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Experimental Study of Quarry Dust and Aluminium Oxide Suspension as Cutting Fluid for Drilling of Titanium Alloy

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ABSTRACT

In the aerospace field, titanium alloys are extensively used for the airframe and engine parts to improve aircraft fuel consumption. Drilling through these parts in a single-shot process to produce high quality holes is challenging. During drilling, high temperatures are generated owing to the friction between the cutting tool and workpiece, causing the process becomes inefficient in terms of tool life and surface quality. To reduce the temperature produced in the cutting zone, different types of cooling techniques during drilling have been used by researchers. In this study, the feasibility of quarry dust suspension as coolant in drilling of titanium alloy was performed. The effects of different concentrations of quarry dust on surface roughness, thrust force, and burr formation were evaluated, and their machining performances were compared with those obtained using aluminium oxide suspension. Before the experiments, both suspensions were prepared by dispersing quarry dust and aluminium oxide particles into deionised water at various concentrations ranging from 0 wt% to 0.10 wt%. Results indicated that by using 0.06 wt% of quarry dust suspension, thrust force and surface roughness showed an improvement by 8.31% and 18.29%, respectively, compared with those of aluminium oxide suspension at the same concentration. The burr height formed at the drilled holes using 0.06 wt% of quarry dust was also lower than that formed with aluminium oxide suspension at the same concentration.

1. Introduction

In the aerospace field, titanium alloy is extensively used for the airframe and engine parts to improve aircraft fuel consumption. High strength, lightweight, and good corrosion resistance are the common characteristics of titanium alloy that lead to its high demand and usage in the industry [1]. Due to the increasing demand for titanium alloy, it is critical to ensure that the product's finish is always of highest quality. Unfortunately, despite the advantages of titanium alloy, cutting this material is challenging because of its high strength. In machining, as the cutting tool makes contact with the workpiece, the friction starts to produce heat and leads to increase temperature in the

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cutting zone. High temperature has negative impacts such as tool wear and poor surface finish on the machining process. Thus, it is important to reduce the heat generated in the cutting zone during the machining of titanium alloy; otherwise, the product is bound to have poor surface roughness [2]. In order to increase lubrication between cutting tool and workpiece and reduce cutting temperature, cutting fluid is one of the most vital roles in the machining process [3,4].

Recently, the use of nanofluids as coolant has become a new research focus and it has been identified as an ideal candidate for enhancing heat transfer [5,6]. The nanofluid is created from the dispersion of nanomaterials (e.g., nanoparticles, nanofibers, nanotubes, nanowires, nanorods or nanosheets) in base fluids, such as water and oils [7]. Various types of nanoparticles have been used in previous studies. For example, Chatha *et al.,* [8] used a mixture of aluminium oxide (Al_2O_3) nanoparticles and soya bean oil as a lubricant for drilling aluminium 6063. Their results showed that the Al_2O_3 nanofluid minimum quantity lubricant (MQL) significantly increases the number of drilled holes and reduces the drilling torques and thrust forces compared with other coolant-lubrication conditions. Besides that, Idris *et al.,* [9] also used the hybrid Al_2O_3: SiO_2 as coolant in distributor cooling plate. It was demonstrated that hybrid nanofluids were superior to single nanofluids and base fluids in terms of heat transfer enhancement.

Quarry dust is one of the by-products of concrete aggregates during rock crushing. According to Sridharan *et al.,* [10] about 20%–25% of the total production in each crusher unit remains in quarry dust as waste material. Leaving these waste materials directly exposed to the environment is a challenging issue because it has several adverse effects, such as dust pollution and environmental deterioration. To control the environmental pollution caused by the disposal of these industrial wastes, converting them into value added raw materials for usable application is important.

According to Ramesh *et al.,* [11] quarry dust contains a high composition of silicon dioxide (SiO_2) followed by Al_2O_3. Sharma *et al.,* [12] showed that SiO_2 and Al_2O_3 nanofluids have excellent properties, and they significantly reduce the cutting force, cutting temperature, tool wear, and surface roughness during machining. SiO_2 solid nanoparticles in mineral oil act as a combination of rolling and sliding bearings at the tool–chip interface. They, in turn, reduce the coefficient of friction and significantly improve the machining performance [13,14].

