NanoWorld Journal

https://doi.org/10.17756/nwj.2023-s3-190

Research Article

Open Access

An Investigation on Impact of Novel Cryogenic Machining on Tool Wear in Milling of Monel in Comparison with Dry Machining

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

Citation: Vinay M, Kumar BN. 2023. An Investigation on Impact of Novel Cryogenic Machining on Tool Wear in Milling of Monel in Comparison with Dry Machining. *NanoWorld J* 9(S3): S1075-S1081.

Published by United Scientific Group

Abstract

The primary focus of the research is to examine the efficacy of a new cryogenic machining method in terms of tool wear while machining of monel alloy and compare this with the results obtained from a dry machining process. For this study, two groups were formed i.e., control group (Dry machining) and the study group machining with cryogenic machining 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 without any kind of lubrication. In the study group using a novel cryogenic machining technique, the compressed lubricant is applied to the area where machining was performed. The wearability of the tool inserts of each group is measured by microscopic images. An investigation into the tool wear rate of the inserts is conducted to study the impact of the novel cryogenic machining technique. The wear rate of the tool insert of the samples from novel cryogenic machining is lesser than the samples obtained from the dry machining operation. Through this study, there is an 30% reduction in tool wear rate when the cryogenic machining technique has been implemented over dry machining. The cryogenic machining technique is a promising technique to achieve sustainable production.

Keywords

Novel cryogenic machining, Monel, Tool wear, CNC machining, Dry machining, SPSS software, Sustainable production

Introduction

The process of removing material from a workpiece using various cutting tools and techniques is called machining. It is a crucial manufacturing process that involves shaping and finishing raw materials to create finished products with high precision and accuracy. A wide range of products, including engine components, aerospace parts, medical implants, and consumer goods, can be created using machining [1]. Green manufacturing is achieved through a variety of strategies designed to reduce the environmental impact of industrial processes. Firstly, implementing energy-efficient machinery and practices in the production process can significantly reduce the carbon footprint. This could include replacing outdated machinery with energy-efficient alternatives, implementing idle-time reduction strategies, or using renewable energy sources. Incorporating environmentally friendly materials in production lines is another significant initiative. This might involve selecting raw materials that are sustainably sourced, recyclable, or non-toxic. Process optimization is yet another aspect; this may entail minimizing waste through lean manufacturing techniques or improving process flow to reduce unnecessary energy consumption. Scrutinizing supply chains to ensure sustainability and ethics in procurement can also contribute to green manufacturing. Moreover, investing in waste treatment facilities or adopting zerowaste policies can help minimize the discharge of harmful environmental pollutants [2]. Finally, education and training for employees about the importance of sustainable practices encourages the integration of green manufacturing values into the company's culture. Implementing these strategies can help industries transition towards green manufacturing and contribute to global sustainability goals [3]. One of the primary goals of green machining is to reduce the use of cutting fluids, which are often used to cool and lubricate the machining process. Traditional cutting fluids can contain harmful chemicals and pollutants that can be harmful to both human health and the environment. Therefore, green machining employs alternative cutting fluids such as cryogenic machining [2, 4]. Cryogenic machining is a cutting-edge machining process that uses extremely cold temperatures to enhance the performance and efficiency of machining. This process involves the liquid nitrogen, or other cryogenic fluids are used to reduce the heat of the cutting tool during the machining process. Cryogenic machining is an innovative technique that employs extremely low-temperature cooling substances, such as liquid nitrogen, to optimize the machining process [5] found that the extreme cold temperatures used in cryogenic machining can significantly reduce the heat over the workpiece and tool, which can result in several benefits. For example, reducing temperature during the machining process can enhance the hardness of the workpiece, making it more resistant to wear and tear. This can lead increase the duration tool life, tool wear rate reduced, and ultimately, lower costs [6, 7]. Another significant benefit of cryogenic machining is the reduction in heat generation during the machining process. In traditional machining operations, heat generation can be a significant problem, leading to thermal distortion of the workpiece, reduced cutting tool life, and poor surface finish [8]. The amount of heat generated during machining can be significantly reduced by using cryogenic fluids to cool the workpiece and cutting tool, resulting in improved surface finish, dimensional accuracy, and overall part quality [5]. The current work is to keep the wear rate minimum of the tool insert while machining monel alloy using novel cryogenic machining and compare it with a surface roughness of the dry machining process.

