Investigation on Processing Technology of Minimum Quantity Lubrication Nozzle and Its Influence on Atomization Effect

LI Donghui, *ZHANG Tao**, *ZHENG Tao*, *QI Wei*

National-Local Joint Engineering Laboratory of Intelligent Manufacturing Oriented Automobile Die & Mould, Tianjin University of Technology and Education, Tianjin 300222, P. R. China

(Received 18 October 2024; revised 5 February 2025; accepted 17 March 2025)

Abstract: Minimum quantity lubrication (MQL) is a technique that achieves effective lubrication and cooling of the cutting zone by using a minimal amount of cutting fluid. This results in a decrease in the cutting temperature, extending the cutting tool life and improving the surface quality of the workpiece. Optimizing the nozzle settings can enhance the cooling and lubrication performance of MQL, leading to increased processing efficiency and product quality. Nozzles with different shapes are fabricated, and different outlet diameters and wall thicknesses are set. The cutting process takes into account the impact of spindle speed and feed rate. An experimental study is conducted to investigate the atomization cone angle and particle size distribution of different nozzles. The circular nozzle is more conducive to the concentrated injection of an atomized liquid beam. The atomization cone angle is the largest when the nozzle outlet diameter is 1.2 mm. Enlarging the nozzle outlet diameter will increase the diameter of the atomized droplets. The atomization cone angle increases while the droplet diameter decreases with the increase of outlet wall thickness. Properly increasing the outlet wall thickness is beneficial to improving the atomization quality. The droplet diameter increases firstly and then decreases with the increase of spindle speed and feed rate. Increasing the MQL gas supply pressure and reducing the lubricating oil flow rate will improve the atomization quality of the nozzle. Studies on the influence of the MQL nozzle processing technology on the atomization effect can help to enhance the cooling and lubrication performance of the MQL technology, leading to improved processing efficiency and quality.

Key words: minimum quantity lubrication(MQL); nozzle processing; spray cone angle; droplet diameter

CLC number: TG50 **Document code:** A **Article ID:** 1005-1120(2025)02-0261-14

0 Introduction

With the continuous progress of the global manufacturing industry, fluid of metal cutting has become an essential component of the cutting process. This field has historically confronted the simultaneous challenges of resource utilization and environmental conservation. Traditional flood cutting not only consumes a lot of resources, but also the harmful substances in the cutting fluid pose a potential threat to the environment and operating workers[1-2]. These issues have attracted increasing attention from all walks of life, promoting the industry to seek more environmentally friendly and efficient processing technology. The emergence of minimum quantity lubrication (MQL) cutting technology occurred in this environment. MQL compresses the gas to atomize with small amount of cutting fluid into micron-sized droplets. This process effectively cools and lubricates both the tool and the workpiece[3]. As an efficient and green new cutting method, MQL has advantages of less cutting fluid, lower cutting force and cutting temperature, less cutting tool wear, and higher surface quality compared with traditional dry cutting and flood cutting[4-5].

The atomization effect of MQL has significantly impact on cutting efficiency and process quality. In the past, scholars focused on the influence of dif-

*Corresponding author, E-mail address: Goldsound@163.com.

How to cite this article: LI Donghui, ZHANG Tao, ZHENG Tao, et al. Investigation on processing technology of minimum quantity lubrication nozzle and its influence on atomization effect[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2025,42(2):261-274.

http://dx.doi.org/10.16356/j.1005-1120.2025.02.010

ferent atomization methods on the spray effect and the effect of application in cutting. Xu et al.[6] investigated the atomization characteristics and grinding performance of electrostatic MQL (EMQL). Compared with pneumatic MQL, the average particle size and droplet distribution range of EMQL droplets were reduced by 7.1% and 40.3%, respectively. Smaller-diameter droplets were more likely to form a lubricating layer at the grinding interface. It reduced the surface roughness of the workpiece by 3.04%. Zhang et al.[7] investigated the droplet size distribution during ultrasonic atomization using the laser diffraction method. It had been observed that the droplet size increases with the increase of fluid flow rate, and the droplet distribution range also increases. When the surface tension of the droplet falls below 42.4 mN/m, the droplet size decreases with the decrease of surface tension. Furthermore, excessive or insufficient liquid viscosity will result in a more scattered droplet distribution. Jia et al.[8] investigated the fluctuation of EMQL liquid film and the range of atomized droplet size distribution. When electrostatic atomization was used instead of pure pneumatic atomization, the liquid film at the nozzle outlet had a clear Taylor cone shape. Additionally, the number of transverse peaks increases and the peak distribution becomes more uniform. The electrostatic atomization can not only reduce the droplet size distribution range, but also significantly inhibit the generation of PM_{10} and $PM_{2.5}$ particulate matter. Liu et al.[9] introduced a novel form of cold gas EMQL technology. The cold gas amplifies the temperature disparity between the cutting zone and the surrounding environment, enhancing the convective heat transfer capability. Lyu et al.[10] introduced an EMQL technology that utilizes graphene nano-lubricants (GPLs) as additives. The addition of GPLs promotes the further penetration of oil droplets into the friction interface, resulting in a significantly reduction in friction and wear.

The droplet size of MQL is influenced by the atomization method, while the cutting effect is directly impacted by the spray angle and distance of the nozzle. Haq et al.[11] set the angle between the nozzle and the workpiece surface to 45° and a distance of 25 mm. The nozzle directs the sprayed oil mist towards the chip fracture point, ensuring that it consistently fills the space between the cutting tool and the chip fracture channel. Pusavec et al.[12] adopted the MQL method of multi-nozzle spray simultaneously to enhance lubrication and cooling efficiency during the turning process of Inconel 718 alloy. The number and angle of nozzles can be adjusted to suit different processing parameters. Huang et al.[13] combined and optimized the parameters of nozzle angle, nozzle spacing, pressure, and flow rate in ultrasonic MQL. The grinding experiment revealed an optimal combination value for each parameter, leading to the achievement of the maximum grinding value.

Furthermore, the internal jet nozzle that places the nozzle inside the cutting tool is also widely used[14]. Internal spray MQL needs to avoid the collision of droplets inside the pipeline. The implementation of internal spray requires modifications to the cutting tool, handle, and even spindle of the machine tool, resulting in a decrease in the performance of these machine tool components[15-16].

The nozzle is an important part of the MQL system. Some researchers began to improve and reorganize the nozzle in order to achieve better atomization effects. Yao et al.[17] conducted a comparative analysis of the atomization performance and cutting performance of four distinct nozzle designs. The shape of the nozzle outlet can significantly affect the atomization and injection of droplets, and then affect the cutting performance. Sharmin et al.[18] improved the traditional circular nozzle by transforming it into a multi-hole side-by-side nozzle. The grinding experiments revealed that the upgraded nozzle outperforms the traditional nozzle in terms of performance. The improved nozzle delivers the cutting fluid more uniformly to the point of contact with the grinding wheel compared with the traditional nozzle, resulting in a decrease in the grinding temperature. Chen et al.[19] studied the atomization behavior of two-fluid spray with or without self-excited vibrating cavity (SVC) to improve processing performance and minimize environmental pollution. The droplet size of the nozzle with SVC was reduced by about 46.85%, and the number concentration of droplets was increased by about 94.73%. They believed that SVC-assisted atomization was advantageous in diminishing cutting tool wear, reducing cutting temperature, and enhancing the surface quality of the workpiece.

