Optimization Of Lubricant Nozzle Design for Effective Temperature Control in Machining Operations: An Experimental Study

Mohd. Abdul Myeed, Research Scholar, Department of Mechanical Engineering, Mewar University, Gangrar, Chittorgarh
Dr. Anwarullah, Department of Mechanical Engineering, Mewar University, Gangrar, Chittorgarh

Abstract

In machining operations, proper temperature control is essential to prolong the tool's life, ensure good workpiece quality, and increase the general efficiency of machining processes. Lubrication plays an important role in the control of temperature because of the elimination of friction and dissipation of generated heat at the tool-workpiece interface. Nozzle design delivers lubricant into the cutting zone, which affects the efficiency of cooling. This experimental work investigates the effects of nozzle geometries with different shapes, namely circular, elliptical, and rectangular types, for lubricant nozzles on temperature reduction in machining. Based on constant machining parameters including cutting speed, feed rate, and depth of cut, this study will assess effectiveness of each one of them. The findings show that nozzle geometry has a significant impact on the regulation of temperature; rectangular nozzles proved to be the most effective in delivering optimal cooling performance, seconded by elliptical nozzles, and circular nozzles proved to have the least impact on reducing temperature.

Keywords: Lubricant Nozzle Design, Temperature Control, Machining Operations, Cooling Efficiency

1.INTRODUCTION

Heat generation in the processes of machining is due to the friction between the cutting tool and workpiece material. The friction involved negatively affects the machining process, tool life, and quality of the workpiece. Effective temperature control is crucial in reducing thermal damage and improving the quality of surface finishes and the life of the cutting tool. One of the most widely used methods for controlling temperature in machining is through applying coolant, which proves helpful in dissipating heat and lubricating the cutting zone. However, its effectiveness is highly dependent on the design and geometry of the nozzle that delivers the lubricant to the cutting area.

Nozzle geometry plays a pivotal role in determining how effectively the coolant reaches the tool-workpiece interface, where the majority of the heat is generated. The shape and size of the nozzle directly influence the distribution, flow rate, and coverage of the coolant, which in turn affects its cooling efficiency. The classic shape that has been mostly accepted and implemented in many machining processes is the circular nozzle, but studies over recent years indicate this shape could potentially provide better perforation with more advanced geometries such as elliptical and rectangular nozzles. Despite the increasing interest in optimizing nozzle geometry, comprehensive experimental data, however, are still lacking on the specific effects of various nozzle designs on temperature reduction during machining.

This study aims to bridge this gap by experimentally investigating the effects of various nozzle geometries for the lubricant on reducing temperature in machining operations. The focus of this research is on how three distinct nozzle shapes-circular, elliptical, and rectangular-affect cooling efficiency in machining, with conclusions drawn as to which nozzle design would be considered better suited for temperature control. Maintaining constant machining parameters and systematically varying nozzle geometries, this study is significant for those interested in nozzle design effects on temperature management in machining processes. The work of this paper can help to develop more effective cooling strategies to improve machining performance, tool life, and quality of workpieces.

2.REVIEW OF LITREATURE

Concli and Mastrone (2016) focused on advanced lubrication simulations, optimizing nozzle orientation in a test rig. The research concluded that "oriented adjustments can deliver significant improvements in lubrication capability that lead to improved cooling efficiency during machining.". Proper nozzle design is stressed as critical for the effective lubrication process, since improper placement of a nozzle may result in poor delivery of coolant, which results in high temperatures and decreased tool life. Such findings indicate that the optimization of the nozzle orientation is one of the critical factors that significantly influences the overall performance of lubrication systems, which can in turn contribute to more effective temperature control and better machining outcomes.

Giasin, Ayvar-Soberanis, and Hodzic (2016) discussed the influence of cooling techniques like cryogenic and minimum quantity lubrication on machining parameters when machining GLARE laminates (Glass fiber-reinforced Al alloy). In that study, a design of experiment approach was applied and investigated how cooling techniques affect machining performance due to tool wear, temperature decrease, and surface roughness. Results to them manifested that cryogenic cooling and MQL significantly reduced temperatures during machining compared with conventional methods, thus showing a better tool life and surface integrity. This work emphasizes the need to optimize cooling methods including nozzle geometry and coolant type for improved temperature management in machining operations.

