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Simulation Study of the parameters that affecting the droplets size produced in a Minimum Quantity Lubrication (MQL) system using a Computational Fluid Dynamic (CFD)

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KEYWORDS

CFD
MQL
Surface roughness
Air pressure
Droplet size

ABSTRACT

In this paper, the influence of surface roughness of the nozzle on the characteristics of atomized droplets in an MQL system is studied using a computational fluid dynamics (CFD) simulation. The study was carried out by first creating a 3-D model of the nozzle using Creo3.0 which was then imported by using the Ansys Fluent software where various parameters such as solver and materials were defined to enable the study of the characteristics of the atomized droplets which were to be formed. The input simulation parameters specified were air pressure inlet, mass flow inlet and pressure outlet. Nine simulation runs were carried out for surface roughness at the range of 1.5-16.8 μm and pressure of 0.275-0.55 MPa. The simulation results showed that under the same pressure and mass flow conditions, the surface roughness of the nozzle will have some influence on the characteristics of the droplet. As the surface roughness of the nozzle increases, smaller droplet diameter will be obtained. Under pressure of 0.55 MPa, and the nozzle with 16.8 μm roughness minimum average droplet size of 5.705×10^{-6} m can be produced. ANOVA performed revealed that both surface roughness and pressure are significant in affecting the droplets formed.

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1.0 INTRODUCTION

Machining is a significant process in various manufacturing industries such as automotive and aerospace and thus it is reasonable to give emphasis to the issue of sustainability. Furthermore, achieving sustainability is important, since it has a direct effect on the production cost as well as on the life and performance of various important components (Hamran et al., 2020). Conventionally, flood cooling or wet machining has been used to improve the machinability of metal cutting. However, this method causes a large amount of cutting fluid to be wasted and increases environmental pollution (Khan et al., 2018). In conventional practice of a machining process, a cutting fluid is needed to cool and lubricate the cutting and deformation area. The traditional flood cooling method will use a lot of cutting fluid to cool and lubricate the cutting area, leading to a lot of fluid waste and consequently resulting in environmental pollution (Khan et al., 2018). Therefore, the minimum quantity lubrication (MQL) method is a good alternative. According to Hamran et al. (2020), the results obtained from the articles reviewed mostly show that the MQL advancements outperformed an independent MQL system by generating better surface quality, while also lowering tool wear and cutting force.

MQL systems utilize the method of atomizing high-pressure air and a very small amount of lubrication liquid into the machining area after mixing and vaporizing in order to effectively lubricate the contact or interface area between the cutting tool and the workpiece. MQL application can help to improve the tool life, heat dissipation and surface quality of the workpiece, thereby reducing operational cost and environmental pollution (Chen et al., 2012). According to Dasch & Kurgin (2010) application of MQL methods can produce similar cooling and lubrication characteristics effect as with wet machining. Nowadays, green machining methods which include dry machining, MQL and cryogenic machining resulted in minimal impact to the environment, and MQL has been proven to yield better results in terms of tool wear, surface finish and cutting force (Ahmad et al., 2021).

The rapid advancement of nanotechnology has led to the introduction of nanofluids as coolants in the machining process. Sayuti et al. (2013) reported that MQL systems using nanofluids have better results compared to conventional flood cooling systems. The drawbacks of using nanoparticles are that they are harmful to the machine operator and will deteriorate the environment as they are non-biodegradable. Due to these negative drawbacks, this study aimed to produce nano size droplets which would serve the similar purpose of nanofluids containing nanoparticles such as SiO2.

Droplet size plays an important role in MQL grinding, as reported by Balan et al. (2017) where from simulation study droplets sizes from 6 to 16.3 μm were more likely to enter the grinding zone. This range of droplet sizes is believed to provide more efficient lubrication, reduced grinding force and improved surface quality.

