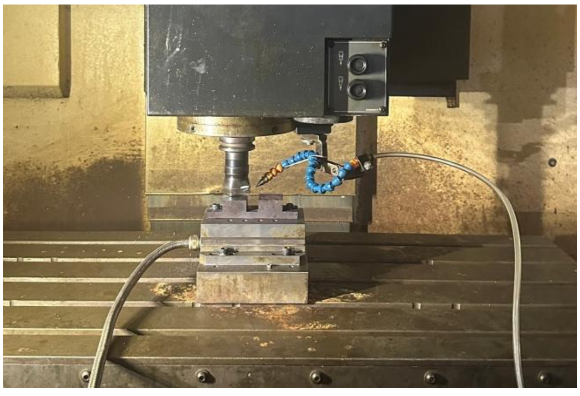

Figure 1. Device set up for hard milling experiments

Table 3. Input variables and their levels

Input parameters	Low level/Type	High level/Type	Output parameter
Cooling/Lubricating mode	MQL	SiC (0.3%) MQL	Surface roughness R_a (μm)
Cutting speed (m/min)	110	150	
Feed rate (mm/tooth)	0.01	0.05	

3.Results and discussion

The hard milling experiments were conducted by following the factorialexperimental matrix. The ANOVA resultsof the effects on surface roughness $R_a$are shownin Table 4. The ANOVA results indicate that the developed model is highly significant, with an F-value of 94.47 and a P-value of 0.000, confirming that the selected factors effectively explain the variation in surface roughness R_a. The block effect is not statistically significant (P = 0.229), suggesting that experimental noise between blocks does not influence the response. Among the linear terms, all factors are highly significant (P = 0.000), with feed rate exhibiting the strongest influence (F = 474.25), followed by the cooling/lubricating mode (C/L mode) (F = 214.58) and cutting speed (F = 87.89). This indicates that feed rate is the dominant parameter governing surface roughness, while the choice of cooling/lubrication strategy also plays a critical role, likely due to its impact on cutting temperature, tool wear, and chip formation. Regarding interaction effects, the interaction between cutting speed and feed rate (V × f) and the three-way interaction (C/L × V × f) are highly significant (P = 0.000), while the interaction between C/L mode and cutting speed is also significant (P = 0.016). In contrast, the interaction between C/L mode and feed rate is not significant (P = 0.394), indicating that the effect of feed rate is relatively independent of the lubrication condition. The low error value further demonstrates good model accuracy and experimental consistency. Overall, the results suggest that optimizing surface roughness requires simultaneous consideration of multiple parameters, particularly feed rate, cooling/lubrication mode, and their interactions with cutting speed.

Table 4. ANOVA results of the effects on surface roughness R_a

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.014859	0.001651	94.47	0.000
Blocks	2	0.000057	0.000029	1.64	0.229
Linear	3	0.013574	0.004525	258.91	0.000
C/L mode	1	0.003750	0.003750	214.58	0.000
V (m/min)	1	0.001536	0.001536	87.89	0.000
f (mm/tooth)	1	0.008288	0.008288	474.25	0.000
2-Way Interactions	3	0.000686	0.000229	13.08	0.000
C/L mode*V (m/min)	1	0.000131	0.000131	7.48	0.016
C/L mode*f (mm/tooth)	1	0.000014	0.000014	0.77	0.394
V (m/min)*f (mm/tooth)	1	0.000542	0.000542	30.99	0.000
3-Way Interactions	1	0.000542	0.000542	30.99	0.000
C/L mode*V (m/min)*f (mm/tooth)	1	0.000542	0.000542	30.99	0.000
Error	14	0.000245	0.000017		
Total	23	0.015103			

