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Performance of recycling abrasives in rock cutting by abrasive water jet

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Abstract: Rock cutting performance of recycling abrasives was investigated in terms of cutting depth, kerf width, kerf taper angle and surface roughness. Gravity separation technique was employed to separate the abrasives and the rock particles. The recycling abrasive particles were then dried and sieved for determination of their disintegration behaviors. Before each cutting with recycling abrasives, the abrasive particles less than 106 μm were screened out. It is revealed that a considerable amount of used abrasives can be effectively reused in the rock cutting. The reusabilities of abrasives are determined as 81.77%, 57.50%, 34.37% and 17.72% after the first, second, third and fourth cuttings, respectively. Additionally, it is determined that recycling must be restricted three times due to the excessive disintegration of abrasives with further recycling. Moreover, it is concluded that cutting depth, kerf width and surface roughness decreases with recycling. No clear trend is found between the kerf taper angle and recycling. Particle size distribution is determined as an important parameter for improving the cutting performance of recycling abrasives.

Key words: abrasive water jet; rock; abrasive; recycling

1 Introduction

The use of granite as a construction and ornamental material has drastically increased recently because of its excellent properties, such as resistance to environmental influence, hardness, and aesthetic properties [1−2]. As a result, the growing interest of granite has stimulated the studies of innovative manufacturing processes. Among the innovative manufacturing processes, abrasive water jet (AWJ) can meet the required standards for cutting and/or processing of rocks, more specifically dimension stones, e.g., granite. This advanced technology is applied both to drilling and excavation of hard rock for winning blocks with an opening of holes or slots and also for end products in the field of dimension stone final beneficiary [3−4].

With the introduction of AWJ technology in cutting of materials including the rock and/or rocklike materials for particular applications, many studies have been documented so far. Effects of some process parameters on the penetration of sandstones machined by high speed water jets were investigated by BROOK and SUMMERS [5]. Coal and rock penetration by fine continuous high pressure water jets was studied by NIKONOV and GOLDIN [6]. CHAKRAVARTHY et al [7] presented a fuzzy based model to suggest a set of process parameters in cutting of black granite by AWJ. CHAKRAVARTHY and BABU [8] proposed an approach based on the principles of fuzzy logic and genetic algorithm (GA) for selection of optimal process parameters in AWJ cutting of granite. LI et al [9] conducted experimental studies on rock cutting by collimated AWJ. MIRANDA and QUINTINO [10] conducted an experimental study to determine effect of material properties on the cutting mechanisms involved in AWJ cutting of calcareous stones. HLAVAC et al [11] explained relationship between the declination angle and cutting wall quality in the theory and performed experiments, proving the theoretical base in AWJ cutting of different samples including granites. CICCU and GROSSO [12] carried out an experimental work to investigate the possibility of improvement mechanical excavation performance by water jet assistance. PON SELVAN and RAJU [13] investigated effects of process parameters on the cutting depth of granite and developed statistical models for the prediction of cutting depth from process parameters. Surface roughness of granite cut by AWJ was investigated by AYDIN et al [14]. ENGIN [15] investigated effects of rock properties and process parameters on the cutting depth of different natural stones machined by injection-type AWJ and modeled the cutting depth using multiple linear and nonlinear regression analyses. KIM et al [16] analyzed effect of traverse and rotational speed of the nozzle on the volume removal rate for concrete, granite and obsidian samples machined by abrasive suspension water jet system. ENGIN et al [17] compared the cutting performance of

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AWJ and circular sawing based on the specific energy. Using Taguchi approach, KARAKURT et al [18] investigated effects of process parameters on the cutting depth of granite in AWJ cutting and determined statistically significant process parameters affecting the cutting depth. AYDIN et al [19] experimentally investigated influence of the textural properties, e.g., grain size and its boundaries, of granite on the cutting performance of AWJ. Using regression analysis, models were developed by AYDIN et al [20] for prediction of the cutting depth from the process parameters and rock properties in AWJ machining of the granitic rocks. KARAKURT et al [21] investigated effects of the operating variables of AWJ on the kerf angle and determined the dominant material properties affecting the kerf angle. AYDIN [22] investigated significant rock properties affecting the recycling of abrasives in AWJ cutting of granites.

