Nano World Journal

https://doi.org/10.17756/nwj.2023-s3-191

Research Article

Open Access

An Experimental Investigation on Influence of Flank Wear in Novel Minimum Quantity Lubrication Technique of Monel Metal

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Received: July 31, 2023
Accepted: November 01, 2023
Published: November 03, 2023

Citation: Vinay M, Kumar BN. 2023. An Experimental Investigation on Influence of Flank Wear in Novel Minimum Quantity Lubrication Technique of Monel Metal. *NanoWorld J* 9(S3): S1081-S1086.

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Abstract

The primary objective of this work is to study the effect of a novel minimum quantity lubrication (MQL) technique on tool flank wear of the tool insert while machining the monel alloy and compare it with tool flank wear of the tool insert used in the dry machining process. Two sets of samples were taken for the study, i.e.,T control group (Dry machining) and the experimental group (Machining with MQL technique). The number of samples is calculated using the sample calculator. Twenty samples were taken for each group. In the control group, the machining operation is carried out on monel alloy without any kind of lubrication. In the experimental group using a novel MQL technique, the compressed lubricant is applied to the machining zone. The tool wear of the inserts of each group is measured by microscopic images. The effect of the novel MQL technique on the tool wear of the inserts is studied. The flank wear of the tool insert samples from novel MQL is lesser than the samples obtained from the dry machining operation. Within the limits of the study, there is a 29% lesser tool wear the MQL technique over the dry machining.

Keywords

Minimum quantity lubrication technique, Monel, Tool wear, CNC machining, Dry machining, SPSS software, Sustainable production

Introduction

A crucial manufacturing technique, machining, commonly referred to as subtractive manufacturing develops the desired shape by eliminating undesired elements from raw materials [1]. The machining process is mostly used to create parts for machines, tools, dies, and mould [2]. MQL presents an effective strategy for minimizing flank wear, leading to extended tool life in machining operations. This process involves the delivery of a minute, accurate quantity of lubricant directly to the tool-workpiece interaction zone. The lubricant serves to create a boundary layer that reduces metal-to-metal contact and, consequently, the frictional heat generated during the cutting process. This reduction in heat loosens its contribution to the tool's flank wear [3]. Further, by limiting thermal deformation of the tool, the lubricant helps maintain its geometry and integrity. Lower lubricant volume in MQL also curbs the chance of the lubricant triggering chemical wear, another significant aspect of tool wear. Hence, the application of MQL can reduce flank wear rates, prolong tool life, and improve the overall machining efficiency. Additionally, the approach aligns with sustainable machining practices, as it significantly lowers coolant consumption and waste [4]. One promising approach that has garnered considerable attention in recent years is MQL. This innovative lubrication technique stands out as a sustainable and effective means to minimize flank wear during metal cutting operations. By delivering a precise and minimal volume of lubricant directly to the cutting zone,

MQL not only reduces the environmental footprint associated with conventional flood cooling but also significantly mitigates the detrimental effects of friction and heat generation on cutting tool surfaces. As a result, the adoption of MQL has demonstrated a remarkable ability to extend tool life, reduce tool replacement costs, and enhance overall productivity in machining operations [5]. This study examines the influence of coating material on tool wear as well as the micro milling of the super alloy. The results show that tool wear typically manifests as fractures along the sides and flank wear. Chipping damage was frequently observed in the uncoated microtool.

The total number of research papers published related to this work and sustainable production was 3530 in google scholar and 1666 in ScienceDirect in the past ten years [6]. It has excellent strength-to-weight ratio, corrosion-resistant exterior, and high performance in harsh environments, carbon fiber-reinforced polymer carbon fiber reinforced plastics (CFRP) composites are now the most frequently used material in automotive and aerospace applications. Due to its capacity to produce complicated forms and change the material's fiber orientation, additive manufacturing, also known as three-dimensional 3D printing, of CFRP composites is becoming more and more popular. Abrasion, adhesion, and chipping are the most frequent wear processes seen while machining CFRPs. The most frequent wear mechanism related to machining is abrasion wear [7]. Author describes that due to its amazing wear resistance, supreme hardness, and high strength, AISI 52100 steel machining has attracted more attention in industrial and manufacturing applications. Because it poses a risk to the environment and its users, conventional cutting fluid-assisted machining is not a desirable solution. The most effective method to encourage sustainable production is dry machining or nearly dry machining. As a result, the work's RSM model can reduce the need for costly machining process experiments [8]. According to the author, a novel method that needs to be investigated involves combining several cooling and lubrication tactics to lessen tool wear and improve Inconel 718's machinability. In this sense, the current work employs two various cooling procedures to improve the Inconel 718's machinability. When compared to other techniques, Inconel 718 may be machined more sustainably without sacrificing surface quality [9]. Monel metal tends to be hard and abrasive, which often leads to accelerated tool wear during machining operations. Its high work-hardening rate can also create issues, as chips do not break easily, potentially leading to the build-up of excess heat and potential damage to both the tool and the workpiece. Finally, due to Monel's low thermal conductivity, it retains most of the heat generated during machining, causing high temperatures that can quickly dull the cutting tool. As a result, machining Monel typically requires specialized techniques, such as slow cutting speeds, continuous lubrication, and the use of hard tool materials to increase efficiency and prolong tool life.