When investigating the currently available MQL systems, it has been noticed that there are many factors which will affect the characteristics of the droplets characteristics, namely air pressure, flow rate of compressed air, liquid velocity, liquid mass-flow, nozzle surface roughness, nozzle angle, nozzle distance, etc. A numerical study using a model was done by Shiva Sai et al. (2015) which showed that the average diameter of the outer of the atomizing air and the median diameter of the droplet decreases significantly with the increase of the air pressure, thus indicating that the increase in air pressure contributes to heat dissipation in the cutting zone. Verma et al. (2017) also came to similar conclusions: the outer mean diameter of the droplet decreases as the air pressure increases and additionally its velocity increases as the pressure increases. Furthermore, it had also been reported that the air pressure is more important than the fluid flow rate, whereby higher flow rate or air pressure increases the wettability area, which helps to reduce the temperature of the cutting area. In addition, Balan et al. (2017) conducted a numerical simulation of droplets and concluded that the droplet size decreases as the flow rate and air pressure increase.

The surface roughness of the inner nozzle also affects the droplet velocity at the outlet exit. A rough nozzle will produce a lower velocity at the outlet exit. A smaller average diameter droplet can be obtained under high pressure and rough nozzle conditions (Khan et al., 2018). Park et al. (2010) revealed from their observation that as the nozzle distance increases, the droplet size becomes smaller, while higher pressure increases the number of droplets. Chen et al. (2012) proposed that larger droplets are generally concentrated in the centre of the spray. Rahim et al. (2015) suggested that the proper nozzle distance is able to reduce lubricant consumption and improve cooling and lubrication ability. According to Emami et al. (2013), when the spray speed is close to the grinding wheel rotation speed, the highest lubrication efficiency can be obtained, but excessive air flow rate will cause a lot of fog and disturb the vision of the machine operator.

When the liquid is ejected from the nozzle at a certain pressure and velocity, it is atomized into a large number of small droplets (Linchun, 2012). The integral distribution function of the number of atomized droplets is given as (Linchun, 2012):

$$PDF_{N,j} = \frac{N_j}{n_j} = \frac{\exp\left[-\alpha_j n_j \left(D - \frac{\Delta D}{2}\right)^3\right] - \exp\left[-\alpha_j n_j \left(D + \frac{\Delta D}{2}\right)^3\right]}{1 - \exp\left(-\alpha_j n_j D_{max}^3\right)} \tag{1}$$

Where;

N_j...... Number distribution function of droplet size

n_j ...... Number of droplets

The average diameter of the atomized droplet can be expressed as:

$$D_{32} = \frac{1 - \left(1 + \alpha_J n_j D_{max}^3\right)\exp\left(-\alpha_J n_j D_{max}^3\right)}{\left(\alpha_J n_j\right)^{1/3} \gamma\left(\frac{5}{3}, \alpha_J n_j D_{max}^3\right)} \tag{2}$$

The method and result obtained from Linchun (2012), were further investigated in this study for the simulation model, simulation parameters and for analyzing the results. This study was mainly focused on the influence of surface roughness of the inner nozzle on droplets characteristics using Ansys Fluent CFD simulation. Ansys Fluent software is also utilized by Rasep et al. (2021) to study the hydrodynamic performance of smooth bearing journals under two different conditions for different types of lubricants.

2.0 METHODOLOGY

Prior to the simulation study, a 3-D model was created using CAD software. Figure 1 shows the flow chart of the simulation study. The steps involved were creating a fluent-module in the workbench, importing and defining a model surface, meshing, setting solver parameters as well as materials parameters, running calculations and analyzing the results.

Figure 2 shows a 3-D geometry for the nozzle. Based on the reviewed literature (Verma et al., 2017), the geometry was simplified into a quarter of the 3-D model and was created using Creo3.0 software.

Figure 3 shows the specified position for the nozzle and the environment (atmosphere). Figure 4 clearly shows the entry of high-pressure air to the nozzle through the air inlet and water entering the nozzle through the water inlet. Later the high-pressure air and water will mix in the nozzle to form a water mist. Figure 5 shows the surface of the outlet and Figure 6 shows the final meshing of the surface outlet after running the grid indepent test.