The atomization cone angle and droplet size distribution are crucial parameters for assessing the atomization performance of the nozzle. There is an optimal combination of the parameters of the MQL system, which makes the atomization effect best. In the cutting process, optimal selection of MQL parameters is beneficial for improving cutting performance[20]. Liu et al.[21] pointed out in the study that the distance between the nozzle and the cutting zone was too large or too small, which was not conducive to the quality of droplets near the cutting zone. Rahim et al.[22] studied the performance of MQL under different parameter combinations. The atomization cone angle of 0.4 MPa pressure was found to be the optimal atomization cone angle in the cutting process, since it effectively covered the entire cutting zone. In addition, the cutting force and cutting temperature reached their minimum values when the nozzle was positioned at a distance of 6—9 mm from the cutting surface.

The machining accuracy of the nozzle directly affects the internal structure and hydrodynamic characteristics of the nozzle. The nozzle surface quality is affected to the surface energy, wettability, and wear resistance of the nozzle material. The machining accuracy and surface quality effect interact with each other to affect the atomization effect of the nozzle. Currently, there is a dearth of systematic investigation on the processing technology of the MQL nozzle and its specific influence on atomization cone angle and droplet size distribution. Based on the above analysis, this paper conducts an experimental study to investigate the effect of MQL atomization. Firstly, the nozzles with different parameters are processed, and then the atomization test of the nozzle is carried out by single factor experiment. The results of this study provide a reference for improving the overall performance of MQL, resulting in improved lubrication and cooling capabilities. Moreover, the result of this paper provides an empirical foundation for improving the design and parameter choice of the MQL nozzle.

1 Experimental Settings

1.1 Nozzle material and processing equipment

The MQL nozzle should have excellent machinability and corrosion resistance. The nozzle material is a 6061 aluminum alloy bar with a diameter of 6 mm. The 6061 aluminum alloy is widely used for its exceptional processing capabilities, strong resistance to corrosion, and no deformation after processing. In addition, 6061 aluminum alloy has a lower density, which makes the nozzle more portable and helps to realize the lightweight nozzle design. The chemical composition and mechanical properties of 6061 aluminum alloy are shown in Table 1 and Table 2, respectively.

Table 1 Chemical composition of 6061 aluminum alloy[23]

%

Cu	Mn	Mg	Cr	Ti	Si	Fe	Al
0.22	0.05	1.06	0.08	0.03	0.7	0.25	Bal.

Table 2 Mechanical properties of 6061 aluminum alloy[24]

Tensile strength/MPa	Compressive yield strength/MPa	Modulus of rupture in bending/MPa	Elastic modulus/GPa
⩾205	55.2	228	68.9

Considering the size of the nozzle and the machining accuracy, a three-axis vertical engraving machine is selected to process the nozzle. The engraving machine has maximum strokes of 200 mm, 300 mm, and 120 mm along X, Y, and Z axes, respectively. The engraving machine fully meets the requirements of nozzle processing, and the processing is shown in Fig.1.

During the initial phase of processing, the end face of the aluminum alloy bar is milled using a 4 mm diameter milling cutter. Subsequently, a high-speed steel (HSS) twist drill with a diameter of 0.6—4 mm is used to perform rough machining. The working part of the twist drill has a hardness ranging from 63—66.5 HRC, which has the advantages of hard and durable, low friction coefficient, and long cutting life. After the completion of rough

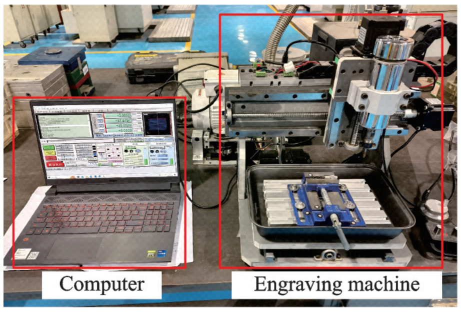


Fig.1 Nozzle machining process

machining, the milling cutter is used to mill the bottom of the hole. Finally, the nozzle outlet is completed by the process of engraving the milling cutter. The diameter of the engraving milling cutter handle is 3.175 mm, the diameter of the milling cutter tip is 0.1 mm, and the angle is 20°. The cutting tool is made of tungsten steel with a titanium coating. This cutting tool is extensively utilized in the machining of aluminum, iron, steel, stainless steel, and other metallic materials. The twist drill, milling cutter, and fixture are shown in Fig.2.

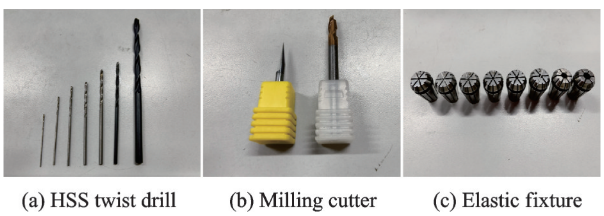


Fig.2 Cutting tool and fixture

1.2 Nozzle design and atomization parameters selection

The parameters such as the shape and diameter of the nozzle will directly affect the pressure and flow state of the lubricating oil, and thus directly affect the size and velocity of the atomized droplets. Therefore, the nozzle design should not only consider the shape and diameter, but also consider whether it can be processed under the existing conditions. Combined with previous studies, the nozzle parameters designed in this experiment are determined[25-26].

In this paper, five kinds of nozzle shapes are designed: Rounded rectangle, inner cone, rectangle, roundness, and square. The nozzle outlet shape is shown in Fig.3. In order to ensure the unity of the variables, the nozzle outlet area of different shapes is set to be 3.14 mm^2, and the nozzle outlet wall thickness is 0.5 mm. In addition, the machining parameters with a rotation speed of 15 000 r/min and a feed rate of 0.015 mm/r are used for cutting.

In practical applications, the function of the atomizing nozzle is not only to decompose the liquid film into small droplets, but also to discharge these droplets in a symmetrical and uniform spray form. In view of the small atomization cone angle of MQL and the uniform distribution of droplets in the whole spray volume, a flat-hole atomizing nozzle is used for the experiment. Since the flat-hole nozzle produces narrow and compact atomized droplets, only a small number of droplets are affected by air resistance. Therefore, the overall distribution of the droplet is mainly determined by the size and direction of the velocity transmitted to it from the nozzle outlet.

