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An Investigation on Cutting Forces in MQL and Nanofluid MQL Milling of Hastelloy C276

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ABSTRACT: In this paper, the main objective is to study the influence of parameters including lubrication/cooling mode (pure MQL and nanofluid MQL), cutting speed, and feed rate on the cutting force component F_z during the milling process of Hastelloy C276 alloy. The influence of input parameters was studied by using the factorial experimental design. The experimental results showed that the feed rate caused the most dominant influence on the cutting force component F_z, followed by the lubrication/cooling mode. Furthermore, the interaction between cutting speed and feed rate significantly impacts on F_z. MQL condition using Al_2O_3 nano cutting oil provide better lubrication and cooling compared to MQL using the based oil without nanoparticles. Based on experimental results, the nanofluid MQL with the cutting speed v = 30 m/min and feed rate f = 0.08 mm/tooth should be selected to achieve the lower cutting force F_z values.

KEYWORDS: Milling; nanofluid; Al_2O_3 nanoparticle; MQL; cutting speed; feed rate; cutting force;

1. INTRODUCTION

In the industrial production, the metal cutting field still plays a key role in the manufacturing industry of each country. Along with that, the rapid development of the field of materials science has brought out many advanced materials, which has created new pressures for machining processes. Machining such types of materials that simultaneously possess many superior mechanical, physical and chemical properties often encounters difficulties in the material removal process [1]. Among them, nickel-based alloys are considered one of the important groups of engineering materials due to their ability to perform stably under harsh environmental conditions. Nickel alloys are metallic materials formed when the element nickel combines with one or more other alloying elements such as chromium (Cr), iron (Fe), copper (Cu), molybdenum (Mo), or aluminum (Al). The addition of these elements significantly improves material properties such as mechanical strength, heat resistance, oxidation resistance, corrosion resistance, and wear resistance [2]. Thanks to these outstanding advantages, nickel alloys are widely used in many important industrial fields such as chemical industry, aerospace, mechanical production, energy industry, etc. [3].

Hastelloy C276 is a typical nickel-based alloy belonging to this group of materials and has a high yield strength and low thermal conductivity, so it is often classified as a difficult-to-machine material by cutting methods [4]. During machining, the phenomenon of cutting tool wear occurs more severely than when machining materials with low hardness. The main reason is that this alloy has high mechanical strength, high ductility and strong strain hardening ability. These characteristics increase the cutting force as well as the temperature in the cutting zone during machining [5]. Besides, the poor thermal conductivity of nickel-based alloys makes it difficult for the heat generated from the cutting zone to be transferred outwards, leading to a large concentration of heat at the contact area between the tool and the chip, thereby increasing the wear rate of the cutting tool. In addition, during machining, the material easily adheres to the surface of the cutting tool, forming a built-up edge, negatively affecting the surface quality of the machined tool and reducing the tool life [3].

Therefore, to effectively machine nickel-based alloys, cutting tools need to have high hardness and good heat resistance to maintain durability under high temperature and cutting force conditions [6]. At the same time, the chosen cutting speed should be lower than the case of machining steels, and appropriate lubrication and cooling conditions should be applied to reduce temperature and friction in the cutting zone [7]. In production practice, flood cooling is a traditional cooling technique and has been widely used in metal cutting. However, due to low flow pressure, the ability to deliver coolant solution deep into the cutting zone is limited, and the amount of solution used is usually very large [7]. Besides, the cost of processing and recycling the used cutting fluids is high, significantly increasing machining costs. In addition, the consumption of a large amount of coolant causes environmental and worker health problems, making this method increasingly unsuitable for the trend of green and sustainable production development [8]. Therefore, some advanced cooling and lubrication technologies have been studied and developed such as minimum quantity cooling (MQC), minimum quantity lubrication (MQL), minimum quantity lubrication (MQL) using nano cutting oil, and so forth. Among them, the use of nano cutting oil as base cutting oil for MQL method has become a new research direction, attracting much attention. The additives of nanoparticles in base cutting oil has improved the lubricating and cooling properties of base cutting oil [9]. This helps improve the machining efficiency of milling SKD 11 steel by using end mills [10]. Directly introducing the cutting oil containing nanoparticles into the cutting zone not only enhances the lubricating efficiency from the properties of the cutting oil but also takes advantages of the lubricating/cooling properties from the nanoparticles [11]. The reduction of tool wear and cutting forces during milling were noted in the studies [11,12]. At the same time, the surface quality was improved when machining with MQL condition using nano cutting oil compared to dry and MQL modes [12]. However, studies on milling Hastelloy C276 alloy under nanofluid MQL method are still limited, so the authors conducted a study on the influence of cutting parameters on the cutting force in the milling process under pure MQL and nanofluid MQL conditions.

