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Improvement of Rock Cutting Performance through Two-Pass Abrasive Waterjet Cutting

Gokhan Aydin *, Izzet Karakurt, Mohammad Reza Amiri and Serkan Kaya

Mining Engineering Department, Karadeniz Technical University, Trabzon 61080, Turkey
* Correspondence: gaydin@ktu.edu.tr

Abstract: Abrasive waterjet (AWJ) has been widely used for the cutting of hard materials such as rocks. The AWJ cutting of rocks has been well documented in the relevant literature. In these studies, one-pass cutting is employed as the cutting mode. There is no study focusing on the two-pass AWJ cutting of rocks. Therefore, this study aims to fill this gap. Therefore, in the current study, the physicomechanical properties of the rock subjected to cutting are first determined. Following, the workpieces are cut with both one-pass and two-pass cutting modes. In the tests, cutting time is kept constant to compare the performances of cutting modes in terms of the smooth cutting depth and surface roughness. Kerf profiles of the cutting modes are also compared. In the study, significant relationships were not determined between the cutting parameters (abrasive flow rate and standoff distance) and performance outputs for the cutting modes. This may be attributed to the cutting parameters studied in a narrow range. The results indicate that two-pass cutting with higher speeds provides higher smooth depths than one-pass cutting at lower speeds. Two-pass cutting increases smooth depth up to 47%. Results show that surface quality could be improved by two-pass cutting, expanding the smooth zone and reducing the sizes of the striations. The results also show that two-pass cutting improves surface roughness by up to 25%. It is revealed that kerf wall inclination is reduced by two-pass cutting in the upper and lower parts of the kerf. A widened portion caused by the first pass is observed in the final kerf. It can be noted that two-pass cutting cannot provide any improvement in the top kerf width.

Keywords: abrasive waterjet; two-pass cutting; rock; cutting performance

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1. Introduction

Abrasive waterjet (AWJ) technology has been increasingly used in the manufacturing industries. AWJ provides many advantages such as no thermal distortion on the workpiece, high machining versatility, cutting direction flexibility, and small cutting forces. It is especially used for cutting hard materials such as rocks [1–4]. In AWJ cutting, the jet (a combination of water and abrasives) removes particles from the workpiece due to the erosive actions of the abrasives [5,6].

It has been demonstrated that AWJ performance is dominantly governed by cutting parameters and workpiece properties [7,8]. For example, the traverse speed and some rock properties (the uniaxial compressive strength, shore hardness, microhardness, etc.) mainly control the cutting depth [9–12]. Additionally, the traverse speed, water absorption, and grain size also have discernible effects on the kerf angle [13–16]. Moreover, the water pressure, abrasive flow rate, and mean grain size of the workpiece are significant factors in terms of surface roughness [9,10,12,17–20]. On the other hand, better cutting efficiency could be provided with higher water pressure [5]. In addition, the cutting depth efficiency tends to increase with the increase in water pressure and traverse speed. It also increases with the decrease in standoff distance and uniaxial comprehensive strength of the workpiece. As another efficiency output, the cutting volume efficiency strongly depends on the standoff distance [21–23]. In the relevant literature, abrasive recycling has also been documented. As known, the recycling of abrasives makes the AWJ cutting operation more economical. It was revealed that rock microhardness and particle size distribution of the recycling abrasives are important parameters in terms of cutting performance [24,25]. Recently, some studies have investigated the performance of commercial abrasives [26]. It was concluded that the density and hardness of abrasives were the main properties affecting AWJ performance [6]. Solid-cutting waste of granite was also used as an abrasive in the cutting of rocks with lower hardness [27]. Moreover, some studies have proposed models for the performance prediction of AWJ in rock cutting [7,12,14,15,28].