Therefore, recycled quarry dust which is high in SiO_2 and Al_2O_3 content can be a great economical alternative to the expensive conventional ceramic particles. In the present study, the feasibility of quarry dust suspension was used as cutting fluid in the drilling process of titanium alloy. The effects of different concentrations of quarry dust on the surface roughness, thrust force, and burr formation were evaluated. A comparison of machining performances by using quarry dust suspension and Al_2O_3 suspension was also carried out.

2. Methodology

2.1 Preparation of Quarry Dust and Al_2O_3 Suspension

Before the drilling experiment, the as-received quarry dust powder was subjected to ball milling process by using planetary ball mill (Retsch PM 400) to reduce the particle size. This apparatus comprised a vial mounted onto a planar disc. As the disc rotated, the vials also moved in circular motion in directions different from that of the disc rotation. The rotational speed was 400 rpm, the milling duration was 72 h, and the interval was 15 min. Stainless steel balls with two different sizes (diameters of 5 mm and 10 mm) and 500 mL volume steel vials were used. The ball-to-powder weight ratio was 4:3. To avoid any air contamination during ball milling, the vials of the planetary ball mill were sealed tightly with the machine body before the start of ball milling. After ball milling, the average particle size of quarry dust was 48.423 µm [15].

After ball milling, quarry dust and Al_2O_3 suspension were prepared using an ultrasonic homogeniser (Labsonic type P series). Deionised (DI) water was used as a base fluid, and sodium lauryl sulphate and sodium dodecyl benzene sulphonate were used as the surfactant for quarry dust and Al_2O_3 suspension, respectively. Six different concentrations were prepared, namely, 0.0 wt% (DI water), 0.02 wt%, 0.04 wt%, 0.06 wt%, 0.08 wt%, and 0.1 wt%. The volume of DI water was 400 mL, and the weights of powder and surfactant were equal. The formula for the quarry dust and Al_2O_3 suspension preparation is shown in Eq. (1).

$$wt\% = \frac{Weight\ of\ solute\ (g)}{Weight\ of\ solution\ (g)}\ x\ 100\% \tag{1}$$

where the weight of solute is the sum of the weight of powder and weight of surfactant, and the weight of solution is equal to the weight of base fluid.

During mixing, a 14 mm diameter titanium probe was mounted onto the machine to transfer the vibration energy and blend the mixture. The surfactant was dissolved in DI water for 15 min, and then the powder was dispersed into the mixture for another 50 min with an ultrasonic homogeniser (50% amplitude at an interval of 0.5). The jar containing the mixed suspension was placed in a basin with cool water to reduce the heat energy released during mixing.

2.2 Machining Setup

Titanium alloy (Ti-6Al-4V) with 50 mm wide, 50 mm long, and 5 mm thick serving as the workpiece throughout this research. Titanium alloy was purchased from Metaplus Engineering Sdn Bhd, Melaka. A high speed cobalt twist drill with a diameter of 6 mm was selected as drill bit in this study. It was selected to drill the titanium alloy because it contained solid carbide which can drill high strength materials such as titanium alloy at an affordable price. Experiments were conducted using a HAAS VOP-C CNC milling machine. Parameters such as feed rate, cutting speed, and depth of cut were held constant. Each drilling test was repeated thrice, and the average was taken. In this research, six different concentrations of quarry dust and Al_2O_3 suspension were used for the machining. The coolant was supplied to the drilling zone using a Masterflex pump, as shown in Figure 1. Table 1 shows the details for each parameter.

Table 1
Machining parameters

Machining parameters	Details
Feed rate, f (mm/rev)	0.09
Cutting speed, V_c (m/min)	20
Depth of cut, d (mm)	5
Powders	Quarry dust and Al_2O_3
Concentration of suspension (wt%)	0.00 (DI water), 0.02, 0.04, 0.06, 0.08, 0.1