The impact on tool wear can vary depending on the material being machined. In a study involving titanium and nickel alloys, it was noted that cryogenic machining slowed the progression of tool wear significantly. Cryogenic machining demonstrates superior output in terms of tool wear. Dry machining often results in high heat generation leading to rapid tool wear, which can be mitigated using cryogenic techniques. While cryogenic machining may reduce tool wear, considerations must be given to the equipment and operational costs involved in adopting this technology. It can present an upfront cost in the context of new equipment and installation. Rajendran et al. [9] cryogenic machining presents a novel approach to mitigate tool wear during the machining process, improving tool cutting life and economic efficiency during material removal operations. Nonetheless, the balance between these benefits and the operational costs of the process should be thoroughly assessed [10].

The total number of research papers published related to this work and sustainable production was 18300 in google scholar and 6124 in ScienceDirect in the past ten years [11] analyzed minimum quantity lubrication (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. MQL 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. 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 [12]. Additionally, because the working conditions of the tool are improved, cryogenic machining can contribute to better surface finish of the workpiece, reducing the need for secondary finishing processes which might lead to further tool wear. It was considered that research work is closely related to this research work.

Based on the research results, there have been limited investigations regarding the influence of cryogenic machining on the tool wear of monel. The experimental and depth of theoretical knowledge about various machining operations, cryogenic machining techniques, tool wear measurement techniques, metals and alloys, and interest in sustainable production motivated me to carry out this research work. This study is related to the machining of monel under different dry conditions and cryogenic machining. The machining type was ending milling. This study aims to examine how the cryogenic machining techniques affects flank wear and crater wear.

Materials and Methods

The primary division of this research comprises two groups: the control group and the study group. The CNC machining operation without any kind of lubrication is considered a control group. The machining operation using a novel cryogenic machining technique i.e., the compressed lubricant is applied to the machining zone is regarded as 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 [13].

For the control group, the machining operations are performed without lubrication. It is called dry machining. For this study, Monel alloy is taken as study material. Monel alloy, a remarkable blend of nickel and copper with traces of iron, manganese, carbon, and silicon, has garnered considerable recognition for its unique properties and varied applications. Characterized by its exceptional mechanical strength, corrosion resistance, and high thermal conductivity, it finds widespread application in environments demanding durability, malleability, and resistance to extreme conditions. The unique combination of properties position Monel alloys as the material of choice across various industries, including chemical processing, the oil and gas industry, electronics, and aerospace. In the chemical processing sector, Monel's superb resistance to chemicals and acids has prompted its use in chemical plant equipment. In the oil and gas sector [14]. Monel finds utility in offshore recovery processes that call for high strength, corrosion resistance, and low corrosion rates at high temperatures. Monel alloys, with their distinctive properties such as corrosion resistance, high strength, and malleability, have proven to be a versatile and reliable solution across various industries. With technological advancements and increasing demands. The material was purchased at Viruvadia Traders, Chennai. The size of the specimen is 150 mm × 150 mm × 10 mm. The coated carbide tools mentioned above are utilized for machining the Monel material. In the control group, the machining is conducted without any lubrication, referred to as dry machining.

For the study group, the machining operations are carried out with cryogenic machining setup shown in figure 1 [15]. Cryogenic machining is a unique cooling technique where super-cold liquefied gases, often liquid nitrogen, are used as a coolant. The method aids in improving the machine life, the product surface finish, reducing temperature, and increasing the machining speed. The machining equipment needs to be prepared for cryogenic treatment. Liquid nitrogen is the most used cryogen due to its very low boiling point (-196 °C) was selected. The cryogen is supplied through the machine spindle, directly onto the cutting tool tip at the cutting area. Once the cryogen is directed at the appropriate area, the machining process starts. The cryogen absorbs the heat produced by the cutting process, thus reducing temperature significantly. The flow rate of the cryogen may require adjustments during machining to achieve optimum results. After the machining is finished, allow the machine and the part to return to room temperature gradually. The setup is shown in figure 2. Six slots were cut to note the flank wear rate of the tool insert. The CNC machining operation has been performed using the vertical machining center EV 1020A which is shown in figure 3. According to the findings from the literature review, the machining parameters are taken. The coated carbide tool insert was used to perform the CNC machining operation. he control group conducted the end milling operation without any lubrication, following dry operation conditions. On the other hand, the study group utilized a cryogenic machining set-up and performed the end milling operation under the

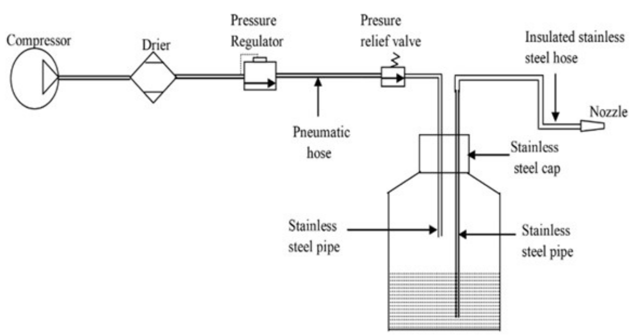

Figure 1: Cryogenic machining set-up line diagram.