The next step was setting the injection. The inlet surface was defined as mass flow rate and the fluid material was set as air and water. The simulation inputs for the properties of air and cutting fluid (water) were as shown in Table 1. The fluid surface tension coefficient was set at 0.071 N/m. Table 2 shows the boundary conditions and their parameters. These range of values are based on the experimental study done by Khan et al. (2018). Furthermore, in their experiment two 3D printed tool adapters were printed with ABS plastic and rigidly attached to the original nozzle of the MQL Unist system. The surface roughness of the as-printed (rough) and acetone polished (smooth) nozzles were measured to be 16.8 *μm* and 3.2 μm respectively, and surface roughness of 1.5 μm is the original surface roughness.

Simulations were carried out for 9 sets at various combinations of surface roughness and air inlet pressure. The roughness value is set on the interior of the nozzle wall using the wall roughness models settings in the software.

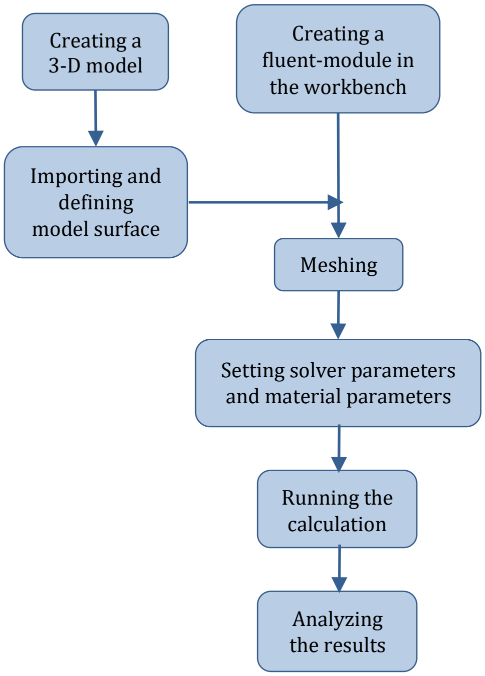

Figure 1: Flowchart of the simulation.

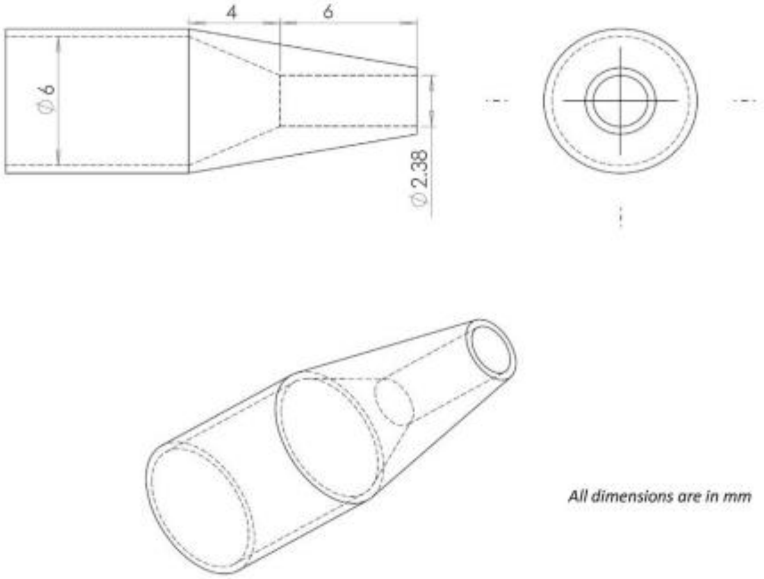

Figure 2: 3-D geometry of the nozzle. Adapted after (Verma et al., 2017).