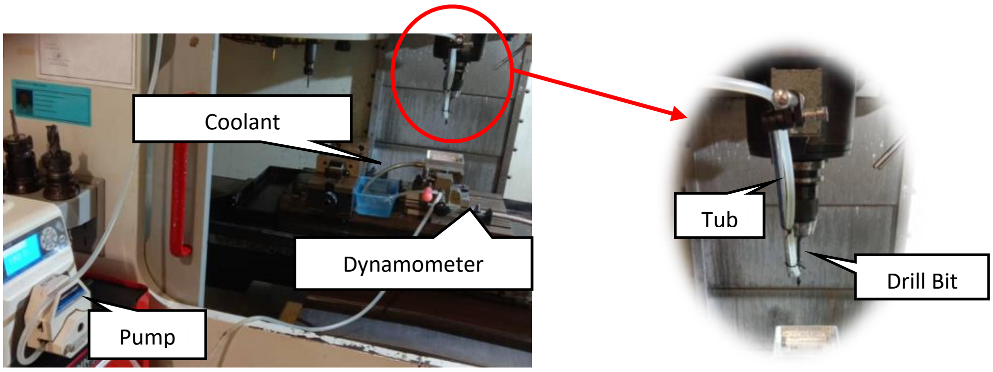


Fig. 1. Experimental setup of drilling process

2.3 Measurement and Evaluation

A Mitutoyo SJ-301 Portable Surface Roughness tester was used to measure the surface roughness in the inner hole of the titanium alloy after drilling. The machine was calibrated before the measurement to maintain data accuracy. The equipment resolution was 1 µm, and the measurement length was 5 mm. Data were obtained three times at different spots in the drilled hole. The final value was calculated after averaging the value at different spots. Thrust force was measured using a dynamometer (DynoWare: Kistler) during hole drilling. For each experiment, data collection and measurement were performed for analysis. To determine the force exerted on the workpiece during drilling, a dynamometer was installed on a CNC milling machine (HAAS VOP-C CNC) and connected to the computer. The measurement was repeated six times, and the values of the thrust forces were analysed after taking the average value. The surface topography of burr was observed using a 10 kV SEM system (model Zeiss Evo 50). Before the measurement, the workpiece was cleaned to remove chips or any contaminant using air spray. ISO 13715 (Edges of undefined shape - indication and dimensioning) standard served as the reference for defining the edges of workpiece as free of burrs, rounded, sharp, chamfered, or with burr.

3. Results

3.1 Thrust Force

The effect of quarry dust and Al_2O_3 with different concentrations on the thrust force is shown in Figure 2. The thrust force during drilling when using quarry dust and Al_2O_3 suspension had the same trend. Thrust force was relatively high without the addition of powders in DI water (0 wt%). However, thrust force rapidly decreased with increased concentration of both suspensions. These results agreed with those obtained by Sharma *et al.,* [12], who found that the presence of particles assists in enhancing heat transfer during drilling owing to the improved heat dissipation, thereby allowing cutting tools to retain their hardness for longer periods of time. This phenomenon increases the wearing time of the drill bits and results in lower thrust force.

Nevertheless, when a higher concentration of powders was used, thrust force also increased. Zhang *et al.,* [16] showed that with increased concentration, particle agglomeration occurs and reduces the surface area of the particles. Thus, it reduces the heat dissipation which then leads to increased thrust force during drilling. Furthermore, according to Al Moajil *et al.,* [17], microsized particles have a higher tendency to agglomerate and sag, resulting in higher thrust force at higher concentration.

However, when quarry dust suspension was used, the thrust force was found to be lower than that of Al_2O_3 suspension. The lowest thrust force value 276.6 N, recorded at a concentration of 0.06 wt% for quarry dust suspension. Quarry dust suspension, which is considered as a hybrid suspension, has a greater amount of lubricating film layer that adheres onto the surface of tool and workpiece surface compared with mono suspension, which is Al_2O_3 suspension. This layer avoids the direct contact between tool and workpiece, so the frictional force can be decreased. Şirin *et al.,* [18] also stated that by using a hybrid suspension, the cutting force is reduced because the lubricating film layer effectively reduces the friction between the tool and workpiece interface, resulting in decreased cutting force.