According to the findings of the research, only a few studies have been conducted on the effects of MQL on Tool wear of the Monel alloy and sustainable production. The experimental and depth theoretical knowledge about various machining operations, MQL technique, tool wear measurement techniques, metals and alloys motivated me to carry out this research work. This study is related to the machining of Monel alloy under different dry conditions and MQL. The machining type was ending milling. The aim of this study is to analyze the influence of MQL technique on flank wear and crater wear.

Materials and Methods

This research work mainly consists of two sets of groups namely control group and the experimental group. The CNC machining operation without any kind of lubrication is considered a control group. The machining operation using a novel MQL technique i.e., the compressed lubricant is applied to the machining zone is considered a study group. To obtain better results, several samples have been taken. Sample size calculation is a crucial step in the design of experiments as it significantly impacts the validity and reliability of the results derived. Essentially, the calculation of an appropriate sample size is a balance between statistical power and practical feasibility. Statistical power refers to the probability that the experiment will detect an effect of a certain size, should it exist. Having a larger sample size increases statistical power, thereby limiting the probability of type II errors (false negatives). However, there is a practical limit to sample size, often imposed by factors such as resource availability and time constraints. Therefore, methodologies such as power analysis, which considering the desired confidence level, expected effect size, and the acceptable error margin, are typically used in determining an optimal sample size. It's important to note that an insufficiently small sample can lead to unreliable results, while an unnecessarily large sample can boundlessly consume resources and time. Thus, careful consideration must be given to sample size calculation to ensure both effective and efficient experimentation [10].

For the control group, the machining operations are performed without lubrication. It is called dry machining. For this study machining Monel in a Vertical Machining Center (VMC) involves a well-defined procedure to address the material's inherent challenges. First and foremost, selecting appropriate cutting tools is critical. Carbide or high-speed steel tools with optimized geometry and coatings for heat resistance and wear protection are typically recommended. Machining parameters, such as cutting speed, feed rate, and depth of cut, should be carefully adjusted to minimize heat generation and tool wear. Additionally, employing a high-pressure coolant system or, in some cases, cryogenic cooling, can effectively dissipate heat, reduce work hardening, and improve chip evacuation. The material was purchased at Viruvadia Traders, Chennai. The size of the specimen is 150 mm × 150 mm × 10 mm. The coated carbide tools are used to machine the monel material. For the control group, the machining operations are performed without lubrication. It is called dry machining. Fixturing and work holding are crucial to ensure stability during the machining process, especially due to Monel's tendency to work harden. Rigorous monitoring of tool wear through sensors or manual checks is essential to maintain consistent cutting performance.

For the study group, the machining operations are carried

out with MQL set up which is shown in figure 1. Machining Monel in a VMC necessitates meticulous tool selection, precise machining parameters, effective cooling methods, stable work holding, and vigilant tool wear monitoring to overcome the material's inherent challenges and achieve the desired machining results. The lubricant is prepared by mixing graphene nanoparticles with castor oil. The lubricant is compressed with the help of the compressor and supplied through the nozzle at the cutting zone. The set-up is shown in figure 2. The tool inserts are collected to measure the tool wear. The CNC machining operation has been performed using vertical machining centre EV 1020A which is shown in figure 3. Based on the literature survey, the machining parameters are taken. Machining monel with the MQL technique requires a carefully orchestrated procedure to harness the benefits of this environmentally friendly lubrication method while effectively addressing Monel's machining challenges. To begin, select cutting tools specifically designed for high-temperature alloys, with coatings that enhance heat resistance and wear durability. Adjust cutting parameters, such as cutting speed, feed rate, and depth of cut, to maintain optimal tool performance while minimizing heat generation. When employing MQL, it's crucial to set up a precise and consistent lubrication system that delivers a minimal amount of lubricant directly to the cutting zone. This not only reduces environmental impact but also assists in heat dissipation, minimizing tool wear and work hardening of the Monel alloy. Monitoring tool wear and maintaining a well-maintained MQL system are essential to ensure continuous and efficient machining of Monel while reaping the benefits of reduced tool wear and improved machining efficiency associated with this innovative lubrication technique. The end milling operation was performed under dry operation conditions for the control group. The MQL set-up is fitted, and the end milling operation was performed under MQL technique for the study group for the same machining parameters.