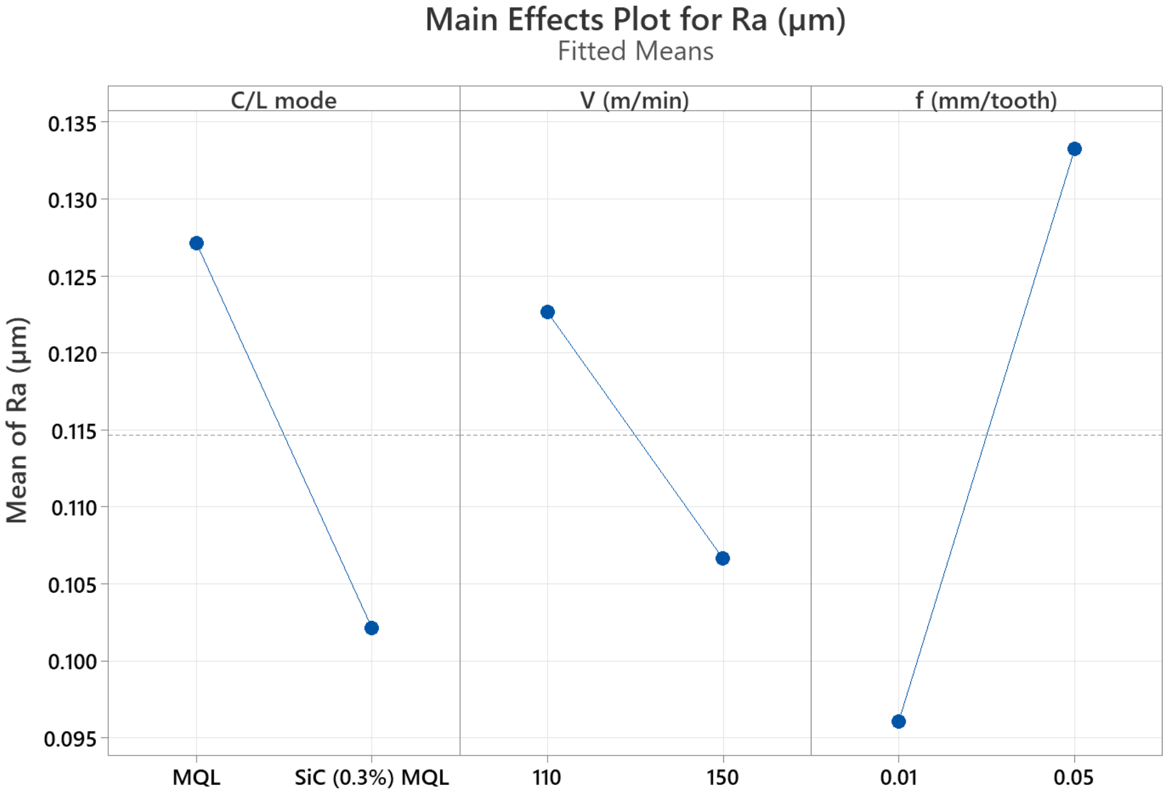

Figure 2. Main effects of input parameters on surface roughness R_a

The main effects in Figure 2 illustrate the influence of cooling/lubricating (C/L) mode, cutting speed, and feed rate on the surface roughness R_a. It can be observed that the C/L mode has a noticeable effect, as the use of SiC (0.3%) MQL results in a lower surface roughness compared to conventional MQL, indicating improved lubrication and cooling performance. For cutting speed, the growth of the cutting speed from 110 to 150 m/min leads to reduce R_a, suggesting that higher cutting speeds contribute to better surface finish. In contrast, feed rate exhibits the most significant effect on surface roughness, as increasing the feed rate from 0.01 to 0.05 mm/tooth causes a sharp rise in Ra. This steep slope confirms that feed rate is the dominant factor affecting surface quality. The trends in the main effects plot are consistent with the ANOVA results in Table 4, highlighting that feed rate has the greatest influence, followed by C/L mode and cutting speed, and emphasizing the importance of selecting low feed rates and appropriate lubrication conditions to achieve the smallervalues of surface roughness.

The interaction plots in Figure 3 provide further insight into how the interaction effects of cooling/lubricating (C/L) mode, cutting speed, and feed rate on surface roughness R_a. For the interaction between C/L mode and V, the lines are not perfectly parallel, indicating a significant interaction effect. Specifically, increasing cutting speed reduces R_a for both lubrication modes, but the reduction is more pronounced under conventional MQL than SiC (0.3%) MQL, suggesting that the effectiveness of cutting speed depends on the lubrication condition. For the interaction between C/L mode and feed rate, the lines are nearly parallel, indicating a weak or insignificant interaction, which aligns with the ANOVA results; although SiC (0.3%) MQL consistently produces lower surface roughness than MQL, the effect of feed rate remains dominant and relatively independent of the lubrication method. In contrast, the interaction between cutting speed and feed rate shows clearly non-parallel lines, confirming a strong interaction effect. At a low feed rate (0.01 mm/tooth), increasing cutting speed slightly improves surface finish, whereas at a high feed rate (0.05 mm/tooth), the reduction in R_a with growing cutting speed is much more significant. Furthermore, the interaction plots confirm that while feed rate is the most influential factor, the combined effects of cutting speed and lubrication conditions must be considered simultaneously to achieve smaller surface roughness.