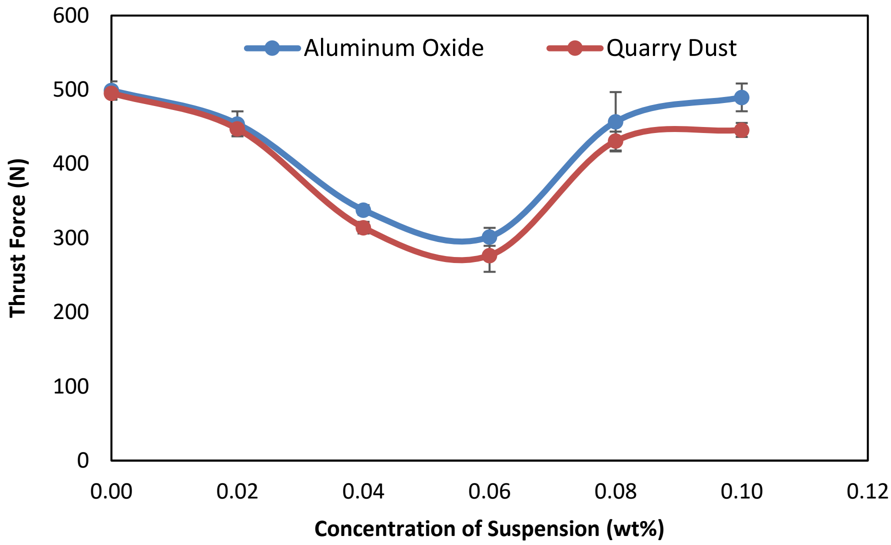


Fig. 2. Effect of different concentration of quarry dust and Al_2O_3 suspension on the thrust force

3.2 Surface Roughness

Figure 3 shows the effect of quarry dust and Al_2O_3 suspension on the surface roughness of drilled hole. A similar trend to thrust force was observed. When pure DI water (without quarry dust and Al_2O_3, 0 wt%) was used, the surface roughness was extremely high. However, the surface roughness of the drilled hole was decreased significantly when the concentrations of both suspensions increased. As known from Sayuti *et al.,* [13], during machining, these particles acted as a combination of rolling and sliding bearings at the tool–chip interface, in turn reducing the coefficient of friction and improving the surface finish.

Clearly, the surface roughness of the drilled hole was higher when Al_2O_3 suspension was used compared with the quarry dust suspension. The lowest surface roughness was 0.67 µm, which was obtained using 0.06 wt% of quarry dust suspension. This finding was due to the combination of SiO_2 and Al_2O_3 in quarry dust suspension acting as rolling and sliding bearings at the tool–chip surface in a greater way than with Al_2O_3 suspension, which consisted only of single particles. Moreover, Hamran *et al.,* [19] found that microparticles in suspension act as helpers that reduce friction by building a protective layer that attached onto the surface of cutting tools, and in turn, reducing the surface roughness of the drilled hole.