2. MATERIAL AND METHOD

The SMART 530C vertical milling center (Mazak, Japan) was used to conduct the milling experiments, and the experimental device setup is illustrated in Figure 1. Hastelloy C276 alloy samples with chemical composition and mechanical properties are presented in Tables 1 and 2. Cutting force values were measured directly during the cutting process by using Kistler 9257BA dynamometer. Al_2O_3 nanoparticles were mixed into vegetable oil at 0.5% by weight. Mechanical stirring and ultrasonic vibration were performed to ensure the uniform dispersion of the nanoparticles in the cutting oil. The factorial experimental design was used to study the effect of input machining parameters (lubrication/cooling mode, cutting speed, and feed rate) on the cutting force F_z. The input variables and their values are presented in Table 3.

Table 1. Chemical composition of Hastelloy C276

Chemical composition (%)										
Ni	Co	Cr	Mo	Fe	W	Mn	Mo	V	Si	C
57 balance	2.5 max	16	16	5	4	1.0 max	0.6	0.35 max	0.08 max	0.01 max

Table 2. Mechanical properties of Hastelloy C276

Yield strength (Mpa)	Tensile strength, (Mpa)	Elongation (%)	Hardness range (HRB)	Modulus of Elasticity (Gpa)	Poison's ratio
355	760	40	88	200	0.32

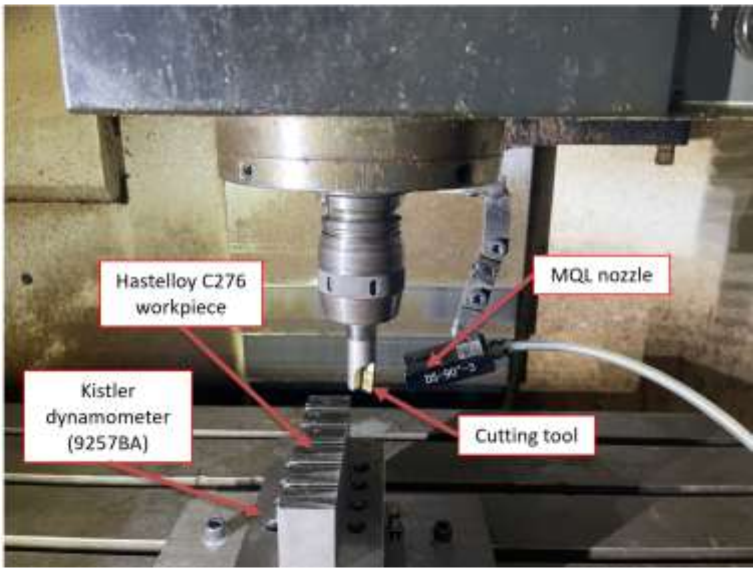

Figure 1. Setup of experimental devices for milling

Table 3. Factorial experimental design with the surveyed variables and response

Input variables	**Low level**	**High level**	**Output variable**
Cooling lubricating mode	MQL	NF MQL	Cutting force F_z (N)

Cutting speed (m/min)	30	70	
Feed rate (mm/tooth)	0.08	0.16	

3. RESULTS AND DISCUSSION

The milling experiments were conducted by following the run order of the factorial experimental design. The Pareto plot in Figure 2 shows the influence of each variable and the interaction of input parameters on the cutting force component F_z. Factors with a significant influence on the output variable are located to the right of the reference line with a value of 10.39, while those to the left of the reference line have negligible influence. In Figure 2, it can be seen that the feed rate has the strongest influence on the tangential force component F_z, followed by the interaction of cutting speed and feed rate, and then the lubrication/cooling mode. Other factors have negligible influence.