In all of the studies above, one-pass cutting was used as the cutting method. There are situations where the material thickness is beyond the jet's capacity to penetrate by one-pass cutting. Furthermore, studies focusing on traditional machining processes have shown that multipass is superior to one-pass cutting. Multipass cutting at higher traverse rates may offer advantages (increasing cutting depth, reducing cutting time, etc.) over one-pass cutting at a low traverse rate [1]. There are several studies focusing on multiple pass cutting. In these studies, stainless steel [29–31], steel alloy [32], aluminum [29], alumina ceramic [1,3,33–36], and carbon fiber-reinforced plastics [37] have been used as workpiece materials. In the relevant literature, there is no study focusing on the multipass cutting of rocks. Therefore, in the current study, an attempt was made to fill this gap. It should be noted that higher cutting depths could be obtained with two-pass cutting. This means a reduction in the cutting time to achieve the same depth. This will also reduce operating costs. This study is expected to create awareness for the application of two-pass AWJ cutting of rocks.

The rest of the paper is organized as follows. Detailed information about the materials used and the method employed is presented in Section 2. Section 3 gives and analyzes the results of the cutting tests. Finally, Section 4 presents the core findings of the study and provides some recommendations for further studies.

2. Materials and Methods

As is well known, granular rocks such as granite consist of different minerals that vary in their percentage contents, size, shape, etc. These properties could affect the cutting performance of an AWJ even though all the parameters related to the AWJ are kept constant. Therefore, in the current study, workpieces from a homogenous rock were used to compare the performances of one-pass and two-pass AWJ cutting. The workpieces were supplied at a thickness of 5 cm, a length of 20 cm, and a width of 10 cm. Water absorption capacity, effective water absorption, natural water content, saturation percentage, unit weight, mineral grain density, total porosity, void ratio, ultrasonic velocity, digital/classic Schmidt hardness, Mohs hardness, uniaxial compressive strength, cohesion, angle of internal friction, indirect tensile strength, and point load strength of the workpiece were determined through standards as suggested by methods of the ISRM [38]. Results are provided in Table 1.

The cutting tests were conducted with the AWJ shown in Figure 1. The test conditions were selected to ensure the feasibility of two-pass cutting (see Table 2). As recommended by Wand and Guo [1], the cutting time was kept constant for the cutting modes. Values of the cutting variables are selected considering the system limitations and previous studies [27,39–41]. The workpieces were cut through their length. In the study, after two-pass, multiple pass did not provide any improvements in the cutting performance (especially for cutting depth) due to the experimental conditions (cutting parameters). For this reason, multiple cuts were limited to two times. After the cutting tests, the smooth depths (cutting-wear zone depth) and surface roughness were determined on the workpieces. Additionally, the characteristics of the kerfs produced in both cutting modes were analyzed for each test.

Table 1. Properties of the workpiece used in the cutting tests.

Properties	Values
Water Absorption Capacity (% Weight)	4.31
Effective Water Absorption (%)	4.07
Natural Water Content (%)	0.07
Saturation Percentage (%)	1.47
Gravity (g/cm^3)	2.30
Mineral Grain Density (g/cm^3)	2.55
Total Porosity (%)	9.90
Void Ratio (%)	11.00
Ultrasonic Velocity (m/s)	4379
Digital Schmidt Hardness (Q)	64.70
Classic Schmidt Hardness (R)	47.25
Mohs Hardness	3
Uniaxial Compressive Strength (MPa)	52.39
Cohesion (MPa)	21.86
Angle of Internal Friction (degree)	69.20
Indirect Tensile Strength (MPa)	6.59
Point Load Strength (MPa)	3.50

Figure 1. The AWJ used in the test.

Table 2. Cutting conditions.

