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ORIGINAL ARTICLE

Robust design of using nanofluid/MQL in micro-drilling

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Abstract The objective of this study is to present a novel nanofluid/minimum quantity lubrication (MQL) technology for a 7075-T6 aluminum alloy micro-drilling. This technology will enhance the life of the tool for the precision machining. Exploration of nanofluid/MQL-related parameters will affect the effectiveness of distance of nozzle, the nanodiamond weight percent concentration, and the MQL air volume process using the Taguchi robust design method. Additionally, using the Taguchi robust process design also yields the best results when compared with the other micro-drilling characteristics of the dry and MQL methods. Experimental results show that the use of nanofluid/MQL (2 wt%) can effectively reduce the micro-drilling force and micro-drilling torque force as well as the micro-drilling tool for micro-drilling burr wear. Furthermore, there is a significant improvement in the quality of its micro-drilling when the temperature of the drilling process can be significantly decreased.

Keywords Micro-drilling · Nanofluid · Nanodiamond · Minimal Quantity Lubrication (MQL) · Robust Design

1 Introduction

Miniaturized products are under increasing development and require more sophisticated manufacturing techniques. Micro-drilling is a low-cost, fast fabrication process. It has many advantages, for example better roundness, accurate aperture size, fast processing, and consequently, effectiveness in improving capacity. However, most micro-drilling is dry drilling; the tool diameter is small, and lubrication problems can cause tool wear and tear or even breakage.

Increasing the use of cutting fluid can reduce these problems, but excessive lubricant increases process cost and may cause environment problems. Therefore, a cutting process has been developed, termed minimum quantity lubrication (MQL).

Nanofluids are created by adding nanoparticles (1–100 nm) to a base fluid. The base fluid is usually oil or water. The nanoparticles are usually metals or metallic oxides. Nanofluids have excellent thermal physical properties, such as thermal conductivity, thermal diffusivity, thermal conductivity, and thermal convection coefficient [1–6]. Types of nanoparticles commonly used in nanofluids are carbon nanotubes (CNTs), C60, TiO_2, Al_2O_3, MoS_2, CuO, and diamond. Nano-cutting fluid MQL can be applied to grinding processes. Shen et al. [7] mentioned using nanofluid/MQL for grinding to significantly lower grinding forces and temperatures. Sridharan and Malkin [8] found nanofluids to be effective in reducing surface roughness in the grinding process, as well as reducing the specific grinding energy. With regard to micro-drilling. Jung et al. [9] used different base fluids with different concentrations of nanofluids to conduct experiments on micro-drilling aluminum. It was found that adding an appropriate amount of nanofluid can reduce micro-drilling force, extend tool life, and reduce the formation of burrs.

There have been many studies discussing and comparing the advantages and disadvantages of nanofluid/MQL machining processes. However, relatively fewer studies on the impact of various lubrication conditions have been published.

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Therefore, in this study, lubrication parameters are varied based on the Taguchi robust design method of Wu and Chang [10]. These include the nozzle distance, nanodiamond concentration, and air pressure. Three different lubrications methods were compared—dry, MQL, and nanofluid/MQL—to investigate the characteristics of micro-drilling, tool wear, and the microporous quality of burrs.

2 Experimental setup

The experimental processing machine is TC-510 obtained from L.K. Machinery Corp. The machine's spindle uses static pressure growth, and its maximum speed is 80,000 rpm. The machine can process an *X*/*Y*/*Z*-axis travel range of 510 mm×420 mm×350 mm. A power meter (Kistler 9257B) is used to measure micro-drilling forces and torque in three directions (Fx, Fy, and Fz), with an eight-channel amplifier (Kistler 5070A) to amplify the signal. A DAQ board (Advantech USB-4716) is used for PC data collection and analysis. Infrared thermography (FLIR A320) was performed to measure micro-drilling temperature, specifically the tip temperature. The equipment configuration is shown in Fig. 1. An MQL system manufactured by Accu-Lube is used in this study, as shown in Fig. 2. The nano-cutting fluid is sprayed by high-pressure air in a mist between the micro-drilling tool and workpieces, where the minimum quantity lubricant was supplied continuously (25 ml/h). In this study, the vegetable-based carrier oil was added with different weight percent concentrations of nanodiamond. The characteristics of the nanodiamond particles are shown in Table 1. A micro-drill tool with a