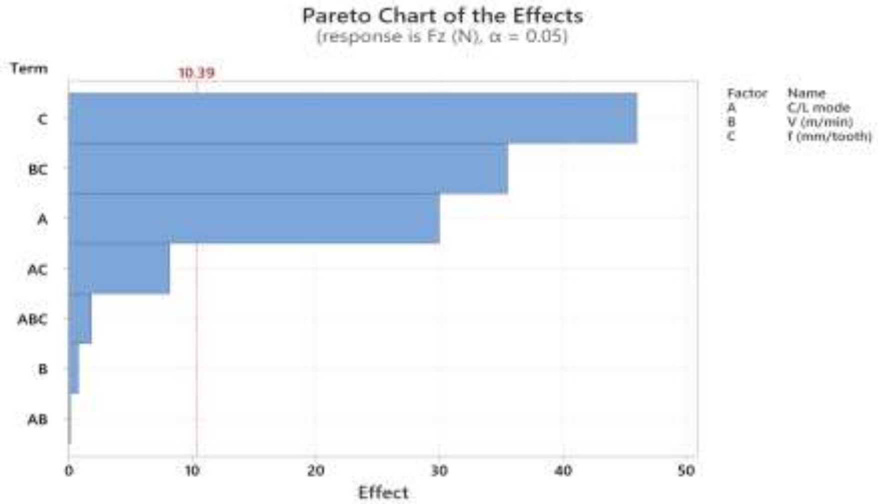

Figure 2. Pareto chart of the effects of input parameters on the cutting force F_z

The main effects of each surveyed factor are shown in Figure 3. Due to the increased cutting layer [13], the F_z values increased rapidly when the feed rate increased from 0.08 mm/tooth to 0.16 mm/tooth. At the same time, a slight increase in the cutting force F_z value was observed when the cutting speed increased from 30 m/min to 70 m/min. In addition, in case of using MQL condition with nano cutting oil, the F_z values were smaller than in MQL condition without nano cutting oil, which reflects that the Al_2O_3 nano cutting oil improved the lubrication and cooling efficiency of the based cutting oil [12,14].

Figure 4 illustrates the interaction of input machining variables on the cutting force F_z. The interaction between lubrication/cooling mode and cutting speed affects the cutting force F_z more than other factors. In addition, at a cutting speed of 30 m/min, the interaction between cutting speed and feed rate also has a significant effect on F_z. From the results obtained, a suitable set of input parameters was selected with MQL method using nano cutting oil, the cutting speed of 30 m/min, and feed rate of 0.08 mm/tooth to achieve the lower cutting force F_z.

