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An Investigation on Effects of Cutting Parameters on Surface Roughness in Hard Milling of AISI D2 Tool Steel Under Nano fluid MQL Environment

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ABSTRACT: The main objective of this paper is to study the effects of SiC nanoparticle concentration, cutting speed, and feed rate on the surface roughness R_a in the hard milling process of SKD 11 tool steel (58 ÷ 60 HRC) under nanofluid MQL condition. The influences of input parameters were studied by usingthe Box-Behnken experimental design. The obtained experimental results indicated that the feed rate is the most influential effect on surface roughness, followed by the cutting speed and then nanoparticle concentration. In addition to that, the interaction effects between nanoparticle concentration and cutting speed and the square effects of cutting speed and feed rate cause the significant impacts on the surface roughness R_a. Moreover, the SiC nanoparticle concentration NC=0.3%, cutting speed v= 150 m/min, and feed rate f=0.01mm/tooth are the appropriate set and should be recommended for reaching the smaller surface roughness R_a values.

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

1. INTRODUCTION

In recent years, the demand for machining high-hardness materials has increased sharply in such the fields as mold and precision manufacturing. SKD11 tool steel (JIS G4404), after heat treatment, achieves a high hardness of 58-60 HRC and is a typical material widely used for cold stamping molds, machine parts, and high-wear applications [1]. Thanks to its high hardness and strength, SKD11 tool steel ensures the working durability of molds and parts, but at the same time, it is very difficult to machine by using conventional cutting methods. Indeed, the hardened steels (45–65 HRC) are generally grouped in "difficult to cut" materials because the cutting process generates large cutting forces, high cutting temperatures, and severe tool wear during turning, milling, drilling, and so on. For this reason, the finishing process of high-hardness steels often requires grinding. However, grinding has disadvantages such as low productivity, high cost, and environmental problems caused by coolant [2]. To meet the demand for increased productivity and quality, hard machining technologies such as hard turning, hard milling, and hard drilling have been developed to support or replace grinding [3].

Nevertheless, the implementation of hard milling process on SKD11 tool steel poses many obstacles. Due to the material's high hardness, strength, and good wear resistance, the hard cutting process generates a large amount of cutting heat and high cutting forces that strongly impact the cutting tool, leading to rapid wear and short tool life, while the surface quality of the machined parts is reduced and reflected by high surface roughness values [1]. Moreover, a less durable white layer may appear on the surface [4]. In hard machining processes, it is often necessary to use cutting tool materials with high hardness and good wear resistance such as coated carbide, ceramics, CBN, PCD, etc., which significantly increases tool costs [5]. These factors make hard milling difficult to simultaneously ensure the productivity, quality and economic efficiency. To reduce heat and friction in the cutting zone, flood condition has been widely used in industrial production. However, this traditional method requires the use of a large amount of cutting oil or coolant, resulting in high operating costs and, especially, very high environmental treatment costs of the used cutting oils or coolants. In fact, the used cutting oil is often discharged directly into the environment or has to be treated at very high costs [2]. In addition, the use of industrial coolants has a negative impact on the environment (water and soil pollution) and poses a risk to the health of workers due to oil vapor and bacteria in the cooling solution. Therefore, in the context of the requirement to develop cleaner and sustainable production, the flood irrigation method is increasingly revealing many economic and environmental limitations.

To overcome the above limitations, Minimum Quantity Lubrication (MQL) technique has been and is being researched and applied. This is a method that uses a very small amount of cutting oil mixed with compressed air to form a mist and sprayed directly into the cutting area [6,7]. This method provides good lubrication, thus contributing to improving the efficiency of the cutting process. In addition, this method significantly reduces the amount of cutting oil used, so it is considered environmentally friendly.

However, low cooling capacity is a major problem when applying this method to machining hard materials [7]. The use of nano cutting oils as the based oils for MQL technology is a new research direction, attracting the attention and research of scientists all over the world. The experimental study shows that lubrication and cooling efficiency are improved when adding nanoparticles to base cutting oil [8], thereby reducing cutting force, tool wear and improving machining surface quality [9]. SiC nanoparticles have a nearly spherical morphology, high hardness and good thermal conductivity [7], therefore SiC nano cutting oil has contributed to improve the efficiency of the cutting process, reported in [10]. However, there is still very little information on the application of SiC nano cutting oil in the milling process of SKD 11 steel. Therefore, the authors made a study on the influence of nanoparticle concentration, cutting speed, and feed rate in the hard milling process of SKD 11 tool steel (58÷60HRC) on surface roughness R_a. The main effect of each input variable and the interaction effects are studied. Also, the technological guides are provided from the study results.