After machining using an end milling operation, the tool inserts were collected and cleaned as shown in figure 4. The Metzer optical microscope is used to observe tool wear shown in figure 5. This is a portable optical instrument that allows accurately measuring tool wear. The tool inserts were kept on the measuring platform. The microscopic images were captured. Then the images were exported to ImageJ software. The tool wear is measured using ImageJ software for the control group i.e., dry machining and study group i.e., MQL technique. The tool wear is tabulated in table 1.

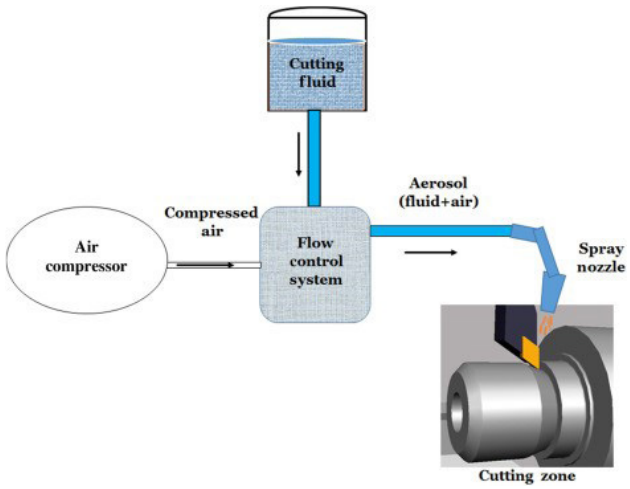


Figure 1: MQL set-up line diagram.



Figure 2: MQL set-up.



Figure 3: Vertical milling machine YCM XV1020A.

Results

Tool flank wear of the tool insert samples from the control group and study group were measured using metzer optical microscope. The tool wear of both machined surfaces

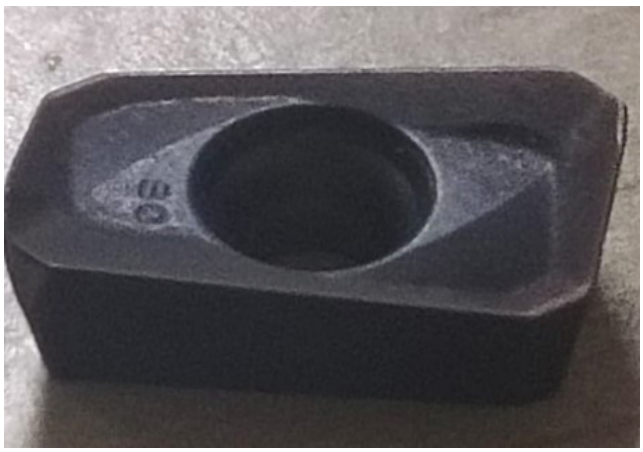


Figure 4: Flank wear of the tool insert.



Figure 5: Metzer microscope.

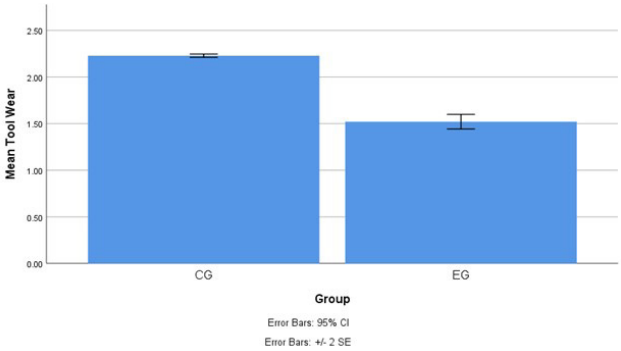


Figure 6: Mean tool wear comparison of machined surface from dry machining and MQL technique using bar graphs. Tool wear of the inserts from dry machining is 2.2285 with a standard deviation of 0.03977 and the tool wear of the inserts obtained in the MQL technique is 1.5685 with a standard deviation of 0.21236. X-axis denotes method of machining technique and Y-axis denotes the mean tool wear. This graph shows that the machined surface obtained in the MQL technique has a better Surface finish with a significant lower error deviation.