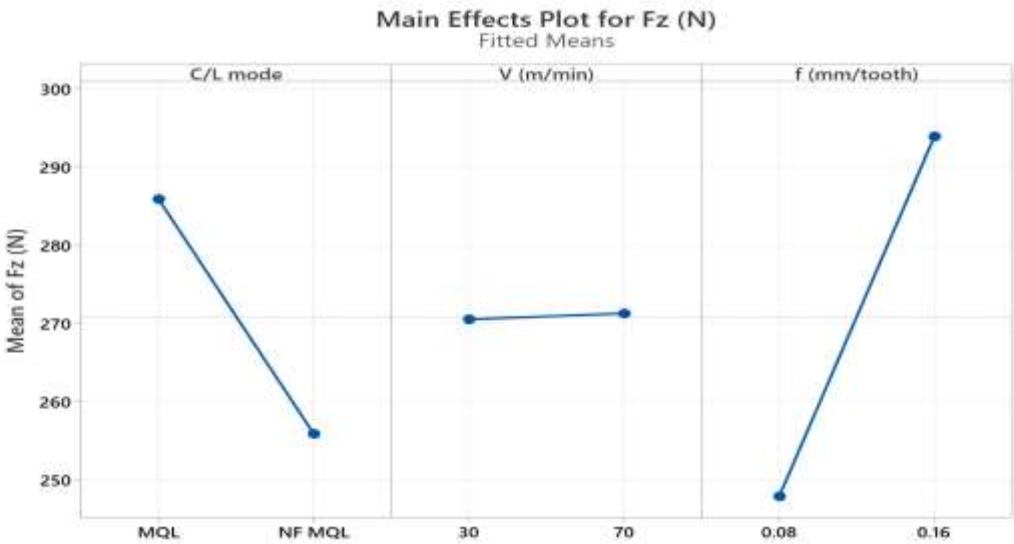

Figure 3. Main effects of input parameters on the cutting force F_z

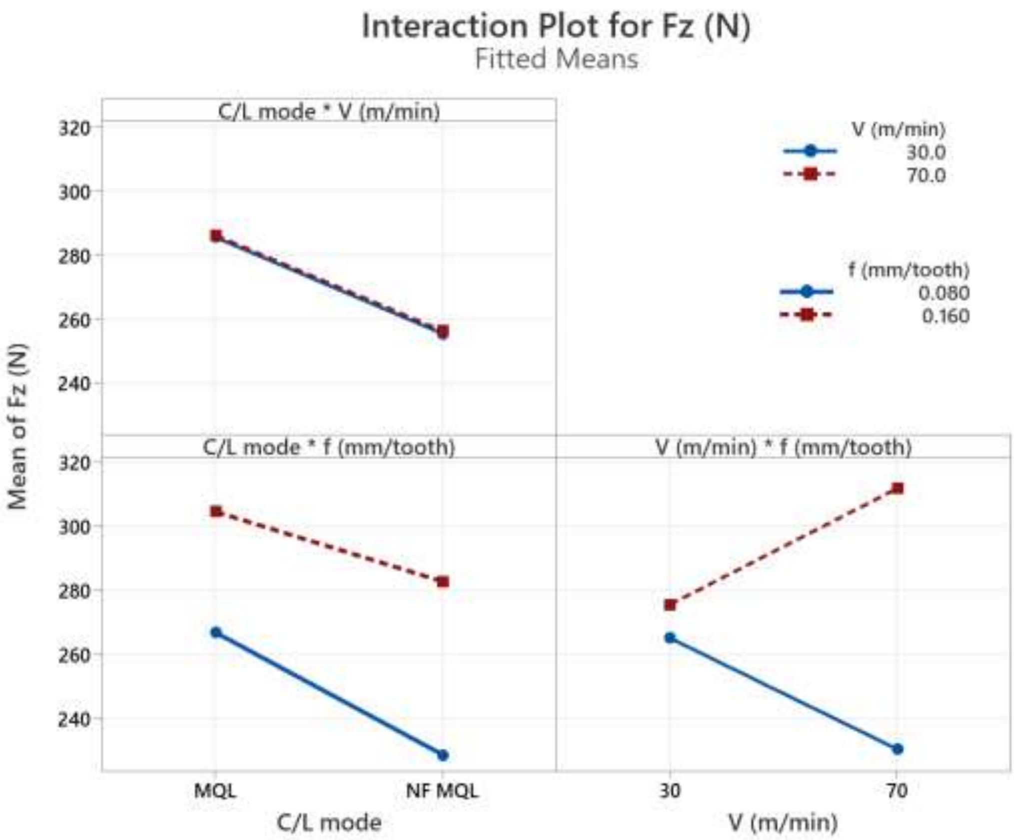

Figure 4. Interaction effects of input parameters on the cutting force F_z

4. CONCLUSION

In this work, the influence of pure MQL and MQL using nano cutting oil on the cutting force F_z in milling Hastelloy C276 alloy was investigated. Also, the effects of cutting parameters are studied and evaluated through the application of the factorial experimental design. Due to the good lubricating properties of Al_2O_3 nanoparticles, the milling process under MQL condition using nano cutting oil provides better lubrication efficiency when compared to MQL using the based oil without nanoparticles. Among the factors investigated, the feed rate has the greatest influence on the cutting force F_z, followed by the lubrication/cooling mode. Furthermore, the interaction between cutting speed and feed rate significantly impacts the cutting force component F_z. To achieve the lower cutting force F_z values, MQL using nano cutting oil, cutting speed v = 30 m/min, and feed rate f = 0.08 mm/tooth should be selected. This is an important technological guideline for further research and application in production.

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