2. METHODOLOGY

The setup of experiments is shown in Figure 1. Vertical Center SMART 530C (Mazak, Japan) was used to conduct hard milling experiments. SKD 11 tool steel samples were hardened to reach the hardness values ranging from 58 to 60 HRC. The chemical composition and mechanical properties of SKD 11 tool steel are given in Tables 1, 2. The surface roughness R_a was measured three times after each cut by Mitutoyo SJ-210 surface roughness tester and the average value was taken. The Box-Behnken experimental design was used to study the effects of input machining parameters (nanoparticle concentration, cutting speed, and feed rate) on surface roughness R_a. The input variables with their levels are given in Table 3.

Table 1. Chemical composition of SKD 11 tool steel (JIS G4404 standard specification)

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 SKD 11 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

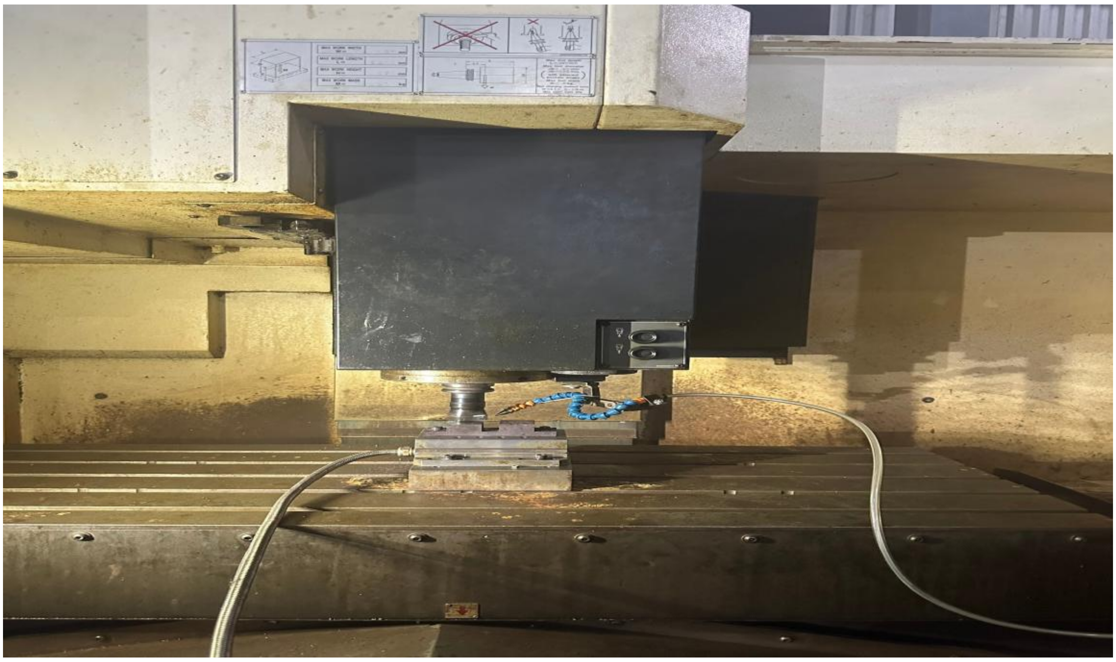

Figure 1. Mazak Vertical Center SMART 530C used for hard milling experiments

Table 3. Input variables and their levels

Input parameters	Low level	High level	Output parameter
Nanoparticle concentration (%)	0.1	0.3	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 Box-Behnken experimental design. The Pareto chart in Figure 2 shows the influences of each parameter and the interactive effects of the input parameters on surface roughness R_a. In Figure 2, it can be observed that the feed rate causes the strongest impact on surface roughness R_a, followed by the cutting speed and then the nanoparticle concentration. At the same time, the square effects of cutting speed and feed rate also contribute the significant influences. Other interactive effects have little impact on the response.