As clearly seen from the relevant literature, no study has been conducted on performance of recycling abrasives in AWJ machining of rock. With proper cleaning and sorting, an important portion of sludge may be recycled and fed back to the cutting process [23]. Recycling of the abrasives makes the process more effective and environmentally friendly. In this study, an attempt is made to fill the indicated gab in relevant literature.

2 Materials and method

“Giresun Vizon” was used in the cutting tests with the recycling abrasives. Some properties of the rock and the references followed for determination of these properties are presented in Table 1. Thin sections (see Fig. 1) were prepared from the rock and examined with the polarizing microscope for determination of composition and grain-size of the minerals for the rock. Petrographic descriptions, mineralogical compositions and grain size ranges of the rock are given in Table 2.

Table 1 Some properties of rock and references followed for determination of these properties

Property	Value	Reference
Specific weight/(kN·m^{-3})	26.7	[24]
Water absorption by volume/%	0.20	
Porosity/%	3.30	
Ultrasonic velocity/(m·s^{-1})	5866	
Schmidt hammer hardness	54	
Shore hardness	83.1	
Mohs’ hardness	6.0	Similar procedure with determination of microhardness
Cerchar abrasion index	3.868	[25−26]
Microhardness (HV)	505.5	[27]

The experiments were conducted on an AWJ cutter, consisting of a high output pump with an operating pressure of up to 380 MPa, as schematically shown in Fig. 2. The nozzle diameter and length are 1.1 mm and 75 mm, respectively. The abrasives are delivered using compressed air from a hopper to the mixing chamber and

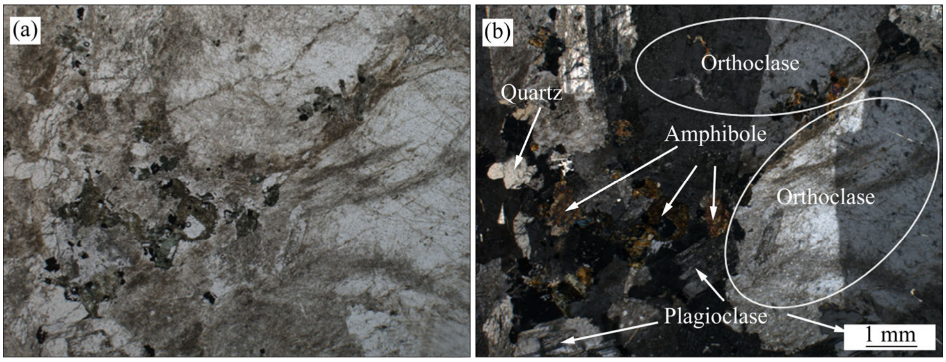

Fig. 1 Photographs of thin section of rock: (a) Single nicol; (b) Cross nicols

Table 2 Mineralogical properties of rock

Mineral	Grain size/mm			Proportion/%	Summary of petrographic description (texture, grain size)
	Minimum	Maximum	Mean		
Alkali feldspar (orthoclase)	0.80	6.80	1.1	47	Allotriomorphic, coarse-grained, grains between 0.16 mm and 6.80 mm
Plagioclase	0.32	4.88	2.2	27	
Quartz	0.24	2.40	1.9	16	
Amphibole	0.16	0.96	0.2	4	
Biotite	0.48	3.44	1.4	4	
Other and secondary components (pyroxene, apatite, zircon, opaque)	0.16	0.36		2	