Round nozzles are most widely used in practical applications. The diameter of the round nozzle and the nozzle outlet wall thickness are selected as parameters to explore the influence of the nozzle outlet parameters on the atomization effect. The rotational speed and feed rate are selected as processing parameters to explore the influence of processing technolo-

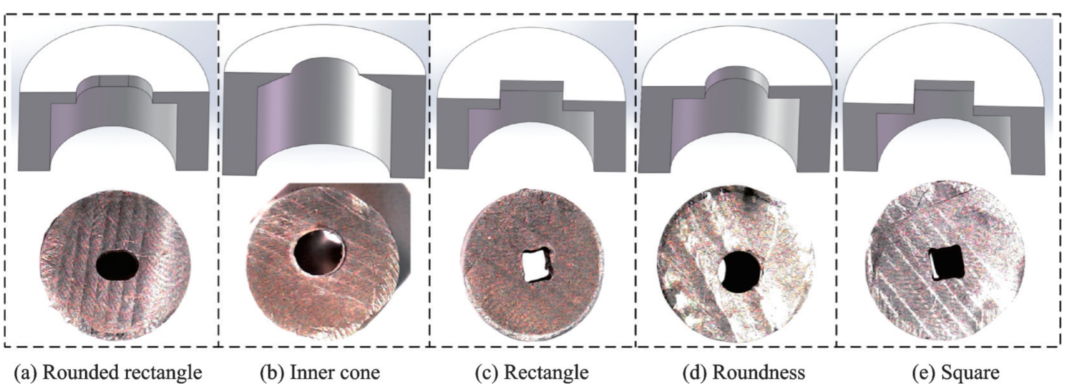


Fig.3 Three-dimensional and physical maps of MQL nozzle

gy on the atomization effect of MQL. On this basis, two MQL system parameters of gas supply pressure and lubricating oil flow are added. Finally, the impact of various factors on atomization, including nozzle outlet shape (s), outlet diameter (d), outlet wall thickness (h), rotational speed (n), feed rate (f), gas supply pressure (p), and flow rate (q), are studied. The range of experimental parameters for atomization of the MQL nozzle is displayed in Table 3.

Table 3 MQL nozzle atomization experimental parameters

s	d/mm	h/mm	n/(r•min^{-1})	f/(mm•r^{-1})	p/MPa	q/(mL•h^{-1})
Rounded rectangle/inner cone/rectangle /roundness/square	0.6—1.8	0.5—1.3	13 000—21 000	0.005—0.025	0.2—0.4	18—90

1.3 Set of atomization experiment

The pneumatic MQL device (Model: CH2000) is used in this study. The device modulates the gas pressure by adjusting the output gas volume, and the pressure adjustment range is 0.03—1.0 MPa. The oil channel outputs 0.03 mL oil when the oil supply pump works once, with a total of three oil channels. The plant-based lubricating oil (Model: M-106) is used in the experiment, which is composed of base oil and additives. The physical properties of the lubricating oil are shown in Table 4.

Table 4 Physical properties of lubricating oil

Color	Relative density/(kg•m^{-3})	Boiling point/℃	Flash point/℃	Viscosity/(Pa•s)
Amber	812	316	176	14.616×10^{-3}

The atomization experiment comprises two components: The nozzle atomization cone angle experiment and the atomized droplet size distribution experiment. The schematic diagrams of the atomization cone angle experiment and the atomized droplet collection are presented in Fig.4. The nozzle injection state is captured using a high-speed industrial camera (Model: NPX-GS6500UM). The camera has a maximum frame rate of 10 000 frames/s, as well as a minimum exposure time of 0.001 24 ms.

In order to avoid the issue of droplet overlap during droplet collection, a baffle with a narrow aperture is employed to obstruct the liquid stream. The diameter of the small hole in the middle of the baffle is 1 mm. The distance between the baffle and the collecting plate (L) and the distance between the nozzle and the baffle (l) are adjusted to 145 mm and 120 mm, and the nozzle injection time is set to 10 s. The droplets on the collection plate are as many as possible and do not overlap.

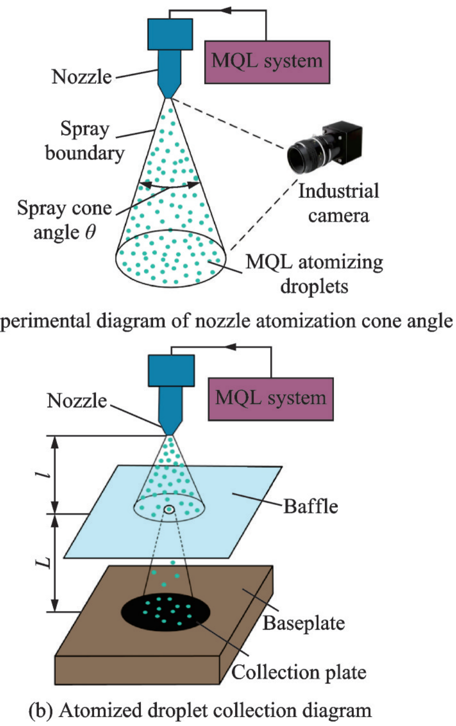
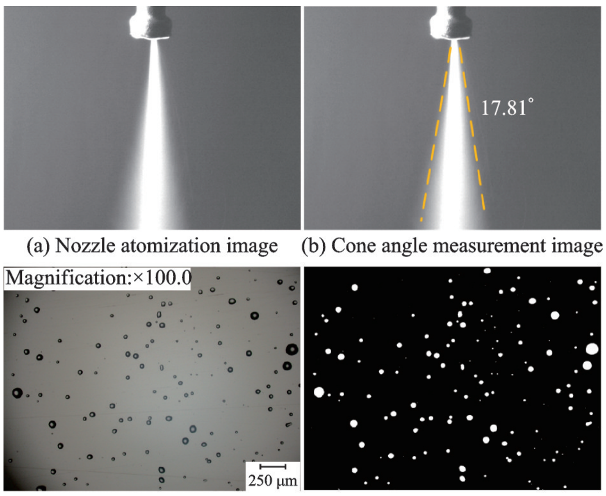


Fig.4 Experimental schematic diagram

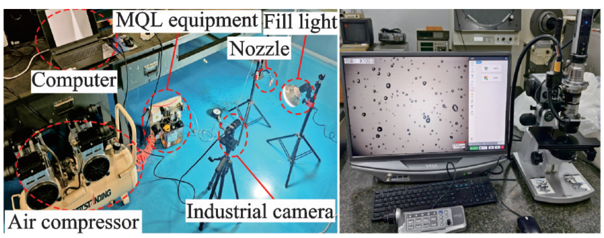
A major difficulty in defining and measuring the cone angle is that the spray cone has a curved boundary due to the interaction between air and droplets. In order to overcome this problem, the angle formed by the two cutting spray contours drawn at the nozzle outlet is usually used as the cone angle. A common method for measuring the spray cone angle is to record the contour image of the spray at an appropriate magnification. Fig.5(a) is the nozzle atomization photograph. The cone angle of the liquid beam in the picture is measured to obtain the atomization cone angle of different nozzles, as shown in Fig.5(b). The droplets are observed by an ultra-depth-of-field microscope (Model: VHX-970F). Then, the droplet photo is binary processed to obtain each droplet size data. The photographs of the droplets and the binary processed images are shown in Figs.5(c, d). Fig.6 displays the atomization cone angle experiment of the MQL nozzle and the atomization droplet shooting scene.