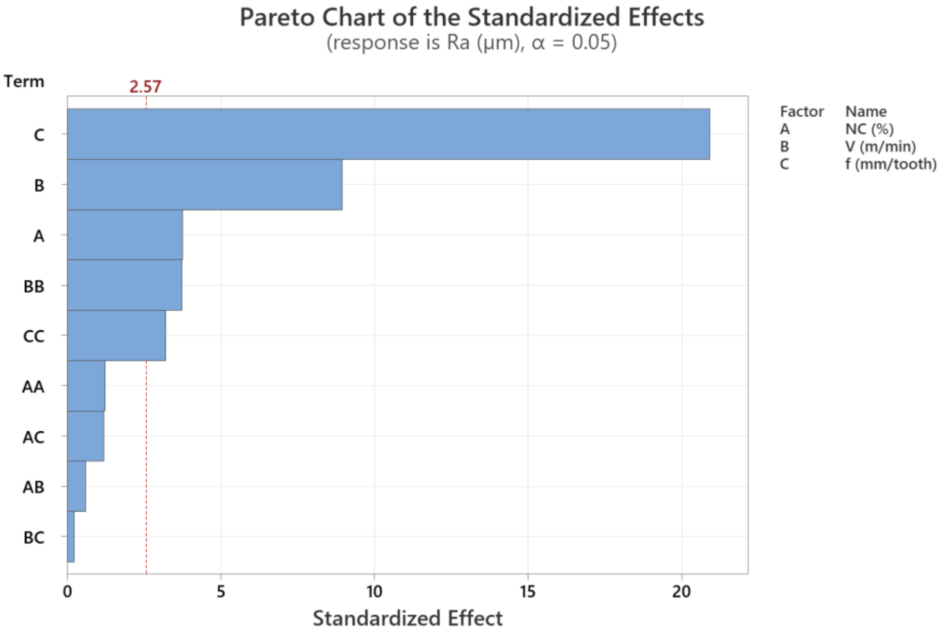

Figure 2. Pareto chart of the effects of input parameters on surface roughness R_a

The main effect of each factors is shown in Figure 3. Due to the increase of the cutting layer area [3], R_a values go up quickly when the feed rate rises from 0.01 mm/tooth to 0.05 mm/tooth. At the same time, the declining rate of surface roughness R_a were observed when the nanoparticle concentration and cutting speed increase. The growth of cutting speed from 110m/min to 150 m/min contributes to reduce the surface roughness R_a, which can be explained by the reduction of cutting forces and cutting heat [3]. Besides, the reduction of R_a with the rise of SiC nanoparticle concentration links to the better lubrication performance resulted from the increase in the nanoparticle number [10].

Figure 4 is the graph of interaction effects of input machining parameters. The interaction effect between the nanoparticle concentration and cutting speed causes more influences on surface roughness R_a than the other ones. From the obtained results, the reasonable set of input parameters is selected with the SiC nanoparticle concentration of 0.3%, cutting speed of 150 m/min, and feed rate of 0.01mm/tooth for achieving the smaller surface roughness R_a values.