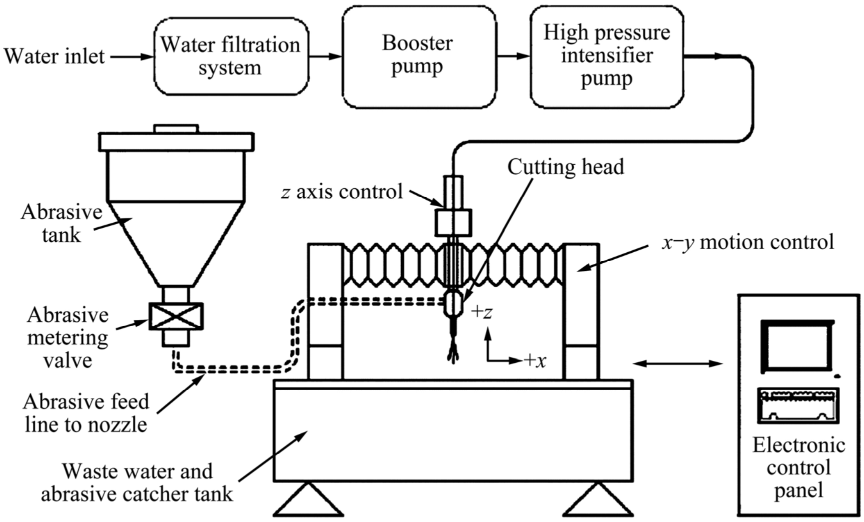

Fig. 2 A schematic illustration of experimental set-up

are regulated using a metering disc. The debris of material and the slurry are collected into a catcher tank. Garnet having the chemical composition in Table 3 was used as an abrasive material. In the work, the operating variables, such as traverse speed, abrasive flowrate, standoff distance and water pressure, were kept constant as indicated in Table 4. Those levels were selected based on previous works reported in literature on rock/rocklike cutting by an AWJ. After the cutting of each rock sample, the abrasive particles were allowed to settle while many of rock particles with excessive fragmentation were discharged from the tank with water. The gravitated abrasives and the remaining rock particles were then collected in a special container for following procedures. Gravity separation technique was employed to separate the abrasives and the rock particles having lower gravities. To study the disintegration behavior of abrasives, abrasive particles were then dried and sieved. The standard 300, 212, 150, 106, 75, 53, 45, and 38 μm sieves were used to determine the particle size distribution. After classification, each series of abrasive particles were weighed.

Table 3 Chemical composition of garnet used

Compound	Mass fraction/%
FeO	36
SiO_2	33
Al_2O_3	20
MgO	4
TiO_2	3
CaO	2
MnO_2	2

Table 4 Levels of operating

Operating viable	Value
Traverse speed/(mm·min^{-1})	100
Abrasive flow rate/(g·min^{-1})	200
Standoff distance/mm	4
Water pressure/MPa	250
Commercial grade abrasive of mesh size/μm	180

The cutting tests with fresh abrasives were continued until an adequate amount of abrasive was collected for further cuttings with recycling abrasives. The rock samples were cut through their lengths (30 cm×10 cm×3 cm section). Among all cutting, five of them were selected to evaluate performance of recycling abrasives in terms of cutting depth, kerf taper angle, kerf width and surface roughness. Following the cutting process, 20 measurements for each cutting (totally 20×5) were carried out and the average was taken as final reading for the cutting depth and kerf width. Additionally, surface quality of the cutting surfaces of the granite at the upper zone (smooth zone) of the cutting surface along the cutting line was measured using a stylus-type profilometer, Mitutoyo Surftest SJ−301. 20 measurements for each cutting surface (totally 20×2×5) were taken and the average was recorded as the final reading for the surface roughness (R_a). A schematic diagram of the kerf profile and the kerf taper angle is shown in Fig. 3. Named as also the kerf wall inclination, the kerf taper angle for each cut is determined from the equation below.

$$\theta = \tan^{-1}\left(\frac{W_{\text{top}} - W_{\text{bottom}}}{2h}\right) \tag{1}$$

where θ is the kerf taper angle; W_{top} and W_{bottom} are the top and the bottom kerf widths, respectively; h is the distance from the top kerf to where the W_{bottom} is measured. In this work, five measurements on the rock sample for kerf taper angle were taken and the average result was recorded as the final kerf taper angle.