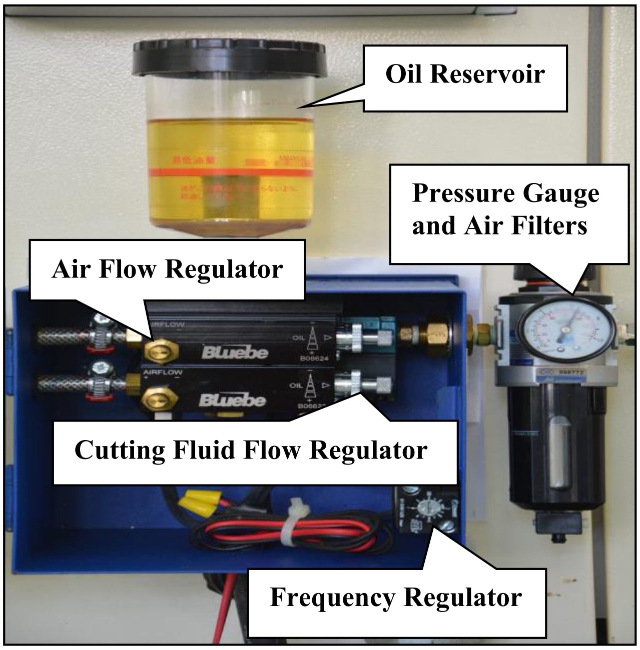
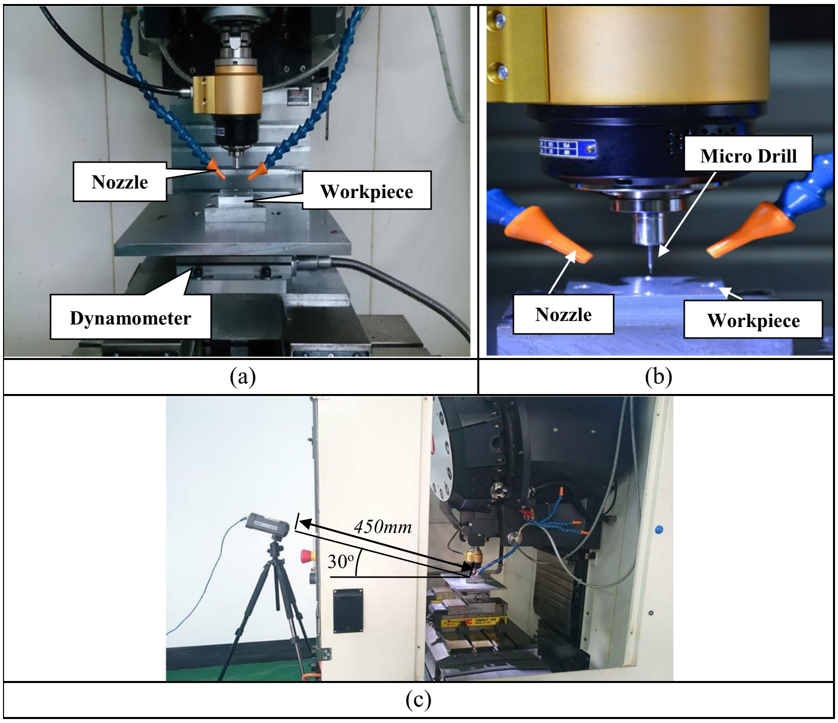


Fig. 2 Nanofluid/MQL unit used during machining



(a) (b) (c)

Fig. 1 **a** Spindle and dynamometer system configuration diagram. **b** Micro-tool and nozzle location. **c** Infrared thermography (FLIR A320) to measure micro-drilling temperature

Table 1 Chemical properties of diamond particles

Thermal expansion	0.8 (10–6) (K)
Bulk weight	3.2~3.45 (g/cm^3)
Density	3.0~3.5 (g/cm^3)
Heat conductance	298~200,077 K~17,500 (W/m/K)
Thermal conductivity	900~2000 (W/m/K)
Young's modulus	90~100 (GPa)

diameter of 200 μm (DIXI 1135) is used in this experiment, with parameters shown in Table 2. The workpieces are made from 7075-T6 aluminum alloy, with length of 52 mm, width of 52 mm, and thickness of 10 mm.