Cutting Condition	Values
Abrasive Size (mesh)	80
Abrasive Type	Garnet
Nozzle Diameter (mm)	1.1
Nozzle Length (mm)	75
Orifice Diameter (mm)	0.33
Nozzle Inclination (degree)	90
Water Pressure (MPa)	200
Standoff Distance (mm)	2, 4, 6
Abrasive Feed Rate (g/min)	200, 250, 300
Traverse Speed (mm/min)	60, 120
Number of Pass	1,2

In the AWJ cutting of workpieces, the cutting zones (at superficial and broad angles of attack) and deflection zone were produced [1,6,16]. Hashish [42] defined the cutting mechanism in the first two zones as cutting wear and deformation wear, respectively. Additionally, he explained that the cutting process in the third zone is controlled by erosive wear at large particle attack angles. As a result of these machining mechanisms, two characteristic surfaces (the upper smooth zone which is free of striations, and lower rough zone characterized by wavy striations) are generated on the workpiece. Smooth cutting depth is one of the major characteristics of AWJ cutting. It is determined from the top of the workpiece down to the cutting surface where striations are observed. The low smooth depth means that the AWJ shows poor performance [12,14,43]. For each test, a total of 9 measurements were taken for the smooth depth using a digital caliper (precision 0.01 mm). The average of the measurements was recorded as final smooth depth. Following this process, the roughness levels of the machined surfaces were determined. The surface roughness (central-line average measure Ra) was measured at 1 mm from the top edge of the kerfs at the upper zone (smooth zone) using a stylus-type profilometer. For each test, a total of 5 measurements were taken and the average was recorded as the final surface roughness.

3. Results and Discussion

Smooth depths obtained for one-pass and two-pass AWJ cutting are provided in Table 3. As also shown in Figure 2, increasing the abrasive flow rate generally increases the cutting depths for both cutting modes. This increase almost remains stable after the second level of the abrasive flow rate. AWJ machining is a hydro-abrasive deformation process in which abrasive particles are added to increase the effect of the jet. Therefore, the effect of abrasive is mainly dependent on the number of particles in the jet. More material is removed from the workpiece with more abrasive particles in the jet. However, there is a critical value of abrasive flow rate for obtaining higher cutting depths. Further increasing abrasive flow rate leads to an increase in the collision of particles and reduction in size [9]. As is well known, the abrasive particles in the AWJ disperse/break down in the nozzle (abrasive–abrasive impact and the abrasive hitting the inner surfaces of the nozzle) and inside the workpiece (abrasive–abrasive impact and the abrasive hitting the inner surface of the workpiece). Particularly at high abrasive feed rates, abrasive particles can be expected to hit each other and other surfaces more frequently. This causes more fragmentation of the abrasive particles resulting in a decrease in kinetic energy. Moreover, with the increase in the abrasive flow rate, the velocity of the water moving in the focusing tube decreases and again the kinetic energy of the AWJ decreases. This may result in nonlinear changes in the overall cutting performance in terms of cutting depth. In the case of the standoff distance, it can be noted that within the range of the standoff distance tested, the cutting depths were initially decreased and then increased. The standoff distance is closely related to the spreading of the jet (therefore, the abrasive particles) around the cutting line. A high standoff distance produces a wide jet diameter and the abrasive particles in the jet spread produce wider kerfs [9]. At higher standoff distances, the energy density of the jet impinging decreases and, consequently, generates a lower jet penetration depth. In the study, the values of the standoff distance were selected in a narrow range (between 2–6mm). Therefore, it can be stated that this kind of effect was not observed.

Table 3. Experimental results for smooth depth.

Experiment No.	Standoff Distance (mm)	Abrasive Feed Rate (g/min)	Smooth Depth (mm)	
			One-Pass Cutting	Two-Pass Cutting
1	2	200	23.11	34.03
2	2	250	24.37	30.29
3	2	300	24.52	31.11
4	4	200	15.84	20.69
5	4	250	24.04	27.41
6	4	300	22.50	23.77
7	6	200	25.20	26.12
8	6	250	26.30	30.44
9	6	300	26.43	26.64