(a) Nozzle atomization image (b) Cone angle measurement image

(c) Droplet real shot image (d) Droplet binary image

Fig.5 Atomization and droplet images



(a) Experimental diagram of atomization cone angle (b) Ultra-depth-of-field microscope photograph of atomized droplets

Fig.6 Experimental equipment

1.4 Data processing

The process of atomization will form a large number of micron-sized droplets and eject with high-pressure gas. The size of the ejected droplets is uneven, and the mean diameter of the droplets is used to replace the droplet diameter of the uneven droplet group. The standard deviation is used to represent the dispersion degree of the droplet size of nozzle atomization under a certain parameter. The calculation method of the mean diameter and standard deviation of droplets are shown in

$$\bar{D}=\frac{\sum_{i=1}^{n}D_i}{n} \tag{1}$$

$$s=\sqrt{\frac{\sum_{i=1}^{n}(D_i-\bar{D})^2}{n}} \tag{2}$$

where $\bar{D}$ is the average diameter of atomized droplets, D_i the particle size of the ith droplet, and n the total number of droplets.

The Sauter mean diameter (SMD) is a key parameter to evaluate the atomization quality, which can better reflect the atomization degree of the nozzle. In this experiment, the SMD is introduced to quantify the influence of different parameters on the atomization effect. The calculation of the SMD is shown as

$$D_{32}=\frac{\sum_{i=1}^{n}N_iD_i^3}{\sum_{i=1}^{n}N_iD_i^2} \tag{3}$$

where D_{32} is the SMD of atomized droplets and N_i the number of droplets with a diameter of D_i.

2 Experiment Results and Analysis

2.1 Influence of nozzle outlet shape on atomization effect

Fig.7 shows the result of nozzle outlet shape on the atomization cone angle and droplet size. The experimental conditions are as follows: d=1.2 mm, l=0.5 mm, n=15 000 r/min, f=0.015 mm/r, p=0.3 MPa, q=54 mL/h. As shown in Fig.7(a), the square nozzle has the largest atomization cone angle, whereas the round nozzle is the smallest. The four right-angle edges promote the dispersion of the liquid when the lubricating oil flows through the square nozzle. The edge right-angle effect makes it easier for the oil mist to form a dispersed flow in multiple directions, thus forming a larger atomization cone angle. The edge of the round nozzle is smooth, and the oil mist maintains a relatively concentrated flow through the circular nozzle, resulting in a relatively small atomization cone angle. The atomization cone angles of round, rounded rectangle, rectangle, and square nozzles increase. Therefore, the round nozzle is more suitable when precise control over the spray range is required. In addition, due to the structural characteristics of the round noz-

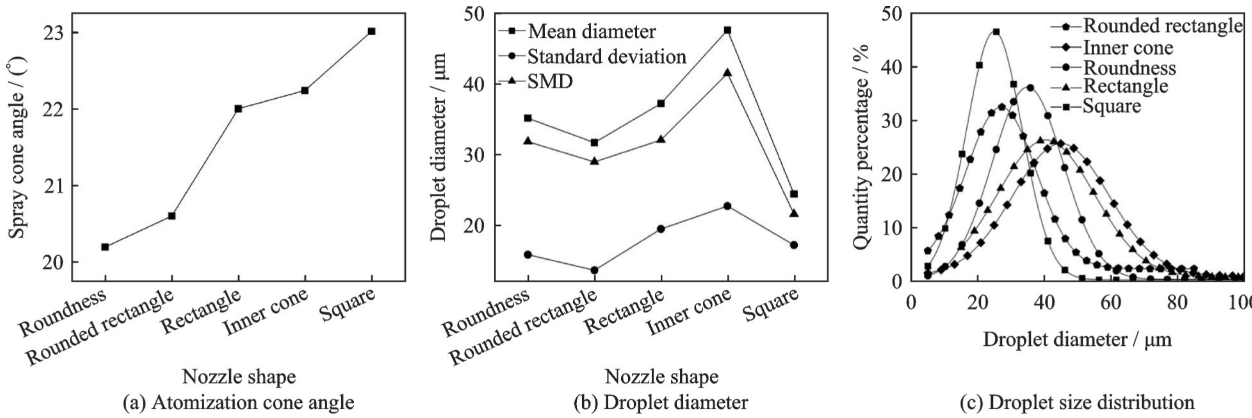


Fig.7 Influence of nozzle outlet shape on atomization effect

zle, the spray shape is axisymmetric conical. From the perspective of the cost of nozzle processing, round nozzle processing is the easiest and the lowest cost.

As shown in Figs.7(b,c), the square nozzle produces atomized droplets with the smallest mean diameter and SMD. Additionally, the droplet distribution range is the narrowest. The inner cone nozzle produces the largest atomized droplet size and also is the largest standard deviation in droplet size. The outlet of the inner conical nozzle is a conical shape. As the diameter of the nozzle outlet gradually decreases, a certain pressure gradient is created when the oil mist flows through the outlet. Therefore, the oil mist is unevenly stressed during the ejection process. This non-uniform force can impede the rapid formation of tiny droplets after liquid is ejected. Among the round, rounded rectangle and rectangle nozzles, the rounded rectangle nozzle has the smallest diameter and standard deviation of atomization droplets. The rounded rectangle nozzle reduces the mean diameter of its droplets by 14.88% and lowers the SMD by 9.69% compared with the rectangle nozzle. However, the mean diameter of the rounded rectangle nozzle increases by 22.97% compared with the square nozzle, and the SMD decreases by 25.49%.

The square nozzle has the widest atomization cone angle, and the mean diameter of the atomized droplets is the smallest and the distribution is more uniform. However, the round nozzle has more advantages in precision injection. In the fields of ultra-precision machining and micromachining, square nozzles will be beneficial to improve the lubrication and heat dissipation performance of MQL. In traditional metal processing, the use of round nozzles will help reduce lubrication costs.

2.2 Influence of nozzle outlet diameter on atomization effect

Fig.8 shows the influence of nozzle outlet diameter on atomization cone angle and droplet size. The experimental conditions are as follows: s=roundness, l=0.5 mm, n=15 000 r/min, f=0.015 mm/r, p=0.3 MPa, q=54 mL/h. The atomization cone angle of MQL initially increases firstly and then decrease as the diameter of the nozzle outlet increases. When the nozzle outlet diameter is 1.2 mm, the atomization cone angle reaches the maximum of 19.296°. When the nozzle outlet diameter is small, increasing the nozzle outlet diameter increases the gas-liquid ratio, resulting in more dispersed spray. However, the dispersion effect may reach saturation or transition when the nozzle outlet diameter increases to a certain extent. The mixing effect of gas and liquid is the best when the nozzle diameter is 1.2 mm, so the atomization cone angle is the largest. As the nozzle outlet diameter increases even more, the process of nozzle atomization begins to converge, resulting in a decrease in the atomization cone angle. The cutting area is smaller than the spray area, and the appropriate spray area helps to maximize the lubrication and cooling effect. According to different processing methods, the appropriate atomization nozzle diameter is selected to maximize the MQL efficiency.