was further statistically analyzed using SPSS software and obtained values of various tests. The results are shown in table 2. The mean tool wear of the dry machining is 2.2285 with a standard deviation of 0.03977 and the mean tool wear for machined surface obtained in the MQL technique 1.5685 with a standard deviation of 0.21236. The bar graph is shown in figure 6. The X-axis denotes method of machining technique and Y-axis denotes the mean tool wear. This graph shows that the machined surface obtained in the MQL technique has a better surface finish with a significantly lower error deviation.

The results prove that surface finish has been improved in the MQL machining compared to machining without lubricants. The mean tool wear of dry machining is 2.2285. The mean tool wear of MQL machining is 0.4133 which is evident that surface finish has improved. Table 3 shows the levene's test for equality.

Discussion

The obtained results were compared with similar kinds of research work. In this study, MQL delivers a minimal amount of lubricant directly to the cutting zone, reducing the friction between the cutting tool and workpiece. This lubrication film acts as a barrier that prevents direct metal-to-metal contact, thereby lowering the abrasive wear on the tool's flank surfaces. Shinge and Pable [11] compared various technologies such as conventional cooling, MQL and nanofluid cooling. They

Table 1: Tool flank wear of the inserts from dry machining and MQL technique.

Sample no.	Tool wear dry machining (mm)	Sample no.	Tool wear dry machining (mm)	Sample no.	Tool wear MQL technique (mm)	Sample no.	Tool wear MQL technique (mm)
1	2.24	11	2.22	1	1.67	11	1.65
2	2.25	12	2.18	2	1.68	12	1.50
3	2.28	13	2.29	3	1.45	13	1.93
4	2.26	14	2.17	4	1.57	14	1.95
5	2.21	15	2.19	5	1.44	15	1.34
6	2.23	16	2.25	6	1.51	16	1.62
7	2.19	17	2.26	7	1.22	17	1.33
8	2.27	18	2.16	8	1.82	18	1.37
9	2.29	19	2.22	9	1.83	19	1.29
10	2.20	20	2.21	10	1.72	20	1.48

Table 2: Descriptive table representing mean and standard deviation of tool wear of dry machining with MQL set-up.

Group statistics					
-		N	Mean	Std. deviation	Std. error mean
Flank tool wear	Control group	20	2.2285	0.03977	0.00889
	Study group	20	1.5685	0.21236	0.04749

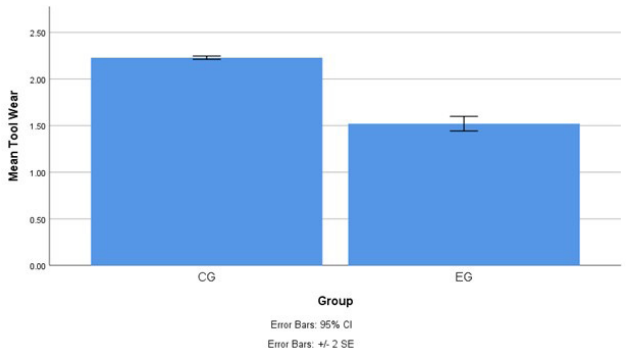


Figure 6: Mean tool wear comparison of machined surface from dry machining and MQL technique using bar graphs. Tool wear of the inserts from dry machining is 2.2285 with a standard deviation of 0.03977 and the tool wear of the inserts obtained in the MQL technique is 1.5685 with a standard deviation of 0.21236. X-axis denotes method of machining technique and Y-axis denotes the mean tool wear. This graph shows that the machined surface obtained in the MQL technique has a better Surface finish with a significant lower error deviation.