3 Taguchi robust design for nanofluid/MQL processing parameters

3.1 Taguchi method

A Taguchi robust design approach was employed to investigate optimal combinations of nanofluid/MQL processing parameters by maximizing the value of S/N based on minimized micro-drilling force during micro-drilling of 7075-T6 aluminum alloy. The problem is defined as *static*, with the micro-drilling force regarded as a *smaller-the-better* characteristic. For setting up the lubrication experiment's main process parameters, the experimental factor numbers and standard numbers are described below. This experiment uses an $L_4(2^3)$ orthogonal array, with three main parameters influencing lubrication: the distance of the nozzle, the nanodiamond weight percent concentration, and the air pressure. The nozzle distance diagram is shown in Fig. 3. The angle of the nozzle is fixed relative to the workpiece plane at 45°. The nozzle distance is measured from the spout to the micro-drilling tool and workpiece contact zone. Table 3 presents the number of design parameter factors and standards. The micro-drilling force cause-defect diagram is shown in Fig. 4.

Table 2 Experimental condition

Workpiece	
Material	7075-T6
Area	52×52 mm^2
Micro-drill	
Type	DIXI 1135
Drill diameter	200 μm
Flute length	1 mm
Coolant	Dry, MQL, nanofluid/MQL
Spindle speed	48,000 rpm
Feed rate	8 μm/rev
Drilling depth	0.52 mm

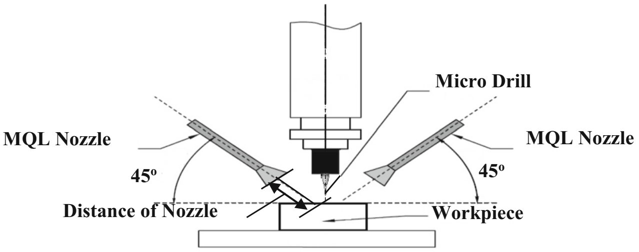


Fig. 3 The schematic diagram of the distance of the two nozzles

3.2 Analysis of mean

Analysis of the average S/N calculated results is shown in Table 4. The S/N response table and the S/N response graph are shown in Table 5 and Fig. 5, respectively. According to the principles behind the Taguchi method, the maximum S/N ratio corresponds to the lowest micro-drilling force. Thus, Fig. 5 shows that the best combination of the standards is as follows: A2, air pressure of 5 bar; B1, nozzle distance of 15 mm; and C2, nanodiamond concentration of 2 wt%.

The best lubrication parameters are A2B1C2. The results in Table 5 also show that the nanodiamond weight percent concentration is the most important factor affecting the cutting force during micro-drilling, while the air pressure is of minimal influence.

4 Results and discussions

4.1 Comparing micro-drilling force and torque for different lubrication methods

This section describes three different lubrication processes: dry, MQL, and nanofluid/MQL (2 wt%) and compares micro-drilling forces and torque. Micro-drilled 400 holes and for each of 20 holes determined the average force and torque to generate the graphs shown in Figs. 6 and 7.

From Figs. 6 and 7, find out that the MQL and nanofluid/MQL (2 wt%) can be used to reduce the magnitude of torque in micro-drilling. In order to clarify the analysis

Table 3 Design parameters and level

	Level	
Factors	1	2
A. Air compression (bar)	3	5
B. Distance of nozzle (mm)	15	25
C. Nanodiamond (wt%)	1	2

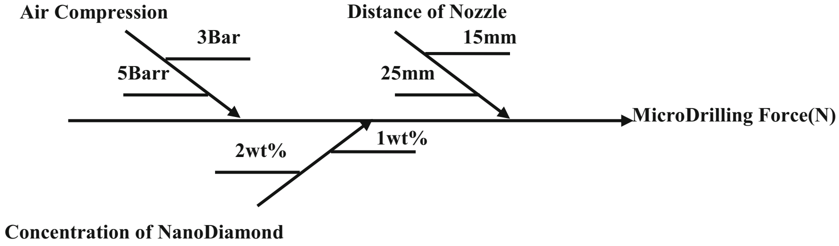


Fig. 4 Drilling force cause-effect diagram related to the MQL processing parameter

and compare lubrication methods for influence on micro-drilling torque, after micro-drilling 400 holes in total and calculating the average micro-drilling torque, draw the results as shown in Fig. 8. Nanofluid/MQL (2 wt%) is the most effective method in reducing micro-drilling torque, followed by MQL; the dry method is the worst.