As shown in Figs.8(b,c), the mean diameter and the SMD of the atomized droplets increase as the nozzle outlet diameter increases. Compared with the nozzle outlet diameter of 0.6 mm, the mean diameter and SMD at 1.8 mm increase by 55.75% and 54.32%, respectively. The flow state of MQL in the pipe and nozzle is an annular liquid film[27]. By maintaining a steady gas supply pressure and flow rate, the gas-liquid ratio of the nozzle increases with the diameter of nozzle outlet increases. The flow rate of MQL is significantly lower than that of gas. Therefore, the probability of fragmented droplets reaching the middle of the liquid beam decreases, resulting in a reduction in the secondary atomization effect. Thus, both the mean diameter of the MQL atomized droplets and the SMD show an overall increasing trend when the outlet diameter of the nozzle increases.

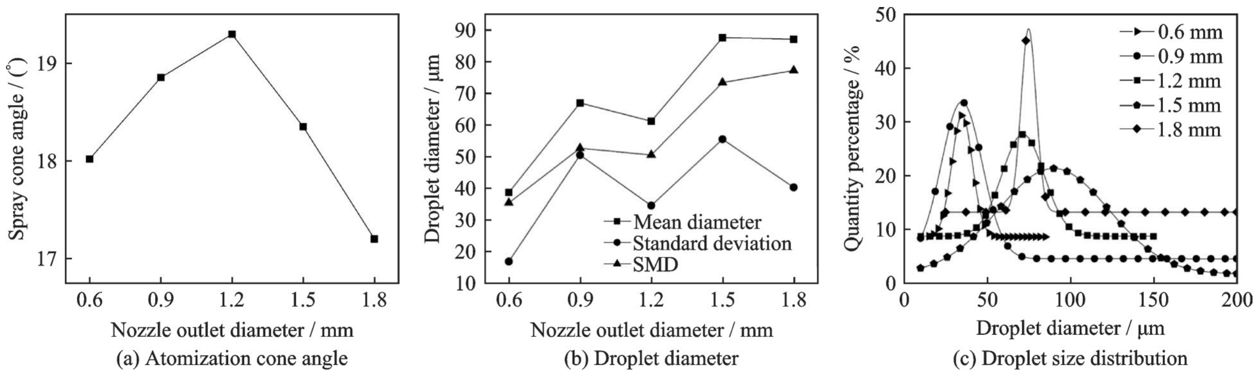


Fig.8 Influence of nozzle outlet diameter on atomization effect

2.3 Influence of nozzle outlet wall thickness on atomization effect

Fig.9 shows the influence of nozzle outlet wall thickness on atomization cone angle and droplet size. The experimental conditions are as follows: s= roundness, d=1.2 mm, n=15 000 r/min, f= 0.015 mm/r, p=0.3 MPa, q=54 mL/h. As shown in Fig.9(a), the MQL atomization cone angle shows an overall increasing trend as the wall thickness of the nozzle outlet increases. When the nozzle outlet wall thickness is increased to 1.3 mm, the atomization cone angle increases by 15.86% compared with 0.5 mm. The increase in the wall thickness of the nozzle outlet means that the liquid film needs a longer distance of friction to be ejected. Therefore, the resistance of the liquid film increases as the wall thickness of the nozzle outlet increases, and the injection speed decreases. The internal pressure of the liquid beam is relatively low compared with the low-speed spray, forcing the atmospheric pressure to squeeze the liquid beam. Therefore, the lower wall thickness of the nozzle outlet will result in a decrease in the atomization cone angle.

The diameter of the MQL droplets decreases rapidly when the wall thickness of the nozzle outlet increases from 0.5 mm to 0.7 mm, the mean diameter and the SMD decrease by 50.7% and 45.72%, respectively, and the droplet standard deviation decreases by 60.04%. In general, the MQL atomization cone angle increases but the atomization droplet diameter decreases with the increase of the wall thickness of the nozzle outlet. The reason may be that with the increase of wall thickness, the action time and area of gas and liquid film increase accordingly. The longer-time effect helps the gas to break the liquid film and form smaller atomized droplets. In addition, the distribution of MQL atomized droplets is more concentrated with the increase of nozzle outlet wall thickness. In practical production, the nozzle is easy to be worn by chips and tools. The wear of the nozzle with thinner wall thickness at the outlet has a great influence on the atomization effect, which increases the frequency of nozzle replacement and the maintenance cost. Therefore, appropriately increasing the nozzle outlet wall thickness can make the liquid beam coverage wider and the droplet size distribution more concentrated.

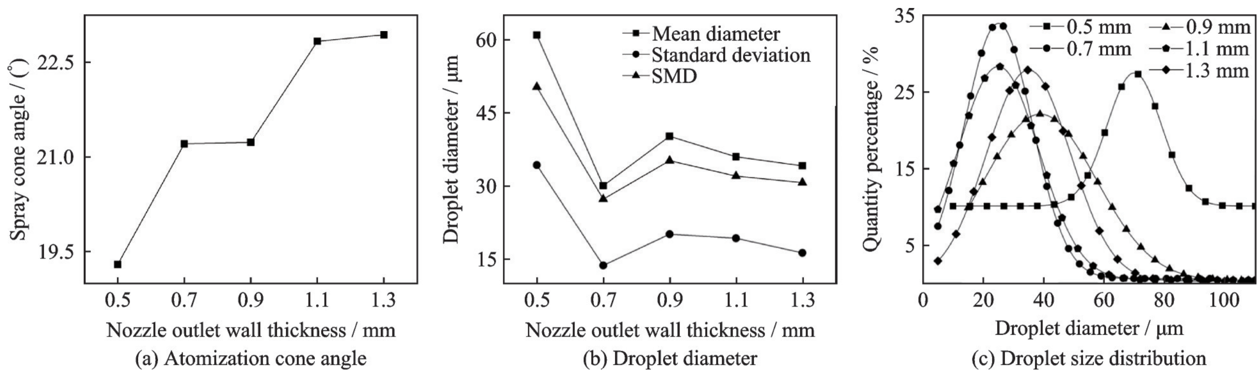


Fig.9　Influence of nozzle outlet wall thickness on atomization effect

2.4　Influence of nozzle machining spindle speed on atomization effect

Fig.10 shows the influence of nozzle machining spindle speed on atomization cone angle and droplet size. The experimental conditions are as follows: s= roundness, d=1.2 mm, l=0.5 mm, f=0.015 mm/r, p=0.3 MPa, q=54 mL/h. As shown in Fig.10(a), when the nozzle machining spindle speed is below 17 000 r/min, the nozzle atomization cone angle increases with the increase of the nozzle machining spindle speed. However, when the spindle speed exceeds 17 000 r/min, the atomization cone angle fluctuates greatly. In addition, the diameter of MQL atomized droplets increases first and then decreases with the increase of nozzle machining spindle speed. Increasing the spindle speed will reduce the roughness of the machined surface[28]. Lower roughness helps to reduce the friction and retention of the liquid in the nozzle, which may improve the atomization effect and make the droplets more easily broken into smaller particle sizes.

In the process of precision machining and ultra-precision machining, the atomization effect of MQL has a great influence on the processing performance. Therefore, nozzles with high surface quality are often needed to improve the atomization effect of MQL. In the traditional rough machining process, considering the cost of nozzle manufacturing and post-maintenance, the surface quality of the nozzle is usually low.