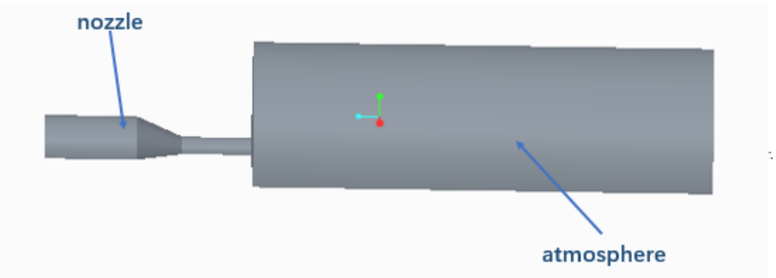

Figure 3: The position of the nozzle and the atmosphere.

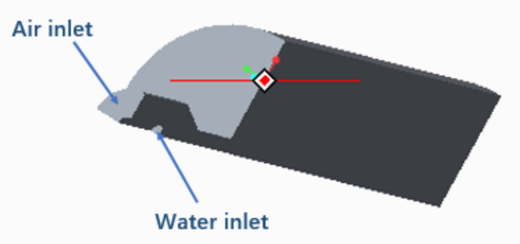

Figure 4: High-pressure air entering the nozzle through the air inlet and water entering the nozzle through the water inlet.

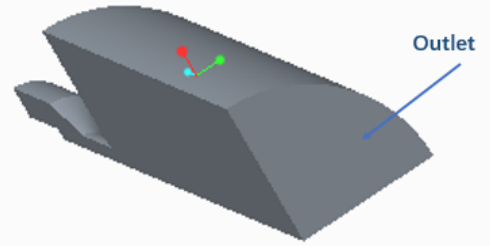

Figure 5: The surface of the outlet.

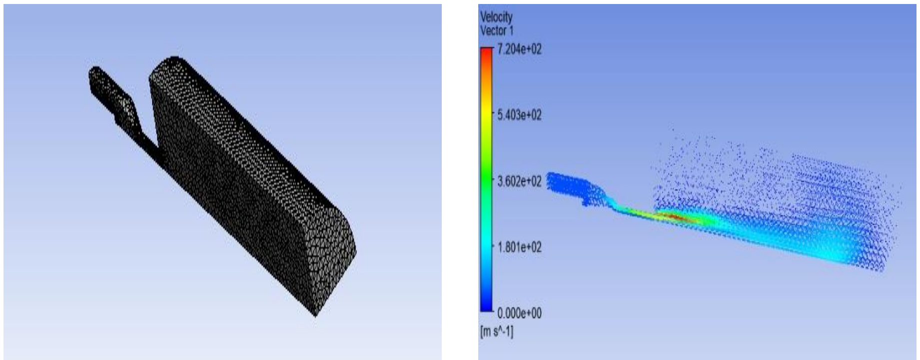

Figure 6: Meshing of the model which contains 37 311 elements and the preliminary velocity output showing good streamline trend from the inlet to outlet boundary.

Table 1: Input properties for air and cutting fluid.

Type	Values
Air density	1.225 kg/m3
Air viscosity	1.789e-05 kg/m-s
Water density	998.2 kg/m3
Water viscosity	1.003e-03 kg/m-s

Table 2: The boundary conditions and their parameters.

Boundary	Type	Values
Air inlet	pressure-inlet (MPa)	0.275, 0.415, 0.55
Water inlet	mass-flow-inlet (ml/h)	500
Outlet	pressure-outlet (MPa)	0.101325
Wall	surface roughness (μm)	1.5, 3.2, 16.8

3.0 RESULTS AND DISCUSSION

The results of minimum and maximum droplet sizes for the 9 simulation runs were as shown in Table 3. In general, coarser surface values and higher pressures of air inlet resulted in smaller sizes of droplets. This finding is similar with the statement from Khan et al. (2018), that smaller average diameter droplets can be obtained under high pressure and rough nozzle conditions.

Table 3: Simulation results for the droplet sizes for the 9 simulation runs.