Figure 2: Cryogenic machining setup.

Figure 3: Vertical milling machine YCM XV1020A.

cryogenic machining technique, using the same machining parameters.

After machining for the specified time, 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 evaluated using ImageJ application for both the control group (dry machining) and the study group (MQL technique). The tool wear is tabulated in table 1.

Statistical analysis

An independent samples t-test in SPSS was conducted. This kind of test is commonly used in experiments when comparing two different groups of subjects, for instance, a treatment group and a control group. These groups are defined by one categorical variable (the independent variable) with two levels, while the dependent variable is ensured to be continuous. In SPSS, the t-test can be accessed under the "Compare Means" category in "Analyze" menu. The output from this procedure includes the t-statistic, degrees of freedom, and the two-tailed p-value. These provide information about the magnitude of the difference between group means in relation to the variability within the groups [16].

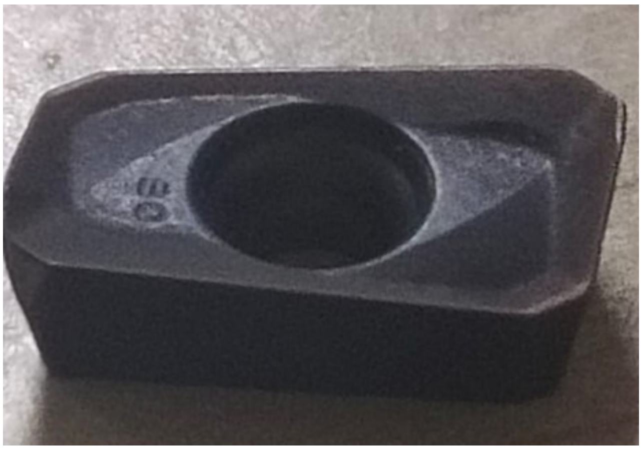

Figure 4: Flank wear of the tool insert.

Results

The measurement of flank wear on the tool insert samples from both the control group and study group was conducted using a Metzer optical microscope. The flank wear of the tool insert of both machined surfaces was further statistically analyzed using SPSS software and obtained values of various

Figure 5: Metzer microscope.

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

Sample no.	Tool wear in mm	Sample no.	Tool wear in mm	Sample no.	Tool wear in mm	Sample no.	Tool wear in mm
1	2.28	11	2.25	1	1.34	11	1.51
2	2.27	12	2.16	2	1.62	12	1.22
3	2.20	13	2.47	3	1.33	13	1.82
4	2.21	14	2.24	4	1.37	14	1.83
5	2.44	15	2.29	5	1.29	15	1.72
6	2.23	16	2.28	6	1.48	16	1.67
7	2.19	17	2.21	7	1.65	17	1.68
8	2.17	18	2.31	8	1.50	18	1.45
9	2.22	19	2.35	9	1.93	19	1.57
10	2.26	20	2.20	10	1.95	20	1.44

tests. The outcomes are shown in table 2. The mean flank wear of the tool insert of the dry machining is 2.2615 with a standard deviation of 0.08177 and the mean flank wear of the tool insert for the machined surface obtained in the cryogenic machining technique is 1.5685 with a standard deviation of 0.21236. The bar graph is shown in figure 6. The X-axis denotes a method of the machining technique, and the Y-axis denotes the mean flank wear of the tool insert. This graph shows that the machined surface obtained in the cryogenic machining technique has a better surface finish with a significantly lower error deviation as shown in table 3.