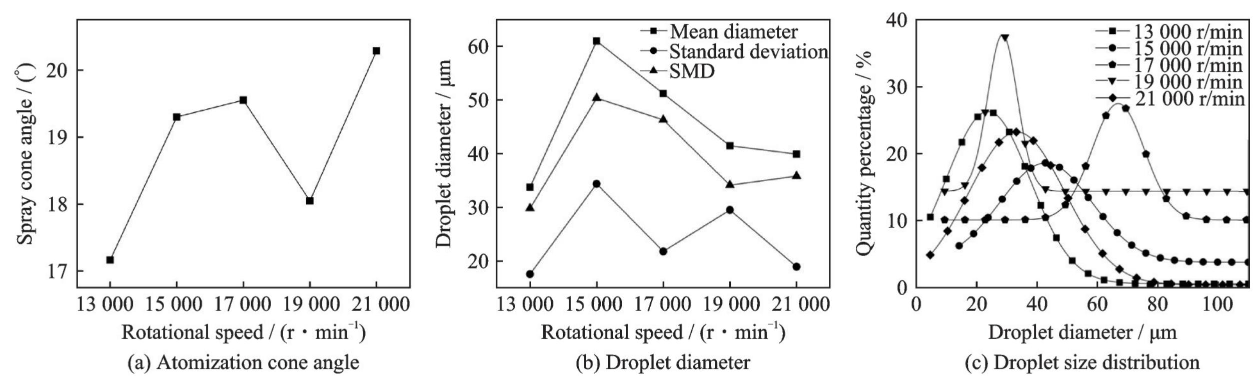
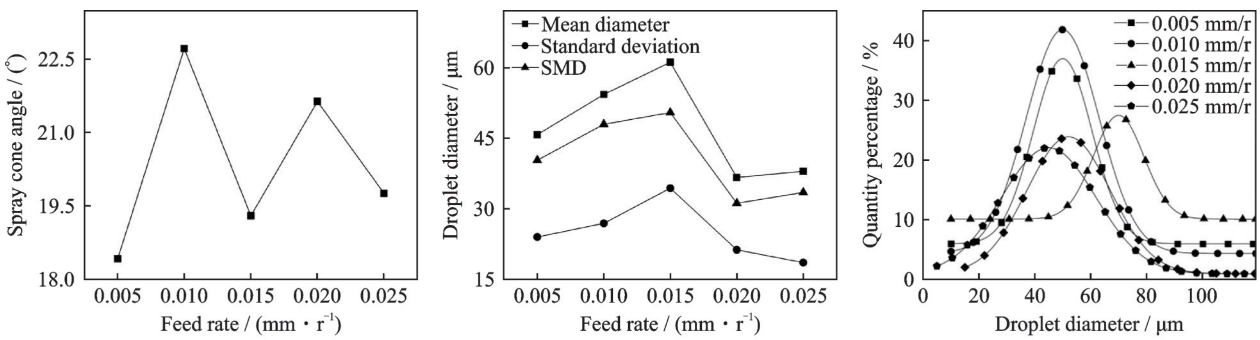


Fig.10　Influence of nozzle machining spindle speed on atomization effect

2.5　Influence of nozzle machining cutting tool feed rate on atomization effect

Fig.11 shows the influence of the nozzle feed rate on the atomization cone angle and droplet size. The experimental conditions are as follows: s=roundness, d= 1.2 mm, l=0.5 mm, n=15 000 r/min, p=0.3 MPa, q=54 mL/h. It can be seen from Fig.11(a) that the feed rate has a poor effect on the atomization cone angle. This may be because increasing the feed rate leads to irregular shape or size deviation of the nozzle outlet, which in turn affects the stability and consistency of the atomization cone angle. As shown in Figs.11(b,c), the diameter and standard deviation of the atomized droplets increase firstly and then decrease and tend to be stable as the feed rate of the nozzle increases. When the feed rate of the nozzle is 0.015 mm/r, the droplet diameter is the largest and the particle size distribution curve is the rightmost. During the initial phase of the feed rate increase, the surface roughness and geometric accuracy of the nozzle change. The flow resistance of the fluid inside the nozzle increases, making it more difficult for the droplets to break or the breaking mode changes, thereby increasing the droplet diameter. The diameter and standard deviation of the MQL atomized droplet decreases with the further increase of the feed rate. This may be because the turbulence intensity of the liquid film inside the nozzle increases so that the liquid film and gas have a stronger mixing. However, it should be noted that this trend of increasing firstly and then decreasing is not absolute. The atomization quality of the nozzle is affected by many factors, such as the surface roughness and geometric accuracy of the nozzle, etc.

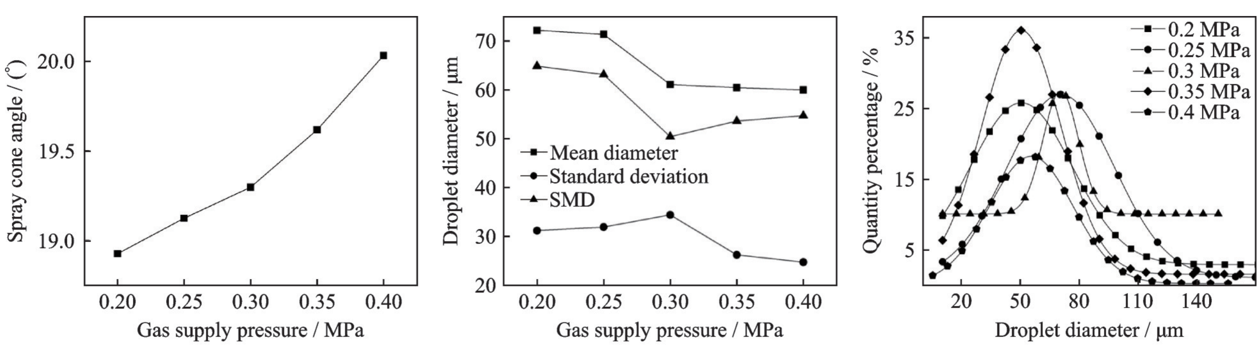


(a) Atomization cone angle (b) Droplet diameter (c) Droplet size distribution

Fig.11 Influence of nozzle machining cutting tool feed rate on atomization effect

2.6 Influence of MQL gas supply pressure on atomization effect

Fig.12 shows the influence of gas supply pressure on the atomization cone angle and droplet size. The experimental conditions are as follows: s=roundness, d=1.2 mm, l=0.5 mm, n=15 000 r/min, f=0.015 mm/r, q=54 mL/h. The atomization cone angle of the MQL nozzle shows an increasing trend as the gas supply pressure increases. The increase of gas supply pressure will improve the flow characteristics of gas-liquid two-phase flow. The airflow velocity at the nozzle outlet increases significantly with the increase of gas supply pressure. The shear effect of high-speed gas on the oil film increases, which helps the oil film to break into smaller droplets. As shown in Fig.12(b), the mean diameter of atomized droplets decreases with the increase of gas supply pressure. The mean diameter at 0.4 MPa is 16.92% lower than that at 0.2 MPa. The SMD of atomized droplets decreases firstly and then increases with the increase of gas supply pressure. When the pressure is high, the mean diameter of the droplets decreases, and the number and speed of the droplets increase. The high pressure environment increases the collision between droplets, so the SMD



(a) Atomization cone angle (b) Droplet diameter (c) Droplet size distribution

Fig.12 Influence of MQL gas supply pressure on atomization effect increases. As shown in Fig.12(c), increasing the supply pressure reduces the probability of generating too large or too small droplets, making the droplet distribution more concentrated. In summary, increasing the gas supply pressure helps to increase the atomization effect of MQL.