4.2 Comparing micro-drilling temperatures for different lubrication methods

Figure 9 illustrates three different lubrication methods: dry, MQL, and nanofluid/MQL (2 wt%). The micro-drilling compares processes with respect to temperature, drilling 400 holes, and measuring temperatures for each of 20 holes to generate the graph. In order to clarify the analysis and to compare lubrication methods in terms of micro-drilling temperature, the temperatures for 400 holes are averaged and mapped to the results shown in Fig. 10. The figure shows that the nanofluid/MQL (2 wt%) method has the lowest drilling temperature, followed by MQL, and the dry method is the worst.

These results confirm that the use of nanofluid/MQL (2 wt%) can reduce the micro-drilling temperature.

4.3 Comparing micro-drilling tool wear for different lubrication methods

Figure 11 again illustrates three different lubricating methods: dry, MQL, and nanofluid/MQL (2 wt%). After micro-drilling 400 holes, scanning electron microscopy (SEM) photographs were taken to examine tool wear. From the figure, it can be seen that the main tool wear pattern is at the corners; the wear type is cutting edge failure. In order of descending tool wear, the worst results are for dry micro-drilling, followed by MQL; the minimum tool wear was associated with nanofluid/MQL (2 wt%). From Fig. 11a, it can be seen that the cutting edge failure in the dry method is very obvious, with tool corner wear due to high temperature damage [10]. As shown in Fig. 11b, it is a tool wear condition which lubricating MQL after processing occurs in the region of the main wear margin. As shown in Fig. 11c, it is the use of nanofluid/MQL (2 wt%) after processing tool lubrication conditions and wear situation is better than the previous two lubrication methods. The temperature measurements clearly indicate that MQL and nanofluid/MQL can reduce temperatures and, thus, tool wear. The nanodiamond weight percent concentration (2 wt%) of the nanofluid results in low micro-drilling temperature, so nanofluid/MQL (2 wt%) decreases tool wear to a significant degree.

Table 4 The experiment of the results

No.	Factors			The data of experiments	
	A Air compression (bar)	B Distance of nozzle (mm)	C Nanodiamond (wt%)	Sample (*N*)	S/N ratio
1	3	15	1	1.33	−2.50
2	3	25	2	1.29	−2.23
3	5	15	2	1.21	−1.67
4	5	25	1	1.41	−2.97

4.4 Comparing micro-drilling hole quality of chips and burrs for different lubrication methods

SEM was performed to examine the burrs generated from micro-drilling as shown in Fig. 12. In the image of the results of dry drilling, the large chip residues and the obvious burrs around holes are clearly seen, as shown in Fig. 12a. On the other hand, MQL and nanofluid/MQL (2 wt%) effectively remove hole scraps and reduce micro-porous burr phenomena. Nanofluid/MQL (2 wt%), because it is effective in suppressing tool wear, can keep edges sharp and so can effectively reduce microporous

Table 5 Factor response table for signal-to-noise ratio

	Factors		
	A	B	C
Level 1	-2.368	-2.089	-2.742
Level 2	-2.325	-2.604	-1.951
Effect	0.043	0.515	0.791
Rank	3	2	1