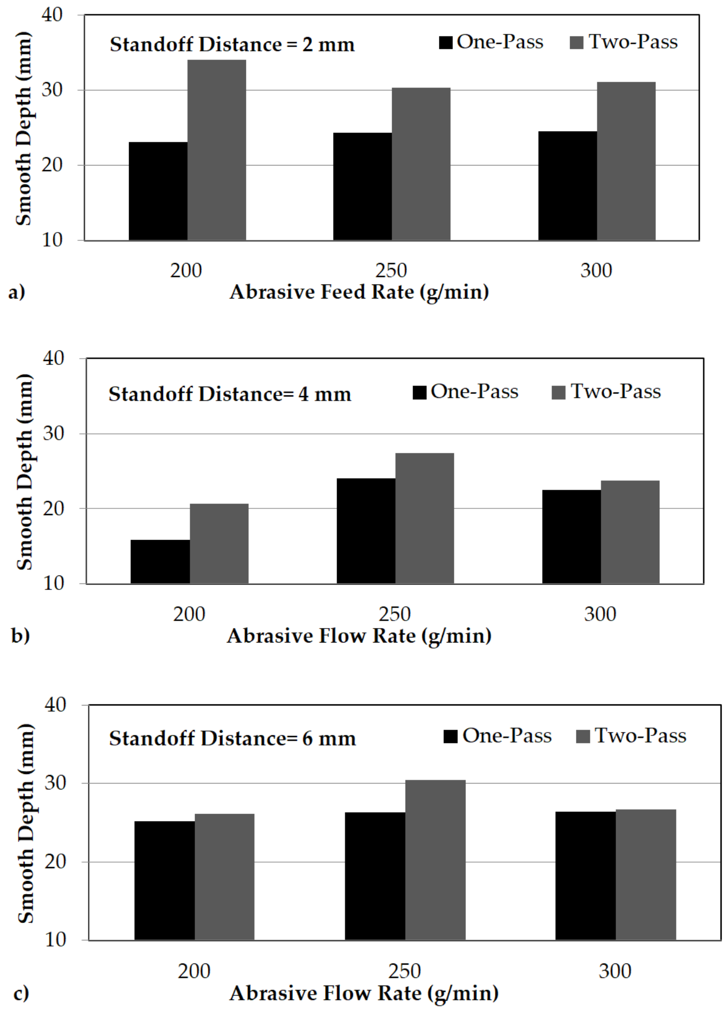

Figure 2. Effects of abrasive flow rate on the smooth depths for standoff distances of (**a**) 2 mm, (**b**) 4 mm, and (**c**) 6 mm.

The overall results indicate that two-pass cutting at a higher speed is superior to one-pass cutting at a lower speed. It can be stated that two-pass cutting enables the jet to penetrate deeper into the workpiece when compared with one-pass. These findings also indicate that the cutting time could be decreased with two-pass cutting. Therefore, two-pass cutting could be recommended to increase the productivity of AWJ cutting. Smooth depth was increased up to 47% with two-pass cutting. The results are supported by the previous studies as well [1,36]. Researchers have reported that one-pass was just able to cut through the workpiece whereas two-pass cutting at a higher speed easily penetrates the workpiece. Wang [33] also explained that smooth depth can be considerably increased with two-pass cutting. He noted that two-pass cutting provides a reduction in the cutting time to obtain the same smooth depth. These findings were also supported by Whang and Zhong [35]. They recommended two-pass cutting to increase the capability and application domain of AWJ technology.

Surfaces of the workpieces obtained for one-pass and two-pass AWJ cutting are presented in Figures 3 and 4, respectively. As seen, non-uniform damage zones were created on the machined surfaces with the irregular pits caused by abrasive particles.