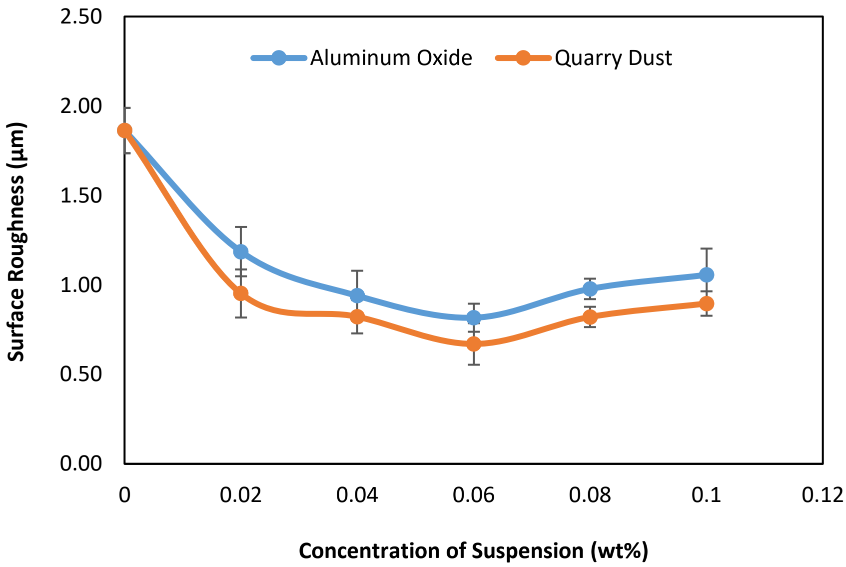
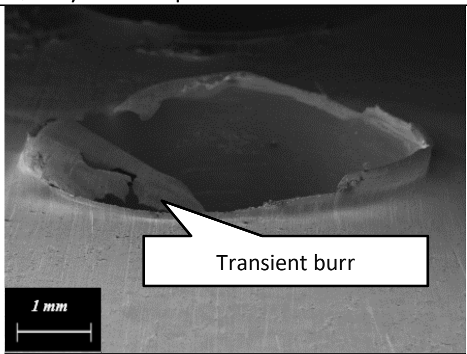
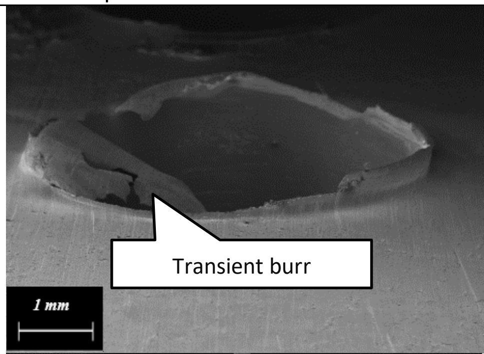
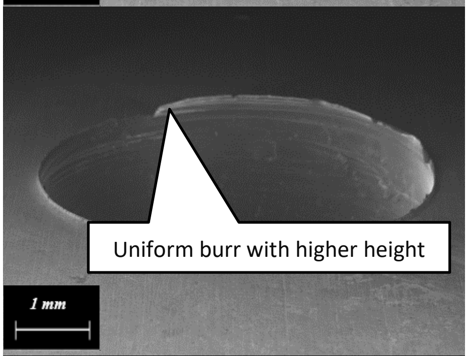
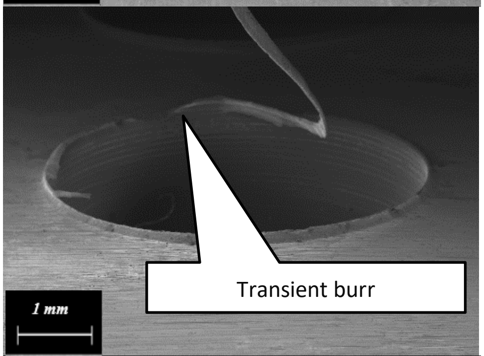
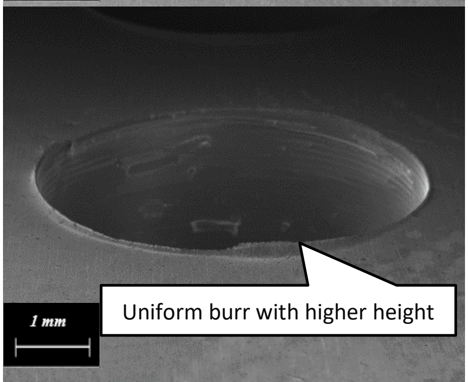
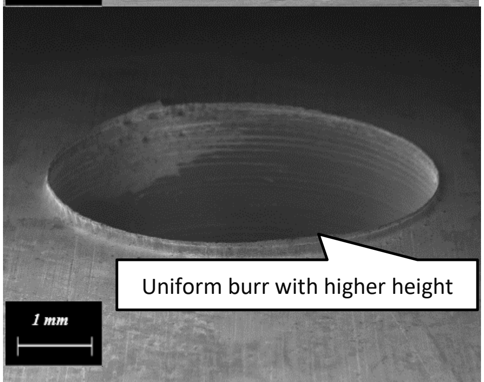
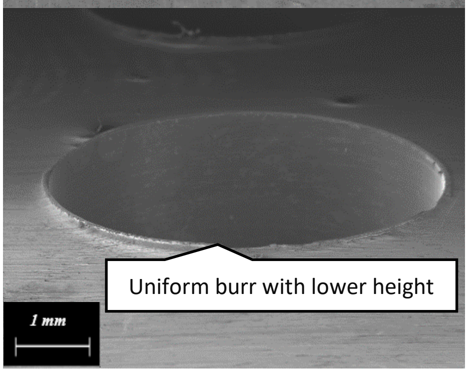
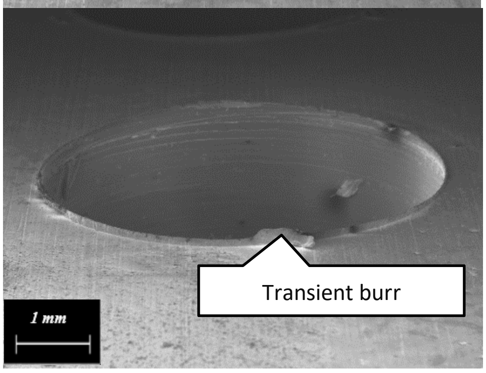