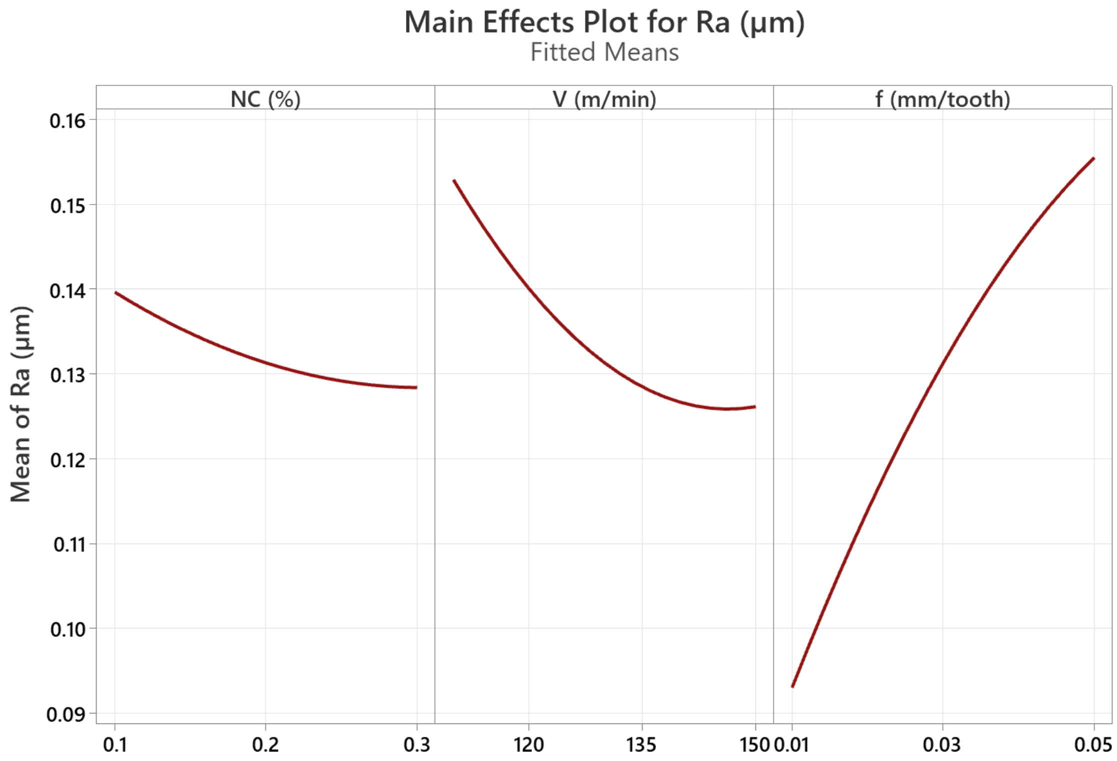

Figure 3. Main effects of input parameters on surface roughness R_a

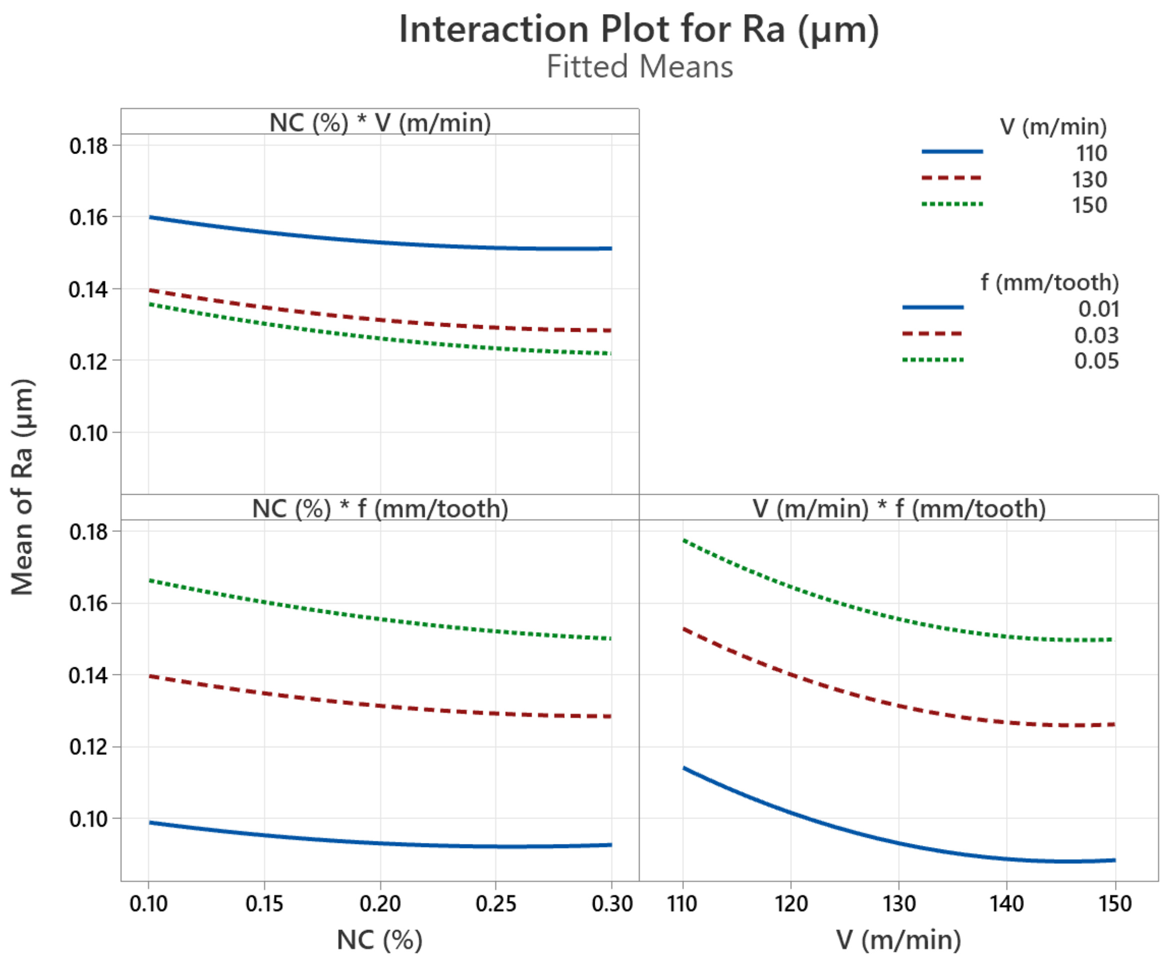

Figure 4. Interaction effects of input parameters on surface roughness R_a

4. CONCLUSION

In the presented work, the effects of the input machining parameters on the surface roughness R_a in the hard milling process of SKD 11 tool steel (58÷60HRC) using coated carbide inserts under SiC nanofluid MQL environment were experimentally studied. The Box-Behnken experimental design was applied to investigate the impacts of nanoparticle concentration, cutting speed, and feed rate. The obtained results clearly indicate the effects of each parameter and the interaction effects between them on surface roughness R_a. Among the investigated variables, the feed rate is the most dominant factor on surface roughness R_a, followed by the cutting speed and then nanoparticle concentration. Also, the interaction effect between nanoparticle concentration and cutting speed contributes the significant impact on surface roughness R_a. Moreover, the technological guide is provided from the obtained results for further studies. The SiC nanoparticle concentration NC=0.3%, cutting speed v= 150 m/min, and feed rate f=0.01mm/tooth should be chosen for attaining the better machined surface quality.

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