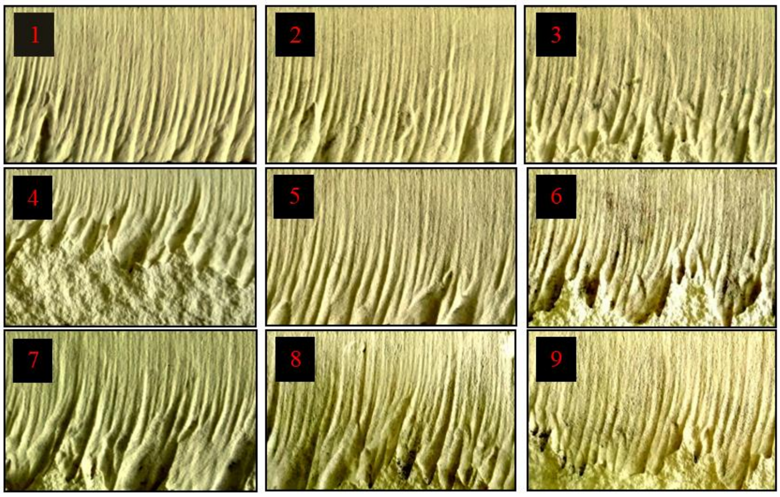

Figure 3. Cutting surfaces of the workpieces subjected to one-pass cutting for each test.

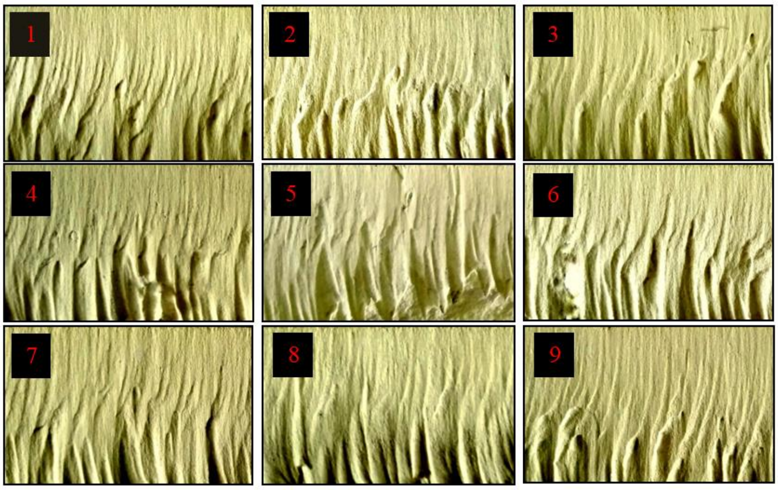

Figure 4. Cutting surfaces of the workpieces subjected to two-pass cutting for each test.

It was revealed that the smoother surfaces were produced by the jet impacting at a shallow angle in the cutting wear zone. In this zone, the small grooves lying through the cutting depth were encountered randomly. It was seen that the orientations of these grooves were parallel to the jet direction. Additionally, in the deformation wear zone, big grooves (described as striations or waviness) with considerable amounts were observed because of the jet impact at a large angle. When cutting further down in the lower region (deflection zone), it was observed that the abrasive particles could not effectively cut the workpiece due to their insufficient energies. These findings are compatible with the literature [27,37,41].

Surface roughness (Ra) levels produced by one-pass and two-pass AWJ cutting are given and compared in Table 4. The surface quality of the upper (good quality) and lower layers (bad quality) are quite different. The lower layers include deep–large erosion pits and striations. The surface quality of the workpieces decreases gradually from top to bottom as indicated by Miao et al. [31]. The higher the abrasive flow rate, the higher the number of particles involved in the mixing and cutting processes [44]. When the abrasive flow rate is increased, the cutting surface becomes smoother, and low surface roughness is expected due to the greater number of impacts and cutting edges available per unit area. However, no clear trend was observed in the current study (see Figure 5). In case of the stand-off distance, as a consequence, an increased jet diameter or a diverged jet can easily lose its kinetic energy and may produce rougher surfaces [17,45,46]. Similar to the effect of the abrasive flow rate, in the current study, any relationship could not be obtained between the standoff distance and surface roughness.

Table 4. Experimental results for the surface roughness.