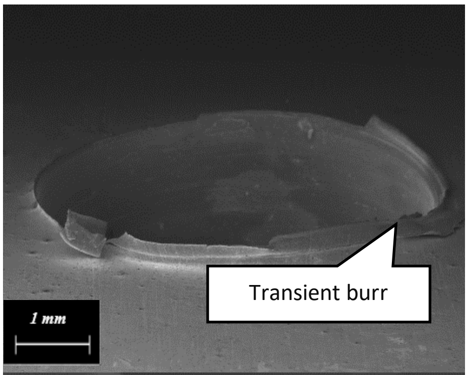
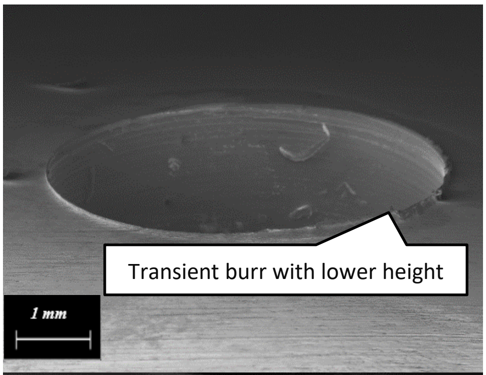
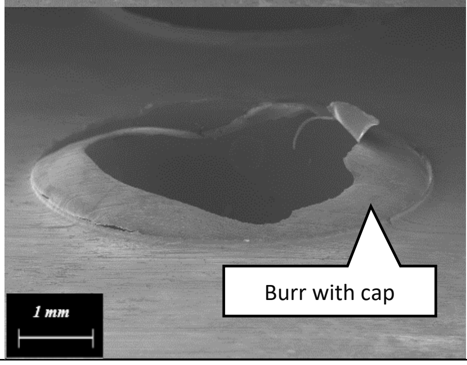
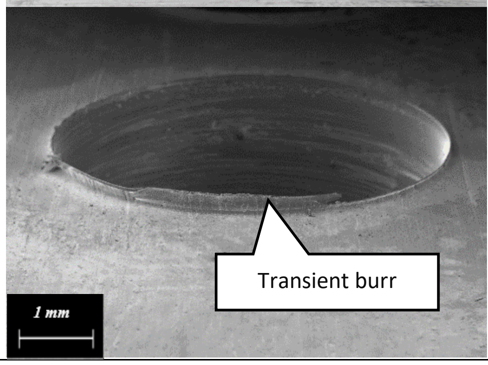
Fig. 3. Effect of different concentration of quarry dust and Al_2O_3 suspension on the surface roughness of drilled hole

3.3 Burr Formation

Table 2 shows the burr formation at the exit holes of titanium alloy by using quarry dust and Al_2O_3 suspension as a coolant. Without the addition of quarry dust and Al_2O_3, a transient burr with greater height was clearly observed at the exit hole. However, when the concentrations of both suspensions increased, better hole quality with lower burr height can be obtained. The highest quality hole can be seen when 0.06 wt% of quarry dust suspension was used. Based on the unpublished data of authors, 0.06 wt% of quarry dust suspension recorded the highest thermal conductivity compared to that of pure DI water and Al_2O_3 suspension at the same concentration. When the thermal conductivity was higher, more heat will be dissipated from the drilling zone, which can reduce temperature at the drilling region and retained the hardness of drill bit. With decreased temperature, tool life increased and thus reduced the tool-wear rate [20]. According to Costa *et al.,* [21], the burr height is closely related to drill wear. Sharp drills generated small burrs, whereas worn drills generated large burrs. As can been seen from Table 2, although the Al_2O_3 suspension also gave a minimal burr height at the exit hole, the drilled hole quality was not as good as that formed using quarry dust suspension at the optimum concentration (0.06 wt%).

Table 2
Burr formation at the exit hole by using quarry dust and Al_2O_3 suspension at different concentration

Concentration (wt%)	Quarry dust suspension	Al_2O_3 suspension
0		
0.02		
0.04		
0.06		

0.08		
0.10		

4. Conclusions

This study aimed to investigate the effect of quarry dust suspension as coolant during drilling of titanium alloy. The surface roughness, thrust force, and burr formation on titanium alloy drilling with various concentrations of quarry dust suspension were studied. A comparison of machining performances by using quarry dust suspension and Al_2O_3 suspension was also conducted.

The main findings of the research are as follows:

i. The thrust force and surface roughness decreased with the increased of quarry dust and Al_2O_3 concentration.
ii. When using quarry dust and Al_2O_3 suspension, better hole quality with lesser burr formation than that of DI water was obtained.
iii. Compared with Al_2O_3 suspension at 0.06 wt%, quarry dust at the same concentration provided better results of thrust force and surface roughness reaching 8.31% and 18.29%, respectively. Burr height was also lower at the drilled holes using 0.06 wt% of quarry dust compared with Al_2O_3 suspension at the same concentration.

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