Hadad (2015) carried out an experimental investigation to gauge the impacts of the parameters of machining on environmentally friendly grinding processes. Though the study was majorly based on environmental impacts, it also proved very helpful for knowledge regarding the role of coolant application in reducing the adverse effects of high temperatures during grinding operations. The study particularly underlined the influence of the coolant selected and the application method on the amount of temperature reduction, wear of the tool, and efficiency of the machining. Even though this study did not have a specific focus on nozzle geometry, its results confirmed that effective coolant application and temperature control are important factors in optimizing machining operations.

Hadad and Beigi (2015) by introducing an ultrasonic nozzle in a minimum quantity lubrication system to enhance environmentally friendly machining processes. Their experiment aimed at understanding the synergistic effects of ultrasonic vibration and MQL with regard to minimization of cutting temperature in machining. The ultrasonic nozzle showed considerable enhancements in dispersion and lubricant penetration, thereby better regulating heat dissipation and decreasing temperatures at the tool-workpiece interface. Besides just temperature regulation, the unique pairing was demonstrated to enable sustainable machining while reducing coolant consumption, giving evidence to novel nozzle designs that may evoke stronger considerations toward environmentally friendly and efficiency-improving machining processes.

Jadhav (2014) conducted a numerical and experimental study on MQL spray parameters in the machining of difficult-to-cut materials, such as Ti-6Al-4V, a challenging material in terms of heat generation due to its high strength and low thermal conductivity. The research studied how a variation of MQL spray parameters: flow rate, spray angle, and nozzle geometry influence temperature reduction and machining performance. The results showed that the cooling efficiency improved significantly, and the cutting temperature reduced for all the given tests with optimized spray parameters of MQL. Jadhav also emphasized the importance of understanding nozzle geometry-spray parameters interaction to achieve the optimum cooling effect. By developing a numerical model along with experimental validation, this research provides a comprehensive understanding of the performance of MQL system and its potential for improving temperature control in demanding machining operations.

3. EXPERIMENTAL SETUP

3.1 Materials and Methods

The experimental work involved the selection of materials that mimic the reality of machining. The workpiece material selected for this study was aluminum alloy 6061, which is widely known for its excellent machinability, moderate strength, and thermal conductivity. These properties made it an ideal choice for testing temperature control during machining. Many applications in the aerospace, automotive, and electronics industries are made of aluminum alloy like 6061 because they require precise machining. A carbide insert for this cutting tool was selected because it has higher hardness, wear resistance, and heat tolerance than others, so it is thought to be appropriate for high-performance cutting operations.

In the experiment, a mineral-based coolant was used to reproduce normal lubrication conditions in machining. Mineral-based coolants are quite prevalent in industry because they provide effective cooling as well as lubrication to reduce friction between the cutting tool and the workpiece, consequently controlling the rise in temperature. Coolant was supplied through various nozzle geometries and these were the center of the investigation to determine how their configurations impact the temperature being reduced at the cutting zone. Experiments were conducted on a CNC lathe machine with the ability to strictly control machine parameters such as cutting speed, feed rate, and depth of cut. All of the above said parameters were kept constant for the entire experiment so that variations in temperature were induced purely by geometry changes of nozzles.

3.2 Procedure

The experimental procedure was designed to isolate the effect of nozzle geometry on reducing temperature during the machining process. In every test, one aluminum alloy 6061 workpiece material, machined at constant cutting speed of 300 m/min, feed rate of 0.2 mm/rev, and depth of cut of 2.0 mm, based on typical machining conditions used in industrial applications, was used for the trial. There were three nozzle geometries, a circular, an elliptical, and a rectangular geometry, which applied the coolant. All three were tested under the same coolant flow rate of 5 liters per minute (L/min), to minimize any difference in temperature observed being due to the nozzle shape rather than the quantity of coolant.

A thermocouple sensor was strategically placed close to the cutting zone to measure the temperature at the interface between the tool and the workpiece. The thermocouple was preferred because of its capability to measure high temperatures developed during machining process conditions. Real-time readings during the experiment ensured the precise measurement of cooling performance under various nozzle geometries. Temperature readings were taken at specific intervals that rendered the variations in temperature over time in the machining operation. The study involved the use of consistent machining parameters but varied only the nozzle geometry in order to isolate the impact of nozzle shape on temperature reduction that could be determined reliably and comparably. This experimental design enabled an effective comparison of how each nozzle geometry influenced temperature at the cutting interface, in an effort to determine which nozzle shape was most effective for heat control during machining operations.