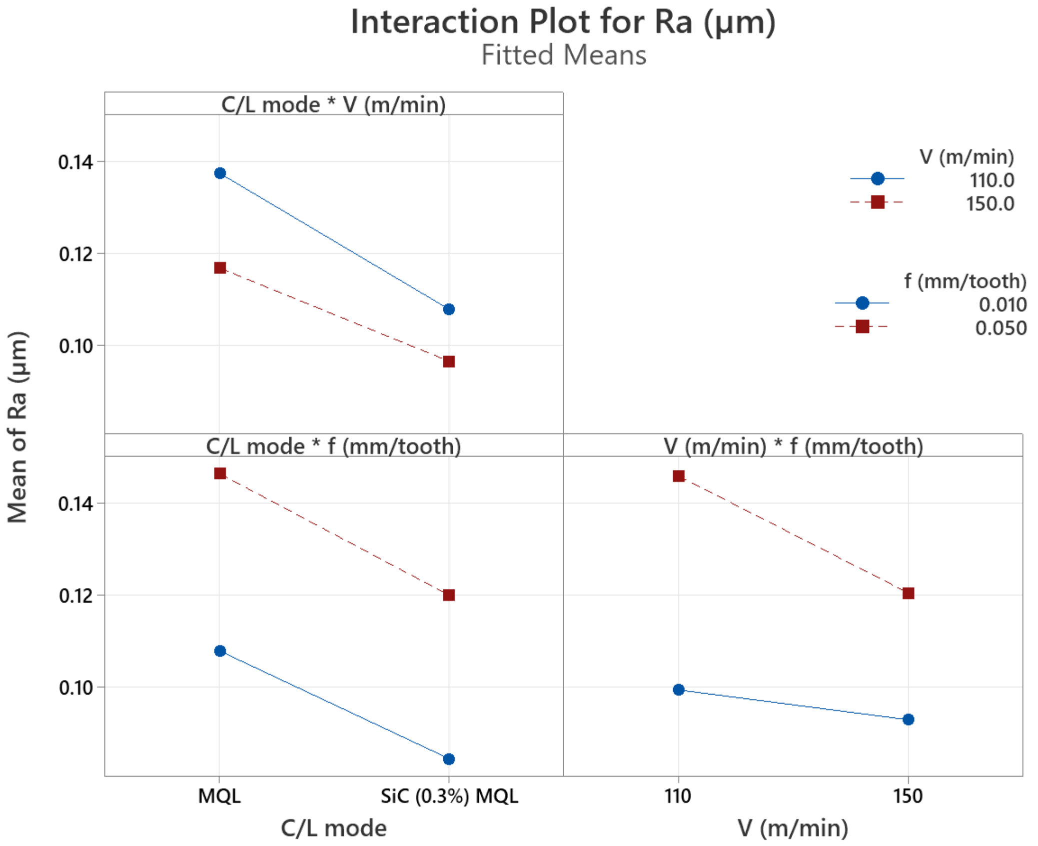

Figure 3. Interaction effects of input parameters on surface roughness R_a

IV. Conclusion

This study investigates the effects of minimum quantity lubrication (MQL), with and without SiC nano-enhanced cutting oil, along with cutting speed and feed rate, on the surface roughness (R_a) during the hard milling of AISI D2 tool steel (58–60 HRC). A factorial experimental design was employed to evaluate the influence of these input parameters. The results reveal that feed rate is the most dominant factor affecting surface roughness, followed by the cooling/lubricating (C/L) mode and cutting speed. These findings highlight the necessity of using low feed rates and suitable lubrication strategies to achieve improved surface quality. Furthermore, although feed rate plays the primary role, the interaction between cutting speed and lubrication conditions should be carefully considered to optimize machining performance. Based on the experimental outcomes, a practical guideline is proposed: the use of MQL with SiC nano cutting oil, a cutting speed of 150 m/min, and a feed rate of 0.01 mm/tooth for obtaining better surface finish.

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