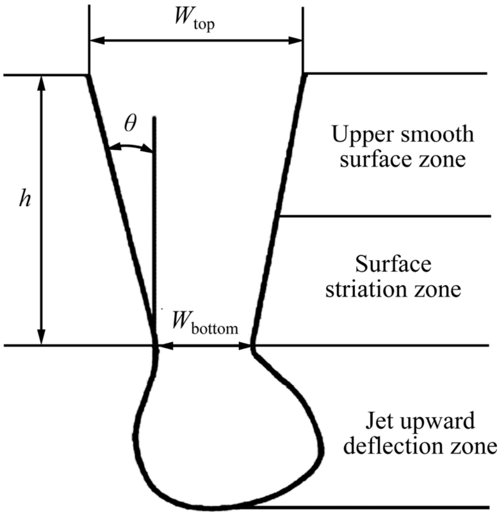

Fig. 3 Schematic diagram of kerf profile [28]

3 Results and discussion

An optical examination was performed and the picture for fresh abrasives is presented in Fig. 4. The energy dispersive X-ray analysis (EDS) observations for fresh abrasives are also summarized in Table 5. SEM micrograph and EDS spectrum are shown in Fig. 5. The figures indicate that the abrasive is predominantly composed of Fe and Si.

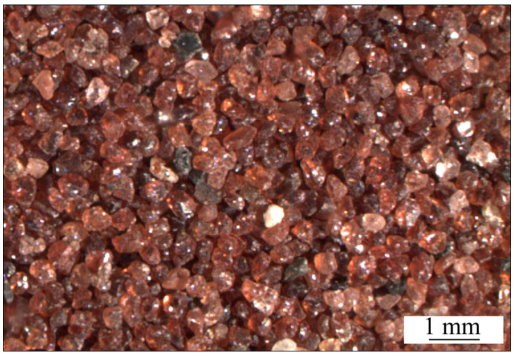

Fig. 4 Microscope image of fresh abrasives

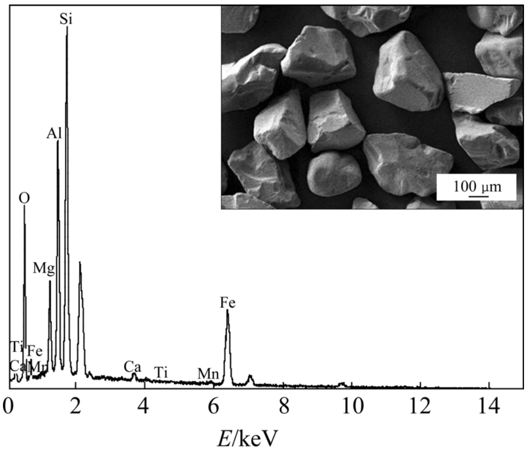

Fig. 5 SEM micrograph and EDS spectrum for fresh abrasives

Abrasive mass percentage above 106 μm ($AMP_{106\mu m}$) was considered a performance criterion. The particle size distributions of fresh and recycling abrasives are presented in Fig. 6. The figure exhibits that a considerable amount of abrasive is present above 106 μm, which can be effectively reused in the rock cutting applications. Before each cutting for recycling abrasives, abrasives with a particle size below 106 μm were removed and the rock was cut using the rest abrasive particles. The reusability percentages of abrasives were determined as 81.77% after the first cutting, 57.50% after the second cutting, 34.37% after the third cutting, and 17.72% after the fourth cutting (see Fig. 6). This result indicates that the abrasives have excellent recycling capacity. The abrasive particles become finer and finer due to disintegration (see Fig. 7) and the $AMP_{106\mu m}$ decreases with reuse as shown in Table 6. This causes to obtain insufficient cutting depth and undesirable fractures on the cut surface. Therefore, recycling was not continued after the fourth cutting.

The experimental data depicted in Fig. 8(a) illustrate the influence of recycling on the cutting depth granite. As can be clearly seen, recycling led to decrease

Table 5 SEM/EDS observations for fresh abrasives

El	AN	Series	w(Unnormalized)/%	w(C Normalized)/%	x(C Atom)%	C error/%
O	8	K	16.51	29.18	47.62	11.5
Mg	12	K	2.78	4.92	5.28	0.2
Al	13	K	7.03	12.43	12.03	0.4
Si	14	K	12.11	21.4	19.9	0.5
Ca	20	K	0.47	0.83	0.54	0
Ti	22	K	0.17	0.31	0.17	0
Mn	25	K	0.55	0.97	0.46	0.1
Fe	26	K	16.94	29.95	14	0.5
Total			56.56	100	100	