selected AISI D3 as a work material which is suitable for blanking and shaping tools. The results proved that MQL technique using nanoparticles. He conducted experimental work oMQL also plays a pivotal role in dissipating heat generated during machining. By minimizing the heat buildup at the cutting edge, MQL helps prevent thermal softening and premature wear of the tool material, particularly in high-speed cutting operations. Dhar et al. [12] suggested that proper chip evacuation is crucial to reducing flank wear. MQL assists in the efficient removal of chips from the cutting zone, preventing their accumulation on the tool's flank surfaces, which can lead to accelerated wear. The combined effects of reduced friction, effective heat management, and improved chip evacuation contribute to prolonged tool life when MQL is employed. Tools subjected to MQL tend to exhibit slower rates of flank wear, ultimately leading to fewer tool changes and increased machining efficiency. MQL is an environmentally friendly lubrication technique, as it uses minimal quantities of lubricant compared to conventional flood cooling methods. This not only reduces the cost associated with coolant usage but also minimizes waste and environmental impact.

MQL minimizes flank wear through reduced friction, efficient heat dissipation, improved chip evacuation, and sustainable lubrication practices. These advantages make MQL an attractive choice for enhancing tool life and optimizing machining processes while minimizing the detrimental effects of flank wear. Flank wear is primarily due to the friction between the machined surface and the tool flank, which can cause overheating and faster tool degradation. The principle of MQL is to provide just enough lubrication at the cutting zone to decrease friction and reduce temperature rise. This is achieved by directing a small amount of aerosolized coolant-lubricant mixture right at the cutting interface, right where it's needed most. The lubrication lessens the contact and friction between the toolbox flank and the workpiece, thus reducing the heat generated. Consequently, there is less thermal shock to the cutting tool, maintaining its performance and extending its lifespan. Moreover, MQL can help in chip evacuation, which also decreases the risk of tool damage. In sum, by reducing friction, heat production, and enhancing chip removal, MQL can successfully minimize flank wear during machining.

The factors affecting this study are wt.% ratio of the nanoparticles, viscosity of the vegetable oil, compressor pressure and nozzle diameter. As the machining operation is performed in the advanced VMC, there is limitation to mention. In future, there is a possibility to study the effect of different nanoparticles, different vegetable oil and mineral oil. The same study can be conducted for different volume fractions of nanoparticles and varying particle sizes.

Conclusion

Within the limits of study, considering the critical need for sustainable manufacturing practices, MQL emerges as a promising technique to usher in the era of 'green machining.' By strategically introducing a minimal quantity of lubrication right at the tool-workpiece interface, MQL not only enhances machining performance but also significantly reduces the environmental impact. It curbs excessive heat generation and mitigates tool wear, which contributes to improving tool life and, in turn, lowering production costs. Additionally, its sparing

Table 3: Descriptive table representing Levene's test for equality.

Independent samples test										
-	Levene's test for equality of variances		t-test for equality of means							
	F	Sig.	t	df	Significance		Mean difference	Std. error difference	95% confidence interval of the difference	
					One-sided p	Two-sided p			Lower	Upper
Equal variances assumed	30.839	0.000	13.661	38	0.000	< 0.001	0.66000	0.04831	0.56220	0.75780
Equal variances not assumed	-	-	13.661	20.331	0.000	< 0.001	0.66000	0.04831	0.55933	0.76067

use of lubricant significantly cuts down on the disposal of toxic waste, a frequent byproduct of traditional flood lubrication. This profound effect on reducing ecological footprint, paired with operational benefits, underscores MQL as the preferred option for sustainable machining operations in a forward-looking manufacturing context. Therefore, the adoption of MQL is a significant stride towards a more sustainability-focused industry, underlining its value to enterprises pursuing a 'green' agenda MQL undeniably stands out as a best-practice technique for promoting green machining in modern manufacturing. Its ability to significantly reduce the consumption of lubricants, minimize waste, and lessen the environmental footprint associated with machining processes is remarkable. MQL's capacity to extend tool life, reduce tool wear, and enhance machining efficiency not only leads to substantial cost savings but also aligns with the imperative of sustainable manufacturing practices. By providing an effective solution for the reduction of both operational costs and environmental impact, MQL demonstrates its potential to revolutionize the machining industry. As industries increasingly prioritize sustainability and environmental responsibility, MQL emerges as a pivotal choice, demonstrating that it is not only beneficial for productivity but also for our planet's well-being. Within the limits of the study, there is a 29% lesser tool wear the MQL technique over the dry machining. In conclusion, MQL is a promising technology that has the potential to improve machining efficiency, reduce costs, and minimize the environment which leads to sustainable production.

Acknowledgements

None.

Conflict of Interest

None.

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