For high pressure environment, the nozzle needs to have good sealing performance. In the medium and low pressure environment, the nozzle sealing requirements are relatively low, but it is still necessary to effectively prevent leakage. Although the high-pressure nozzle is costly, it can significantly improve the processing efficiency and quality. Medium and low pressure nozzles have more cost advantages and are suitable for mass production. Different industries should choose the right nozzle according to the needs to achieve the best benefits.

2.7 Influence of lubricating oil flow rate on atomization effect of nozzle

Fig.13 shows the effect of lubricating oil flow rate on the atomization cone angle and droplet size. The experimental conditions are as follows: s=roundness, d=1.2 mm, l=0.5 mm, n=15 000 r/min, f=0.015 mm/r, p=0.3 MPa. Keeping the gas supply pressure of MQL unchanged, increasing the lubricating oil flow rate leads to a decrease in the gas-liquid ratio at the nozzle outlet. This reduces the shearing and crushing effect of gas on liquid is reduced. The mean diameter of atomized droplets increases with the increase of lubricating oil flow rate, which in turn affects the dispersion of droplets in the gas. Therefore, with the increase of the lubricating oil flow rate, the atomization cone angle gradually decreases. The atomization cone angle is reduced by 20.67% when the flow rate is 90 mL/h compared with 18 mL/h. As shown in Figs.13(b,c), the SMD of the atomized droplets is the smallest and the droplet distribution is the most concentrated when the flow rate is 54 mL/h. Too large or too small flow rates will affect the quality of MQL atomization. During long-term processing, excessive lubricating oil flow will also lead to waste of lubricating oil and increase processing costs.

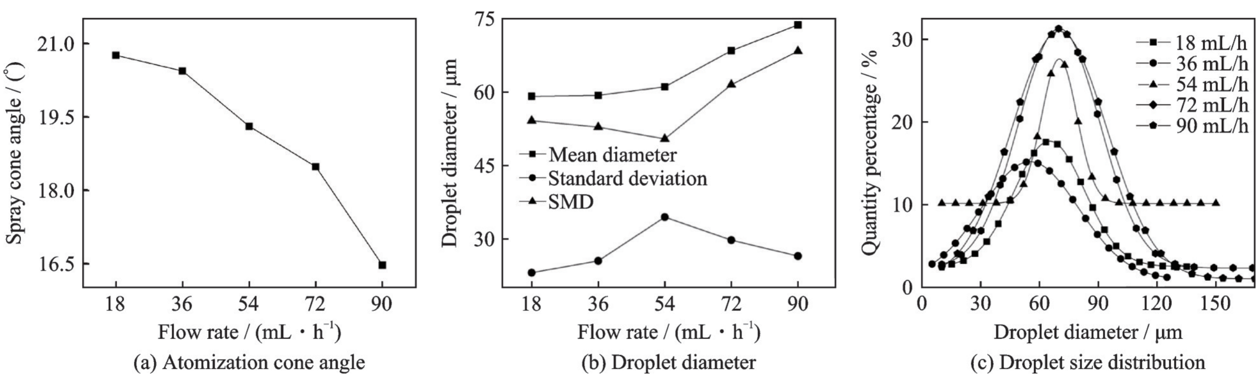


Fig.13 Influence of lubricating oil flow rate on atomization effect of nozzle

3 Conclusions

The MQL nozzles with different parameters are manufactured. The atomization cone angle and particle size distribution by changing the shape and parameters of various nozzles are investigated in the experiment. The conclusions are as follows:

(1) In all shapes, the square nozzle produces atomized droplets with the smallest mean diameter and SMD. The circular nozzle has more advantages in small-area precision injection.

(2) The atomization cone angle reaches its maximum value when the nozzle outlet diameter is 1.2 mm. The mean diameter of the MQL atomized droplets and the SMD show an overall increasing trend with the increase of the nozzle outlet diameter. Increasing the nozzle outlet wall thickness will appropriately reduce the droplet diameter. The larger nozzle outlet wall thickness can make the liquid beam coverage wider and the particle size distribution of the atomized droplets more concentrated.

(3) The diameter of MQL atomized droplets initially increases and subsequently drops as the spindle speed and feed rate increase. Optimal selection of processing parameters can effectively decrease the diameter of atomized droplets and increase the atomization effect.

(4) The atomization cone angle of MQL increases with the increase of gas supply pressure and decreases with the increase of lubricating oil flow rate. However, the mean diameter of atomized droplets decreases with the increase of gas supply pressure and increases with the increase of lubricating oil flow rate. Therefore, the higher gas supply pressure and the lower lubricating oil flow will improve the atomization quality.

(5) Optimizing the nozzle structure and atomization parameters is of great significance to improve the processing quality and reduce the production cost. In practical applications, appropriate nozzle structure and atomization parameters should be selected for different processing methods of different materials in order to maximize benefits. In the future, the nozzles of different materials and the atomization stability of nozzles of different materials can also be studied.

References

[1] PERVAIZ S, KANNAN S, KISHAWY H A. An extensive review of the water consumption and cutting fluid based sustainability concerns in the metal cutting sector[J]. Journal of Cleaner Production, 2018, 197: 134-153.

[2] KUMAR A, SINGH G, AGGARWAL V. Analysis and optimization of nozzle distance during turning of EN-31 steel using minimum quantity lubrication[J]. Materials Today: Proceedings, 2022, 49: 1360-1366.

[3] WANG Y, LIU C F. State-of-the-art on minimum quantity lubrication in green machining[J]. Journal of Cleaner Production, 2023, 429: 139613.

[4] NIU Q L, RONG J, JING L, et al. Study on force-thermal characteristics and cutting performance of titanium alloy milled by ultrasonic vibration and minimum quantity lubrication[J]. Journal of Manufacturing Processes, 2023, 95: 115-130.

[5] YIN Q G, LI C H, DONG L, et al. Effects of physicochemical properties of different base oils on friction coefficient and surface roughness in MQL milling AISI 1045[J]. International Journal of Precision Engineering and Manufacturing—Green Technology, 2021, 8(6): 1629-1647.

[6] XU W H, LI C H, CUI X, et al. Atomization mechanism and machinability evaluation with electrically charged nanolubricant grinding of GH4169[J]. Journal of Manufacturing Processes, 2023, 106: 480-493.

[7] ZHANG Y, YUAN S M, WANG L Z. Investigation of capillary wave, cavitation and droplet diameter distribution during ultrasonic atomization[J]. Experimental Thermal and Fluid Science, 2021, 120: 110219.

[8] JIA D Z, LI C H, LIU J H, et al. Prediction model of volume average diameter and analysis of atomization characteristics in electrostatic atomization minimum quantity lubrication[J]. Friction, 2023, 11(11): 2107-2131.