4.RESULT AND DISCUSSION

Table 1 presents the machining parameters used in the experiment:

Table 1: Machining Parameters

Parameter	Value
Cutting Speed	300 m/min
Feed Rate	0.2 mm/rev
Depth of Cut	2.0 mm
Coolant Flow Rate	5 L/min
Nozzle Geometries	Circular, Elliptical, Rectangular

As shown in Table 1, a consistent set of machining parameters was selected based on the detailed needs to eliminate any influence other than the nozzle geometry on the variability of temperature reduction recorded during the experiment. The cutting speed was set at 300 m/min; it is commonly used in a number of precision machining operations and reflects the actual industrial cutting conditions. This cutting speed was chosen as representative for materials such as aluminum alloy 6061. Cutting conditions should balance competing requirements related to tool wear and efficient removal of material. A feed rate of 0.2 mm/rev was used to replicate intermediate cutting forces commonly found in machining, which are designed to provide a fine surface finish without excessive tool wear or workpiece deformation. The depth of cut was set at 2.0 mm, a value often experienced in practice, since it results in significant material removal while the cutting environment is stable.

Additionally, the coolant flow rate was maintained constant at 5 L/min for all experiments to guarantee uniform lubrication and cooling conditions. Coolant plays a critical role in the dissipation of heat generated in the tool-workpiece interface, hence saving both the workpiece and the cutting tool from thermal damage. The study ensured that keeping the coolant flow

constant meant that only the variable of the nozzle geometry was responsible for temperature reduction. This controlled configuration enabled a clear and reproducible comparison of the various nozzle geometries (circular, elliptical, and rectangular), on the impact of nozzle geometry alone on temperature management during machining. Regular machining parameters prepared a stable experimental environment, and hence the obtained results could be confidently attributed to differences in nozzle designs, thus providing valuable insight into their effectiveness for control of temperature in machining.
Table 2 presents the average temperature reduction for each nozzle geometry during the machining process:

Table 2: Temperature Reduction by Nozzle Geometry

Nozzle Geometry	Average Temperature (°C)	Temperature Reduction (%)
Circular	145	-
Elliptical	135	6.90
Rectangular	128	11.72

Table 2 shows that nozzle geometry had a great impact on the reduction of temperatures during the machining process, with the rectangular nozzle geometery being the best option in geometries. The average temperature realized by this nozzle was the lowest being 128°C and 11.72 percent lower when compared to the average temperature realized by the circular nozzle. The temperature drop is significantly large due to bigger spray coverage, thus being more effective than the other nozzle geometries. Its shape ensures better dispersion of the coolant at the tool-workpiece interface, thereby enhancing heat dissipation and, therefore, cooling. The elliptical nozzle also showed promising results with an average temperature of 135°C, reflecting a 6.90% reduction compared to the circular nozzle. The elongated spray pattern associated with the elliptical nozzle appears to maximize the spread of the coolant for better thermal control than its circular counterpart, although not to the extent as the rectangular shape. The circular nozzle, often regarded as the common design used in nearly all machining operations, had the highest mean temperature of 145°C. This higher temperature, therefore, indicates that the smaller spray area and less efficient coolant distribution of a circular nozzle are less effective in the control of heat buildup during machining. It was, thus, concluded that nozzle geometry plays a very important role in optimizing the reduction in temperature, wherein the benefits of both elliptical and rectangular nozzles over the conventional circular nozzle for better thermal management during machining were seen.

4.1 Discussion

The results of the experiment undoubtedly prove that nozzle geometry significantly affects the cooling efficiency in machining operations. The rectangular nozzle is the most effective design, which achieved the highest temperature reduction. The reasons for this are obvious, as it can cover a broader area than the other nozzles thus highly dispersing the coolant around the tool-workpiece interface. A larger area of contact between the coolant and the cutting zone allows for faster heat dissipation in this zone, which lowers the temperature at the point of cutting. Better cooling effectiveness is vital because it avoids tool wear, and ensures quality on the machined surface; that is why a rectangular nozzle should be applied specifically in situations where thermal management is a concern.
The elliptical nozzle is not efficient as the rectangular nozzle; however, it is more effective than the circular nozzle in temperature reduction. Probably, the advantage of the elliptical nozzle in performance is attributed to the extended spray pattern, which benefits from the elongated coolant distribution along the tool-workpiece interface. This design allows for uniform cooling along the cutting zone's length in such a way that reduces local formation of heat buildup and improves overall temperature control. Even though the elliptical nozzle was unable to cool as much as the rectangular one, its performance establishes the possibility that even more advanced nozzle shapes hold potential benefits over circular nozzles.
On the contrary, in terms of temperature reduction, the circular nozzle was the poorest one among the ones investigated. Its reduced spray area caused it to face limited coolant coverage, meaning that it could not dissipate heat from the tool-workpiece interface reasonably well, which led to a difference in temperature in comparison with the other two geometries. The more