Experiment No.	Standoff Distance (mm)	Abrasive Feed Rate (g/min)	Surface Roughness (Ra, µm)	
			One-Pass Cutting	Two-Pass Cutting
1	2	200	8.18	9.14
2	2	250	8.95	8.77
3	2	300	8.47	8.15
4	4	200	10.70	8.91
5	4	250	10.20	7.69
6	4	300	9.71	7.51
7	6	200	9.01	8.84
8	6	250	8.86	9.39
9	6	300	8.98	8.93

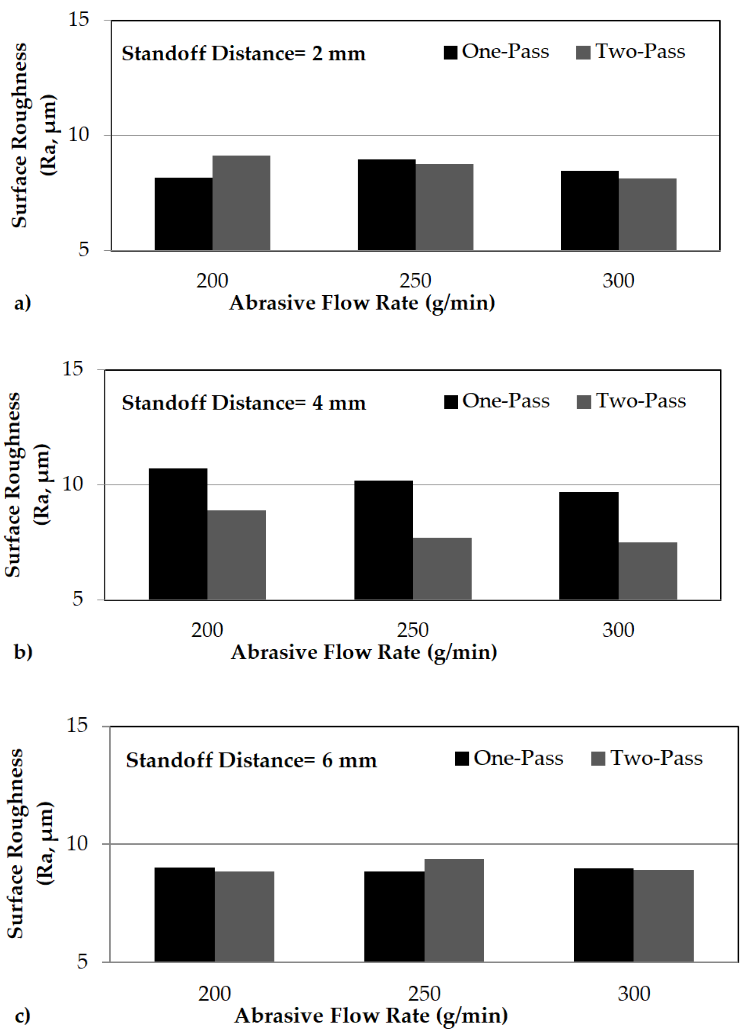

Figure 5. Effects of abrasive flow rate on the surface roughness for standoff distances of (**a**) 2 mm, (**b**) 4 mm, and (**c**) 6 mm.

Results show that two-pass cutting improves the surface quality by expanding the smooth zone and reducing the sizes of the striations. This may be attributed to the cutting mechanism of two-pass cutting with higher traverse speeds. It can be said that the peaks from the one-pass cutting were removed with two-pass cutting. Wand and Guo [1] also determined that surface roughness increases with the increase in traverse speed. It is clear that two-pass cutting and traverse speed have different effects on surface roughness. The current study demonstrated that the positive effect of two-pass cutting on the surface roughness plays a more dominant role than the negative effect of traverse speed. The study showed that the surface roughness could be improved up to 25% with two-pass cutting. Therefore, two-pass cutting could be recommended to obtain smoother surfaces.