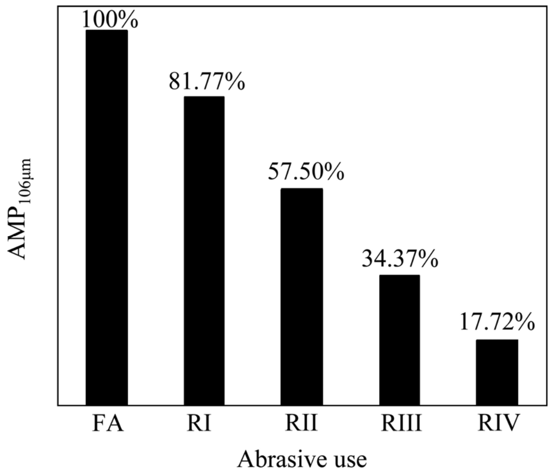

Fig. 6 $\text{AMP}_{106\mu\text{m}}$ for fresh and recycling abrasives: FA−Fresh; FI−After the 1st cutting; RII−After the 2nd cutting; RIII−After the 3rd cutting; RIV−After the 4th cutting

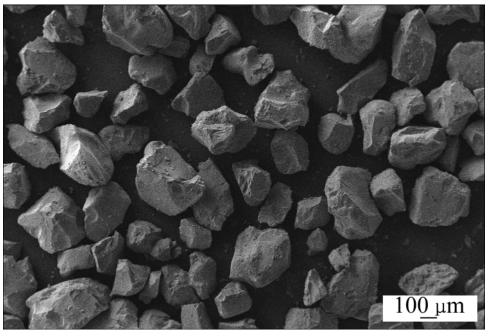

Fig. 7 A representative SEM micrograph for recycling abrasives

in the cutting depth due to the increasing number of finer abrasives having less cutting energy compared with the coarser abrasives. Percentage reduction in cutting depth with the first recycling (RI) compared with fresh

Table 6 Particle size distribution of fresh and recycling abrasives

Abrasive	Fraction/%								
	300−600 μm	212−300 μm	150−212 μm	106−150 μm	75−106 μm	53−75 μm	45−53 μm	38−45 μm	<38 μm
FA	13.25	22.65	22.63	23.24	3.35	6.39	2.71	2.93	2.85
RI	6.61	14.08	16.33	20.48	15.92	9.34	7.27	5.33	4.65
RII	2.06	6.75	10.52	15.05	18.71	15.82	14.06	10.32	6.71
RIII	0.88	2.17	4.40	10.27	19.14	18.00	16.55	15.34	13.26