[9] LIU F C, WU X Z, XIA Y, et al. A novel cold air electrostatic minimum quantity lubrication (CAE-MQL) technique for the machining of titanium alloys Ti-6Al-4V[J]. The International Journal of Advanced Manufacturing Technology, 2023, 126(7): 3437-3452.

[10] LYU T, HUANG S Q, LIU E T, et al. Tribological and machining characteristics of an electrostatic minimum quantity lubrication (EMQL) technology using graphene nano-lubricants as cutting fluids[J]. Journal of Manufacturing Processes, 2018, 34: 225-237.

[11] HAQ M A U, HUSSAIN S, ALI M A, et al. Evaluating the effects of nano-fluids based MQL milling of IN718 associated to sustainable productions[J]. Journal of Cleaner Production, 2021, 310: 127463.

[12] PUSAVEC F, DESHPANDE A, YANG S, et al. Sustainable machining of high temperature Nickel alloy-Inconel 718: Part 1—Predictive performance models[J]. Journal of Cleaner Production, 2014, 81: 255-269.

[13] HUANG W T, TSAI J T, HSU C F, et al. Multiple performance characteristics in the application of taguchi fuzzy method in nanofluid/ultrasonic atomization minimum quantity lubrication for grinding inconel 718 alloys[J]. International Journal of Fuzzy Systems, 2022, 24(1): 294-309.

[14] ZAMAN P B, DHAR N R. Design and evaluation of an embedded double jet nozzle for MQL delivery intending machinability improvement in turning operation[J]. Journal of Manufacturing Processes, 2019, 44: 179-196.

[15] DUCHOSAL A, SERRA R, LEROY R, et al. Tool design effect on microlubrication spray efficiency in milling using inner channels[J]. Proceedings of the In-

stitution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2017, 231(1): 118-128.
[16] ZHANG C L, ZHANG S, YAN X F, et al. Effects of internal cooling channel structures on cutting forces and tool life in side milling of H13 steel under cryogenic minimum quantity lubrication condition[J]. The International Journal of Advanced Manufacturing Technology, 2016, 83(5): 975-984.
[17] YAO K, WANG C Y, DING F, et al. Effect of nozzles on cutting performance when machining with oil-on-water cooling technique[J]. The International Journal of Advanced Manufacturing Technology, 2021, 112(1): 313-322.
[18] SHARMIN I, MOON M, TALUKDER S, et al. Impact of nozzle design on grinding temperature of hardened steel under MQL condition[J]. Materials Today: Proceedings, 2021, 38: 3232-3237.
[19] CHEN B, GAO D R, LI Y B, et al. Experimental analysis of spray behavior and lubrication performance under twin-fluid atomization[J]. Journal of Manufacturing Processes, 2021, 61: 561-573.
[20] HUANG X M, REN Y H, LI T, et al. Influence of minimum quantity lubrication parameters on grind-hardening process[J]. Materials and Manufacturing Processes, 2018, 33(1): 69-76.
[21] LIU Z Q, CAI X J, CHEN M, et al. Investigation of cutting force and temperature of end-milling Ti - 6Al-4V with different minimum quantity lubrication (MQL) parameters[J]. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2011, 225(8): 1273-1279.
[22] RAHIM E A, DORAIRAJU H. Evaluation of mist flow characteristic and performance in Minimum Quantity Lubrication (MQL) machining[J]. Measurement, 2018, 123: 213-225.
[23] LI Xiang, WANG Mingdi, GUO Minchao, et al. Research on laser cleaning mechanism and process of oxides after welding of 6061 aluminum alloy[J]. Journal of Nanjing University of Aeronautics & Astronautics, 2023, 55(5): 933-940. (in Chinese)
[24] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. General industrial aluminum and aluminum alloy plates and strips Part 2: Mechanical properties: GB/T 3880.2—2012[S]. Beijing: [s.n.], 2012.
[25] SYED HAMMAD A, YAO Y, WU B F, et al. Recent developments in MQL machining of aeronautical materials: A comparative review[J]. Chinese Journal of Aeronautics, 2025, 38(1): 102918.
[26] KHATAI S, SAHOO A K, KUMAR R, et al. Recent research progress on various cooling and lubrication techniques used in sustainable hard machining: A comprehensive review[J]. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 2024, 238(6): 3009-3053.
[27] YAN K, NING Z, MING L, et al. Interface instability mechanism of an annular viscous liquid sheet exposed to axially moving inner and outer gas[J]. European Journal of Mechanics-B/Fluids, 2015, 52: 185-190.
[28] SCHÖNEMANN L, BERGER D, DÖRGELOH T, et al. Synergistic approaches to ultra-precision high performance cutting[J]. CIRP Journal of Manufacturing Science and Technology, 2020, 28: 38-51.

Authors

The first author Mr. **LI Donghui** received the M.E. degree in mechanical engineering from Tianjin University of Technology and Education in 2025. His research is focused on metal clean cutting technology.

The corresponding author Dr. **ZHANG Tao** received his Ph.D. degree in mechanical manufacturing and automation from Shandong University in 2013. He is currently the master's supervisor of the National-Local Joint Engineering Laboratory of Intelligent Manufacturing Oriented Automobile Die & Mould of Tianjin University of Technology and Education. His research interests encompass metal cutting mechanism and efficient conversion and utilization of mechanical energy.

Author contributions Mr. **LI Donghui** conducted the experiment, interpreted the results, and wrote the manuscript. Dr. **ZHANG Tao** designed the experiment, analyzed results, and proofread the paper. Mr. **ZHENG Tao** participated in experiment. Mr. **QI Wei** designed and processed the nozzle. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: XU Chengting)

微量润滑喷嘴加工工艺及其对雾化效果影响规律研究

李冬辉,张 涛,郑 涛,戚 伟

(天津职业技术师范大学汽车模具智能制造技术国家地方联合工程实验室,天津 300222,中国)

摘要:微量润滑技术通过使用极少量的切削液实现对切削区域的有效润滑和冷却,从而降低切削温度,延长刀具寿命,提高工件表面质量。通过优化喷嘴设计和雾化参数,可以进一步提升微量润滑的冷却润滑性能,从而提高加工效率和产品质量。本文加工制作了不同形状的喷嘴,并设置了不同出口直径和壁厚的喷嘴。切削加工时考虑了主轴转速和刀具进给量的影响。对不同喷嘴分别进行雾化锥角和粒径分布实验研究。圆形喷嘴更有利于雾化液束集中喷射。喷嘴出口直径为1.2 mm时,雾化锥角最大。增大喷嘴出口直径将增大雾化液滴的直径。随着出口壁厚的增加,雾化锥角增大,液滴直径减小。适当增加出口壁厚有利于提高雾化质量。随着主轴转速和进给量的增加,液滴直径先增大后减小。提高微量润滑压力,降低润滑油流量,可以提高喷嘴的雾化质量。研究微量润滑喷嘴加工工艺对雾化效果的影响,有助于提高微量润滑技术的冷却润滑性能,从而提升加工效率和质量。

关键词:微量润滑;喷嘴加工;雾化锥角;液滴直径