No.	**Surface roughness (μm)**	**Pressure - air inlet (MPa)**	**Droplet size (m)**	
			Minimum	**Maximum**
1	1.5	0.275	1.013e-005	1.741e-005
2	1.5	0.415	8.376e-006	1.392e-005
3	1.5	0.55	7.002e-006	1.230e-005
4	3.2	0.275	9.570e-006	1.821e-005
5	3.2	0.415	8.514e-006	1.386e-005
6	3.2	0.55	6.842e-006	1.269e-005
7	16.8	0.275	9.696e-006	1.760e-005
8	16.8	0.415	7.436e-006	1.447e-005
9	16.8	0.55	5.705e-006	1.168e-005

Figure 7 shows the average size of droplets produced by nozzles with three different values of surface roughness and air pressure. It is clearly shown that when pressure increases, the average size of droplets decreases gradually. Under pressure of 0.55MPa, the nozzle with 16.8 μm roughness can produce the minimum average droplet size. In addition, under constant pressure, the nozzle with higher roughness, especially at 16.8 μm, can produce a relatively small average droplet size.

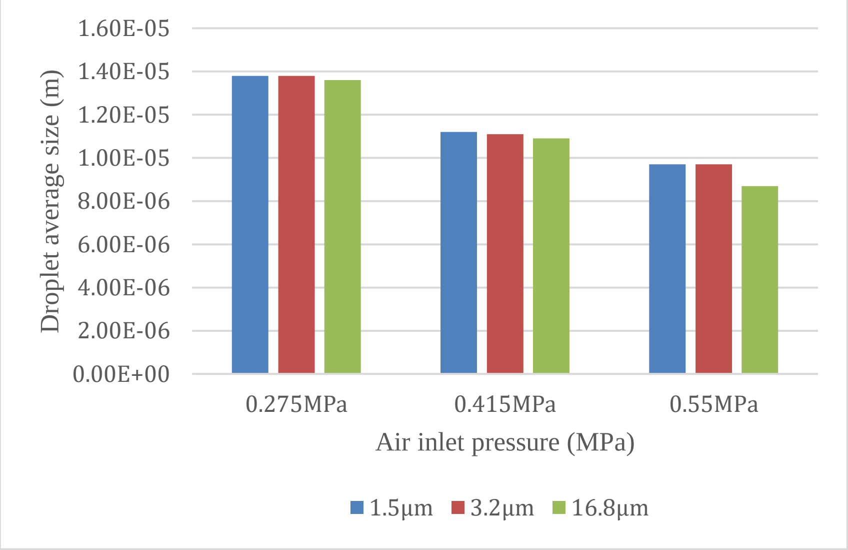

Figure 7: The average droplet size under various air pressures and nozzle surface roughness.

Table 4 shows the comparison with experimental results obtained by Khan et al. (2018). Comparing the result obtained in the simulation with Khan et al. (2018), it was found that the trend is similar i.e., higher pressure and rougher nozzle will produce smaller droplet size. Even though the average droplet size is almost double in the simulation in case of 0.55 MPa pressure and rough nozzle of 16.8 μm, but there is a difference in diameter of the nozzle (Ø2.38 mm) in the simulation as compared with nozzle diameter (Ø3 mm) in the experimental work by Khan et al. (2018). The difference of 0.62 mm is believed resulted in bigger average diameter droplet size. Furthermore, according to Khan et al. (2018) the internal flow of micromist inside a ϕ3 mm nozzle is affected by its surface finish, producing either laminar or turbulent flow that would affect the resulting droplets that caused smaller diameter droplet size at rough nozzle of 16.8 µm.

Table 4: Airborne microdroplets' mean diameters (µm). Their standard deviations are in respective bracket (Khan et al. 2018).