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

Group statistics					
		N	**Mean**	**Std. deviation**	**Std. error mean**
Flank tool wear	Control group	20	2.2615	0.08177	0.01829
	Study group	20	1.5685	0.21236	0.04749

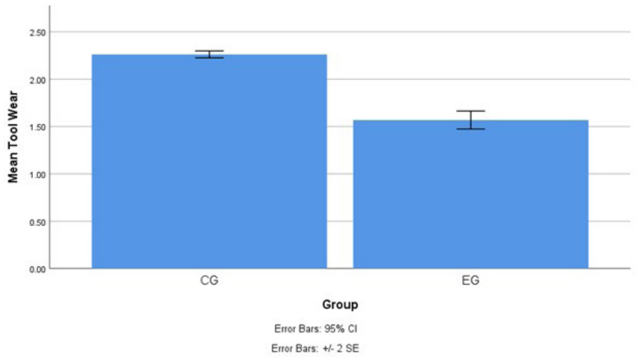

Figure 6: Mean tool wear comparison of machined surface from dry machining and cryogenic machining technique using bar graphs. Tool wear of the tool insert for machined surfaces from dry machining is 2.2615 with a standard deviation of 0.08177 and the tool wear of the tool insert is 1.5685 mm with a standard deviation of 0.21236. X-axis denotes method of machining technique and Y-axis denotes the mean surface roughness.

Discussion

The obtained results were compared with similar research studies [18]. In this study, author conducted an experiment using cryogenic machining technique. Flank wear in cutting tools is generally caused by the rubbing and friction with the finished surface of the workpiece during the cutting operation. With novel cryogenic machining, the flank wear can be significantly reduced. Utilizing cryogenic coolants (such as liquid nitrogen) in machining operations can substantially lower the heat generation at the cutting zone [11]. As cryogenic machining reduces flank wear; the result is an improved surface finish on the machined part. The reduced flank wear ensures that the finishing cut is performed with a sharp tool, thus providing a better surface finish [18]. By minimizing flank wear, cryogenic machining inherently increases the life of cutting tools. The lower temperatures, minimized friction, and reduced material deformation contribute to longer tool lifespan. Babu et al. [19]. conducted experimental work cryogenic machining helps in sustaining consistent cutting forces throughout the operation. This consistency can be attributed to reduced flank wear, which ensures that the tool maintains its sharpness for a more extended period. Researchers simulated cryogenic machining to characterize micro-mist droplet size and distribution. With cryogenic machining, the incidence of BUE is curtailed. BUE, a common phenomenon in machining, often contributes to flank wear. The extremely low temperatures during cryogenic machining harden the workpiece, preventing its material from sticking onto the tool and thereby reducing BUE and subsequent flank wear. One fundamental consequence of reduced flank wear in cryogenic machining is enhanced machining accuracy. With the tool maintaining its original shape and geometry for longer, machining precision is significantly increased. In conclusion, novel cryogenic machining significantly lowers flank wear in cutting tools through numerous mechanisms, leading to outcomes like extended tool life, better surface integrity, and enhanced machining accuracy. However, the effectiveness may depend upon various factors including the tool material, workpiece material aspect, cooling application, and machining parameters. They experimentally studied the effect of nozzle flank wear on the tool insert and air pressure, concluding that it improved tool life by reducing flank wear and crater wear. Notably, no contrary findings related to this research work were reported.

The rate of flow of the cryogen, the different types of glasses, cutting parameters, work materials are the variables affecting this study. The irregularity of the flow of cryogen, working conditions and non-uniform distribution of cryogen in manual feeding are the study's limitations. It is possible to research the effects of various types of gasses, in combination with MQL set-up, and different flow rate. The same investigation can be carried out with other cryogenic gasses and different flow rates to achieve sustainable production.

Table 3: Descriptive table representing Levene's test for equality and t-test for equality of means.

Independent samples test										
	Levene's test for equality of variances		**t-test for equality of means**							
	F	**Sig.**	**t**	**dt**	**Significance**		**Mean difference**	**Std. error difference**	**95% confidence interval of the difference**	
					One-sided p	**Two-sided p**			**Lower**	**Upper**
Equal variances assumed	17.163	0.000	13.619	38	0.000	< 0.001	0.69300	0.05088	0.58999	0.79601
Equal variances not assumed	-	-	13.619	24.513	0.000	< 0.001	0.69300	0.05088	0.58810	0.79790

Conclusion

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. 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 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. As a result, this effect helps reduce the flank wear of the tool insert to a greater extent compared to traditional flood lubrication methods. Within the limits of the study, there is a 30% reduction in tool wear when the cryogenic machining technique has been implemented over dry machining. Ongoing research and development in this area are likely to lead to further improvements in the performance and applicability of this technology which leads to sustainable production.

Acknowledgements

None.

Conflict of Interest

None.

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