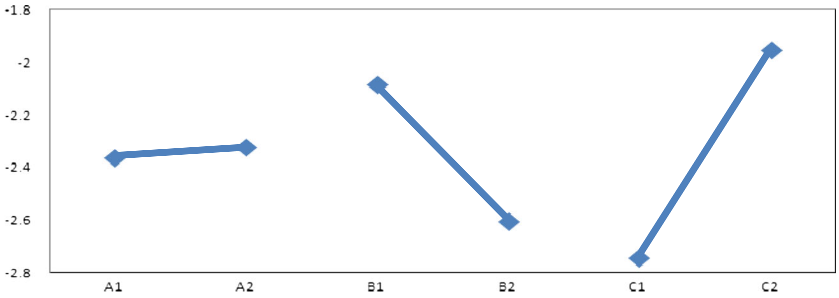


Fig. 5 Factor response graph of S/N

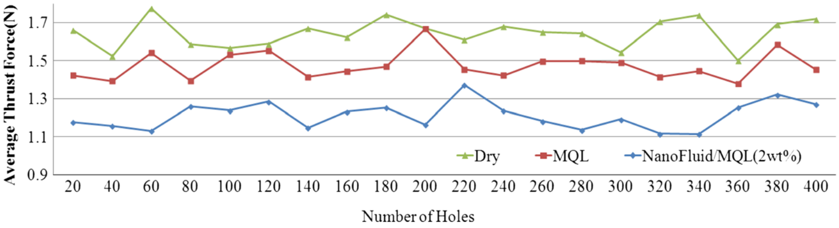


Fig. 6 The comparisons of average thrust force micro-drilling 400 holes under dry, MQL, and nanofluid/MQL (2 wt%)

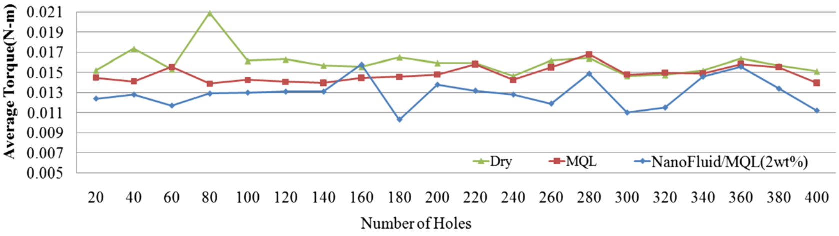


Fig. 7 The comparisons of average torque micro-drilling 400 holes under dry, MQL, and nanofluid/MQL (2 wt%)

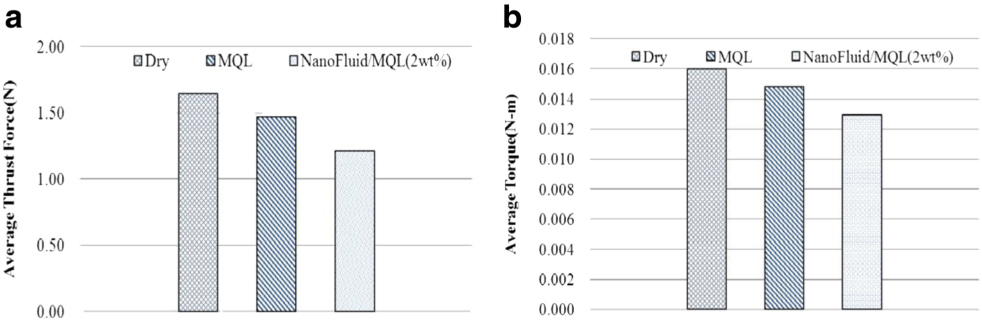


Fig. 8 The comparisons of **a** average thrust force and **b** average torque micro-drilling 400 holes under dry, MQL, and nanofluid/MQL (2 wt%)

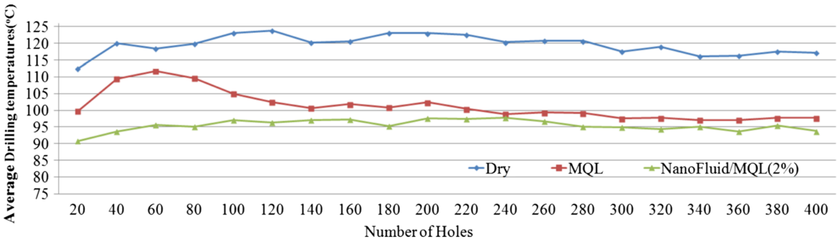


Fig. 9 The comparisons of drilling temperatures micro-frilling 400 holes under dry, MQL, and nanofluid/MQL (2 wt%)