Pressure (MPa)	0.275	0.415	0.550
With original nozzle -1.5 µm (µm)	8.36 (3.3)	7.82 (3.1)	7.47 (2.8)
With rough nozzle - 16.8 µm (µm)	9.20 (4.0)	7.25 (2.3)	4.69 (1.6)
With smooth nozzle- 3.2 µm (µm)	11.42 (2.6)	9.31 (2.6)	7.60 (2.9)

Figure 8 shows the changes in the minimum, maximum and average droplet size using three types of nozzles at various values of surface roughness under 0.55 MPa air pressure. It shows that at constant pressure, the droplet sizes are similar for the surface roughness of 1.5 µm and 3.2 µm. But the minimum, maximum and average size of droplets significantly decreased with nozzle roughness of 16.8µm.

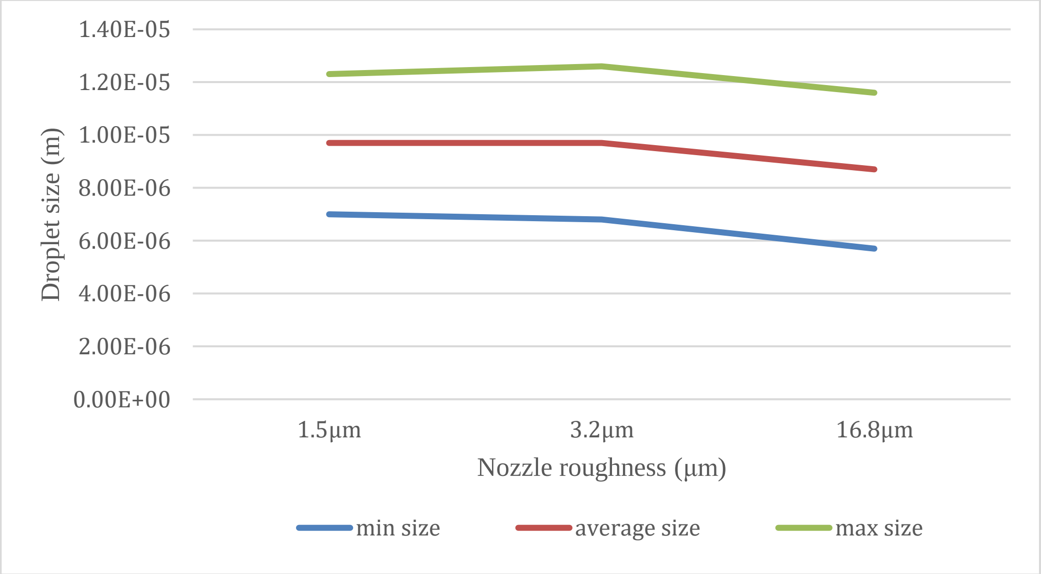

Figure 8: The droplet size under various nozzle surface roughness at 0.55 MPa.

Figure 9 shows the minimum droplet size changes for three different values of nozzle surface roughness and three different air inlet pressures. It can be clearly seen that the minimum droplet size decreases with the increase of air pressure. Furthermore, a smaller minimum size of droplet is produced with higher values of nozzle roughness. This result is similar with the findings of previous researchers (Shiva Sai et al., 2015; Verma et al., 2017). They found that the diameter of the droplet decreases as the air pressure increases.