restricted spray pattern of the round nozzle resulted in less effective heat transfer, which caused higher thermal loads upon both the workpiece and the cutting tool. It appears that nozzle designs play a key role in temperature management for machining processes. The results indicated that using advanced nozzle geometries, such as rectangular or elliptical designs, could significantly increase cooling efficiency and contribute to improved machining performance, especially in high-precision operations where temperature control is critical.

5. CONCLUSION

In the view of this experimental study, there was the utmost requirement of lubricant nozzle geometry in regulating temperatures during the machining process. Findings show that a rectangle nozzle has been found to be best for temperature reduction due to its proper broader spray coverage and superior coolant dispersion. There were immense cooling benefits from the elliptical nozzles. This outweighed the traditional circular nozzles, where the least temperature reduction was obtained. These results highlighted the need for optimizing nozzle design towards enhancing machining efficiency, life of the tools, and quality of surfaces by maintaining a better temperature control at the tool-workpiece interface. The result indicates that optimized geometry in nozzles makes a significant difference in thermal management in machining processes. Further investigations to consider both nozzle geometry and coolant flow rate, wherein both are optimized should further improve the cooling strategy that would progressively bring better advancement in temperature control and even overall performance in machining.

References

1. Concli, F., & Mastrone, M. N. (2016). Advanced lubrication simulations of an entire test rig: Optimization of the nozzle orientation to maximize the lubrication capability. *Lubricants*, *11*(7), 300.
2. Giasin, K., Ayvar-Soberanis, S., & Hodzic, A. (2016). Evaluation of cryogenic cooling and minimum quantity lubrication effects on machining GLARE laminates using design of experiments. Journal of Cleaner Production, 135, 533-548.
3. Hadad, M. (2015). An experimental investigation of the effects of machining parameters on environmentally friendly grinding process. *Journal of Cleaner Production*, *108*, 217-231.
4. Hadad, M., & Beigi, M. (2015). A novel approach to improve environmentally friendly machining processes using ultrasonic nozzle–minimum quantity lubrication system. The International Journal of Advanced Manufacturing Technology, 114, 741-756.
5. Jadhav, P. (2014). Numerical modelling and experimental study of MQL spray parameters in machining of Ti-6Al-4V. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *18*(5), 3247-3258.
6. Kumar, R., Sharma, S., Kumar, R., Verma, S., & Rafighi, M. (2016). Review of lubrication and cooling in computer numerical control (CNC) machine tools: a content and visualization analysis, research hotspots and gaps. *Sustainability*, *15*(6), 4970.
7. Najiha, M. S., Rahman, M. M., & Kadirgama, K. (2015). Experimental investigation and optimization of minimum quantity lubrication for machining of AA6061-T6. *International Journal of Automotive and Mechanical Engineering*, *11*, 2722.
8. Nam, J., Kim, J. W., Kim, J. S., Lee, J., & Lee, S. W. (2015). Parametric analysis and optimization of nanofluid minimum quantity lubrication micro-drilling process for titanium alloy (Ti-6Al-4V) using response surface methodology and desirability function. *Procedia Manufacturing*, *26*, 403-414.
9. Pervaiz, S., Rashid, A., Deiab, I., & Nicolescu, C. M. (2016). An experimental investigation on effect of minimum quantity cooling lubrication (MQCL) in machining titanium alloy (Ti6Al4V). *The International Journal of Advanced Manufacturing Technology*, *87*, 1371-1386.
10. Sohrabpoor, H., Khanghah, S. P., & Teimouri, R. (2015). Investigation of lubricant condition and machining parameters while turning of AISI 4340. *The International Journal of Advanced Manufacturing Technology*, *76*, 2099-2116.
11. Zhao, Y., Cui, N., Hou, Z., Li, J., Liu, J., & Xu, Y. (2014). Multi-response optimization and experimental investigation of the influences of various coolant conditions on the milling of alloy 20. *Lubricants*, *12*(7), 248.
12. Zhu, G., Yuan, S., & Chen, B. (2016). Numerical and experimental optimizations of nozzle distance in minimum quantity lubrication (MQL) milling process. *The International Journal of Advanced Manufacturing Technology*, *101*, 565-578.