A visualization study provided in Figure 5 indicates that the kerfs produced by one-pass cutting are similar characteristics reported in previous investigations [13–16,37]. The kerf produced with one-pass cutting is characterized by a wider opening, reducing gradually with a large pocket at the bottom due to the jet upward deflection. Two-pass cutting reduced the kerf wall inclination in the upper and lower portions (see Figure 6). A widened portion caused by the first pass is observed in the final kerf. It can be noted that any improvement in the top kerf width was not provided by two-pass cutting.

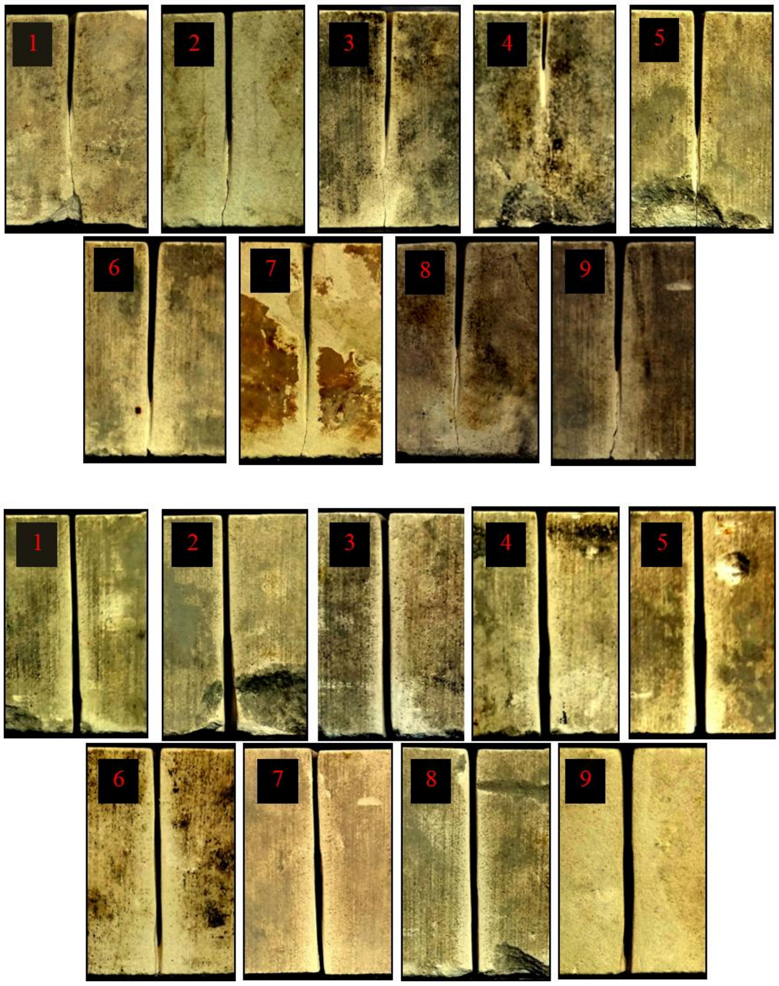

Figure 6. (**up**) Cutting surfaces of the workpieces subjected to one-pass cutting for each test. (**down**) Cutting surfaces of the workpieces subjected to two-pass cutting for each test.

4. Conclusions

From the results and discussion above, the following conclusions can be drawn:

i. It was determined that two-pass cutting at higher traverse speeds provides higher smooth depths than those obtained by one-pass cutting at lower traverse speeds in the same cutting time.

ii. It was revealed that two-pass cutting improves the surface quality by expanding the smooth zone and reducing the striation sizes. Additionally, it was observed that two-pass cutting improves the kerf profile.
iii. It was noted that multipass cutting would be able to reduce the cutting time which, in turn, decreases production costs.

For further studies, the performance of two-pass cutting can be investigated for the workpieces from different origins. Moreover, the cutting performances of two-pass cutting could be modeled using various approaches.

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