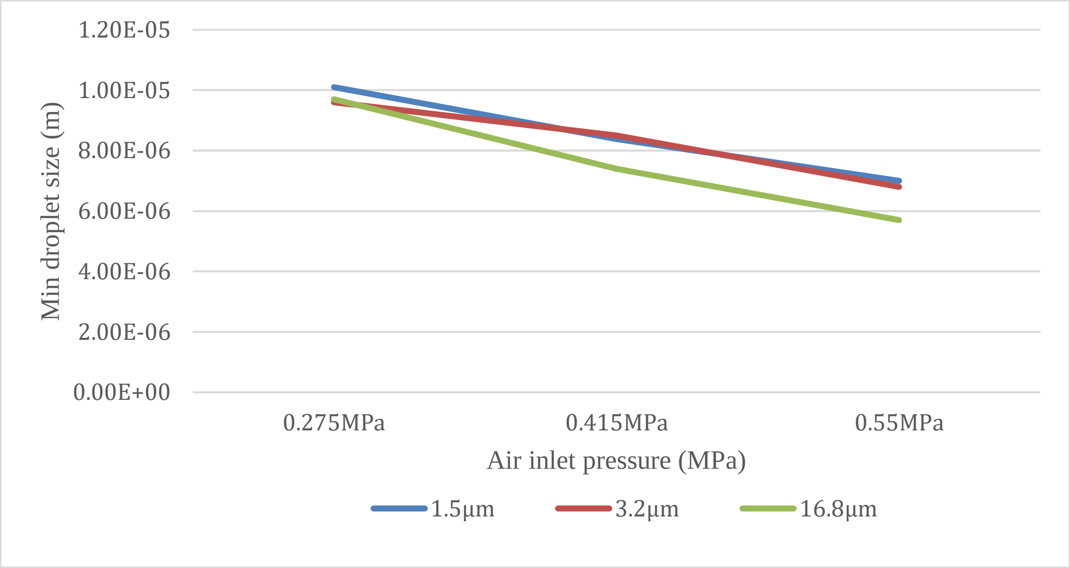

Figure 9: The minimum droplet size under various air pressures and nozzle surface roughness.

The results of this study can be used as a guide in obtaining nano size droplets for MQL systems in the future. This is in line with a statement by Mezhericher et al. (2017) on efforts towards acquiring sub-micron and nano-droplets in atomization techniques. Furthermore, the electrohydrodynamic atomization (EHDA) method has been used in MQL systems known as EHDA-MQL (Bartolomeis & Shokrani, 2020). The result revealed that an estimated 78% of the EHDA-MQL droplets have a radius of size smaller than 4 µm. However, the weakness of EHDA is that fluid with surface tension larger than 0.05 N/m as used in the current study cannot be atomized.

In order to analyze the factors which affected the droplet size, an ANOVA analysis was performed. Table 5 shows the ANOVA results for factors affecting the minimum droplet size in this simulation. Both factors of pressure and surface roughness of the inner nozzle under investigation were found to be significant in affecting the droplet size. In addition, the R-Squared of 98.83% was close to 1, indicating that a strong linear relationship existed between the surface roughness of the nozzle and pressure to the droplet size.

Table 5: ANOVA for Response Surface 2FI Model Analysis of variance table [Partial sum of squares]

Sum of Source	Mean Squares	DF	F Square	Value	Prob > F
Model	1.782E-011	3	5.938E-012	140.79	< 0.0001 significant
A	1.290E-012	1	1.290E-012	30.59	0.0027
B	1.621E-011	1	1.621E-011	384.38	< 0.0001
AB	3.507E-013	1	3.507E-013	8.31	0.0344
Residual	2.109E-013	5	4.218E-014		
Cor Total	1.803E-011	8			
Std. Dev.	2.054E-007	R-Squared		0.9883	
Mean	8.141E-006	Adj R-Squared		0.9813	
C.V.	2.52	Pred R-Squared		0.9452	
PRESS	9.882E-013	Adeq Precision		31.177	

CONCLUSIONS

Through the simulation in ANSYS Fluent, nine sets of parameters related to droplet characteristics were studied. By sorting and analyzing the obtained droplet sizes, the following conclusions can be reached:

(a) The size of the droplet gradually decreases as the atomization pressure increases, indicating that high atomization pressure enables the nozzle to produce finer droplets.

(b) The coarser roughness of the inner surface of the nozzle may allow the droplets to easily broken, resulting in a finer droplet size.

(c) The effect of roughness on droplet characteristics is less than the effect of pressure on droplet characteristics.

This simulation result is useful for obtaining the droplet characteristics under different conditions, which is important in machining processes, grinding, etc. Furthermore, if the result is applied in MQL systems, it will improve the MQL performance in terms of less coolant consumption as well as improved cutting tool performance and product quality.

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