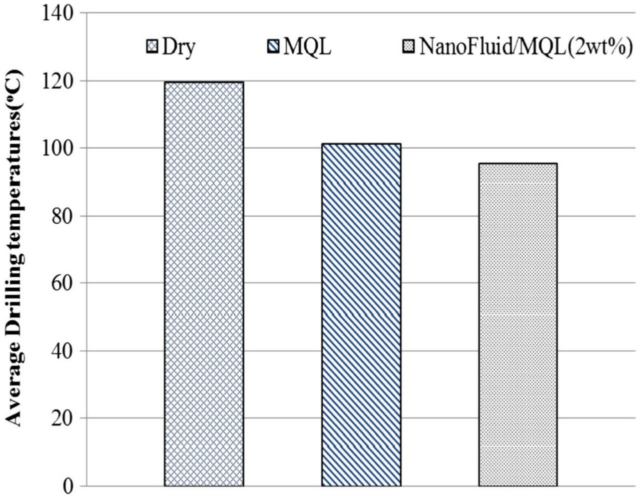


Fig. 10 The comparisons of average drilling temperatures micro-drilling 400 holes under dry, MQL, and nanofluid/MQL (2 wt%)

burrs generated in the micro-drilling process. Figure 12b shows the micro-drilling hole quality of chips and burrs with MQL methods. Figure 12c shows the nanofluid/MQL (2 wt%) micro-drilling hole quality of chips and burrs. In general, during micro-drilling, avoiding chips is not easy and it is difficult to remove burrs. Therefore, nanofluid/MQL (2 wt%) presents an effective solution to avoid burr formation and solve the chip problem.

5 Conclusion

Based on the results of the experimental investigation, conclusions can be drawn as follows:

1. In the Taguchi robust design, nanodiamond concentration is the most important factor affecting the micro-drilling forces, followed by the distance of the nozzle, while air pressure is of minimal influence.
2. Compared with traditional dry drilling and MQL, nanofluid/MQL, due to increased nanodiamond thermal conductivity, can reduce the temperature of the micro-drilling process.
3. Application of nanofluid/MQL in the micro-drilling process can reduce micro-drilling force and torque. It can prevent occurrences of sudden rupture of the micro-drilling tool and can effectively reduce tool wear and extend the life of the tools.
4. Application of nanofluid/MQL can significantly improve the micro-drilling hole quality of chips and burrs. Using this lubrication for micro-drilling, burrs around the holes are significantly reduced, due to nanodiamonds in the nanofluid enhancing the lubrication effect. Therefore, in micro-drilling processes, using nanofluid/MQL can effectively reduce burrs around the holes.

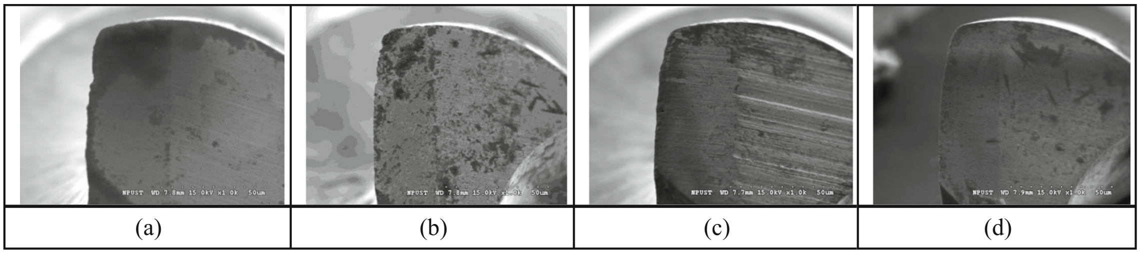
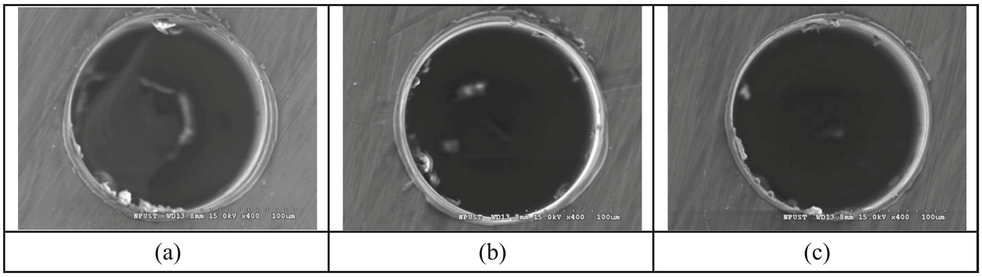


Fig. 11 SEM micrographs of the tool rake face micro-drilling 400 holes under **a** dry, **b** MQL, **c** nanofluid/MQL (2 wt%), and **d** original tool

Fig. 12 SEM micrographs of the drilled holes under **a** dry, **b** MQL, and **c** nanofluid/MQL (2 wt%)



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