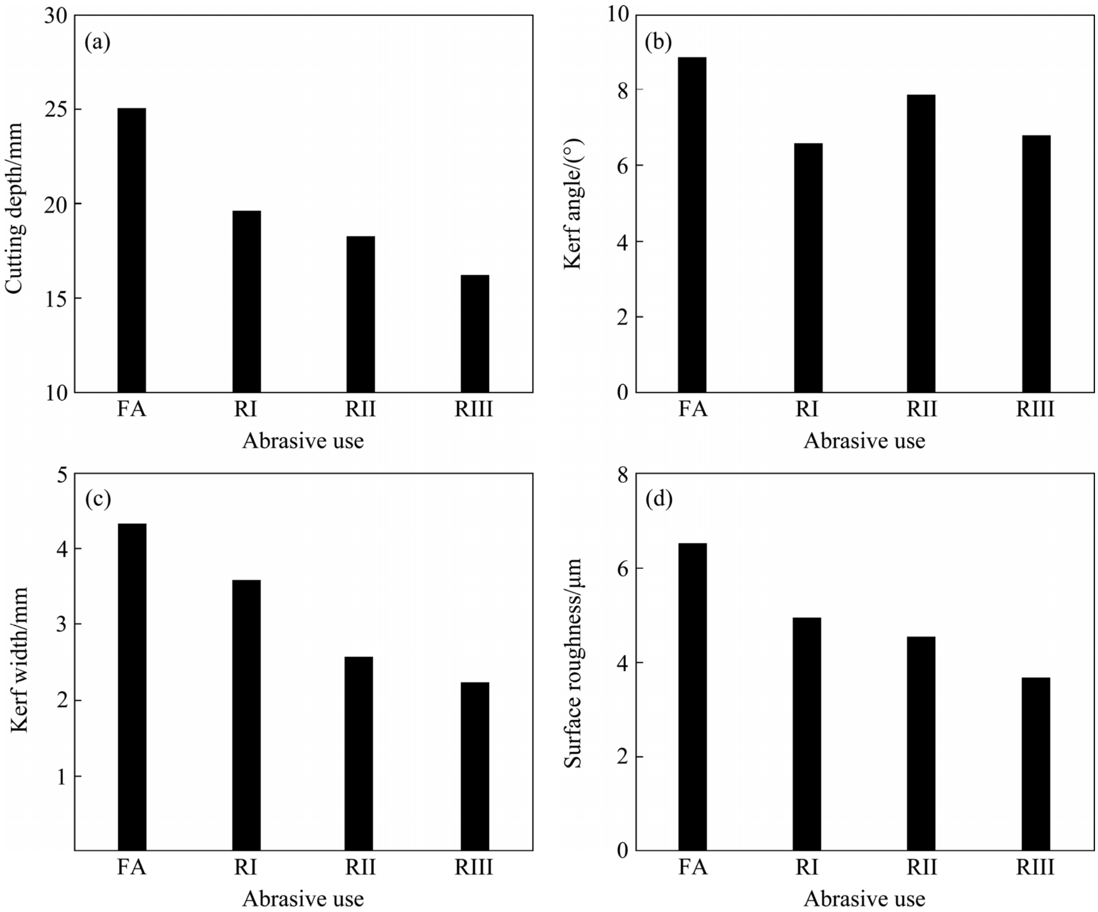

Fig. 8 Effect of recycling on cutting performance: (a) Cutting depth; (b) Kerf angle; (c) Kerf width; (d) Surface ronghness

abrasives was found to be 21.60%. Reduction in depth cutting due to further recycling was found to be 7.14% for the second recycling (RII) and 11.54% for the third recycling (RIII). The results clearly showed the role of particle size distribution in improving the cutting efficiency. The influence of recycling on the kerf taper angle is presented in Fig. 8(b). It can be seen that there is no clear trend of the kerf taper angle with the recycling. It can also be noted that recycling led to decrease in kerf width as a result of the decrease in the percentage of coarser abrasive causing lower jet kinetic energy (see Fig. 8(c)). Reduction in kerf width with RI compared with fresh abrasives was found to be 17.32%. Reduction in kerf width due to further recycling was found to be 28.21% for RII and 13.62% for RIII. Figure 8(d) shows the influence of recycling on the surface roughness. The surface roughness decreased with recycling since the fine abrasive particles removed material in a smaller amount. Reduction in the surface roughness with RI compared with fresh abrasives was found to be 24.31%. Reduction in the surface roughness due to further recycling wasfound to be 8.33% for RII and 19.07% for RIII.

4 Conclusions

1) It is revealed that a considerable amount of recycling abrasives can be effectively used in the rock cutting. The reusabilities of abrasives are determined as 81.77%, 57.50%, 34.37% and 17.72% after the first, second, third and fourth cuttings, respectively.

2) The recycling must not be continued after the fourth cutting for effective cutting. Additionally, particle size distribution was determined as an important factor in improving the cutting efficiency of recycling abrasives.

3) The improved kerf width and surface finish are obtained with the recycling. It is also concluded that recycling leads to decrease in the depth of cutting. Additionally, it is determined that there is no clear trend of the kerf taper angle with the recycling.

4) For the future studies, effect of operating variables on the $\mathrm{AMP}_{106\mu\mathrm{m}}$ should be investigated. Additionally, $\mathrm{AMP}_{106\mu\mathrm{m}}$ can be modeled as a function of operating variables using various methodologies such as regression analysis and neural networks for the prediction of $\mathrm{AMP}_{106\mu\mathrm{m}}$. The cutting performance of recycling abrasives with all particles without screening is also studied and the results can be compared with the current work.

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