**2011 WJTA-IMCA Conference and Expo**
**September 19-21, 2011 • Houston, Texas**
Paper

# EFFECT OF THE UNIAXIAL COMPRESSIVE STRENGTH OF THE ROCK ON THE CUTTING PERFORMANCE OF AWJ

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## ABSTRACT

The machining or processing of hard–brittle materials necessitates the development of compatible techniques, especially for the processing the natural stones such as granite. Abrasive waterjet (AWJ) machining is a powerful tool in both machining and/or processing of granites. In this research, the effect of uniaxial compressive strength of the rock on the cutting performance of AWJ was experimentally investigated. For this purpose, pre-dimensioned granite samples which are similar in mineralogical compositions, but diverse in compressive strength and grain size were cut by an AWJ for various process parameters. Following the cutting, the cut depth, cutting wear zone, surface roughness and kerf angle of the granites were measured as an indicator for cutting performance. The results of study revealed that the uniaxial compressive strength has a considerable effect on the cutting performance more specifically the cut depth and cutting wear zone of the granite.

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## 1. INTRODUCTION

Abrasive water jet (AWJ) cutting technique is based on accelerating small diameter abrasive particles through a high-velocity water jet. The technology is one of the fastest growing machining processes and it can machine and/or process almost any material. A conventional AWJ cutting system normally includes four major modules: an intensifier pump, providing high-pressure water; an abrasive delivery system and a cutting head producing the abrasive waterjet; a computer controlled manipulator, which effectuates the desired motion of the cutting head; and a catcher, which dissipates the remaining jet energy after cutting (Kulekci, 2002).

The technology and applications behind the abrasive waterjet cutting has been investigated for more than fifty years. Among these known attempts, Hashish (1993) visualisated the AWJ cutting process using a high-speed photography of the material removal process in a plexiglass sample. Arola and Ramulu (1996) studied the kerf geometry, kerf wall features, and cutting front characteristics of an AWJ machined Graphite/Epoxy laminate. It was suggested that the geometrical features associated with AWJ machining of Graphite/Epoxy laminates are influenced by three macro regions along the cutting depth. The technical and economic feasibility of the DIAJet for contour cutting of stone slabs was studied using granite and marble samples (Agus et al., 1995). The results showed that cutting rate was strongly influenced by the type of abrasive employed and, for a given abrasive, by the feed rate. However, as traverse speed increased, cut quality deteriorated progressively. Vijay (1991) conducted an experimental study to investigate the drilling and slotting of hard rock samples by abrasive, plain and cavitating waterjets for different mining applications. He found that the hard rocks or rock formations require very high pressure and hydraulic power for drilling and slotting. In a study, the relationship between the calcareous rock properties and material removal characteristics in abrasive waterjet cutting environment was investigated (Miranda et al., 1993). The results of the study revealed that stone hardness seems to play a key role on the cut profile geometry. Additionally, stone hardness and porosity were found as the predominant cutting mechanism. Momber et al. (1993) investigated the abrasive grain size distribution on the abrasive waterjet machining process. It was suggested that striations were the inherent characteristic feature to the AWJ cutting process. More recently, Hlavac et al.(2009) studied the cutting quality of abrasive waterjet for different materials including granite and marble. Aydin et al. (2010) investigated the surface roughness of different granites cut by abrasive waterjet. Karakurt et al. (2010) optimized the process parameters for surface roughness of two granites machined by abrasive waterjet.

In this work, an experimental study was carried out using granite samples in AWJ cutting in order to find out the effect of the uniaxial compressive strength of the granite on cutting performance of AWJ. The cutting performance of AWJ was evaluated on the basis of cut depth, cutting wear zone, surface roughness and kerf angle of the granites.

## 2. EXPERIMENTAL STUDY

### 2.1. Material and Method

In the experiments, pre-dimensioned granite samples of 30 mm thickness, 200 mm length and 100 mm width were cut by an AWJ with an operating pressure of up to 380 MPa. The motion of the nozzle is controlled by a computer as shown in Fig.1. The main properties of the samples are given in Table 1. Abrasive type used in the study is garnet and it consists of chemically 36 % FeO, 33 % $SiO_2$, 20 % $Al_2O_3$, 4 % MgO, 3 % $TiO_2$, 2 % CaO and 2 % $MnO_2$.

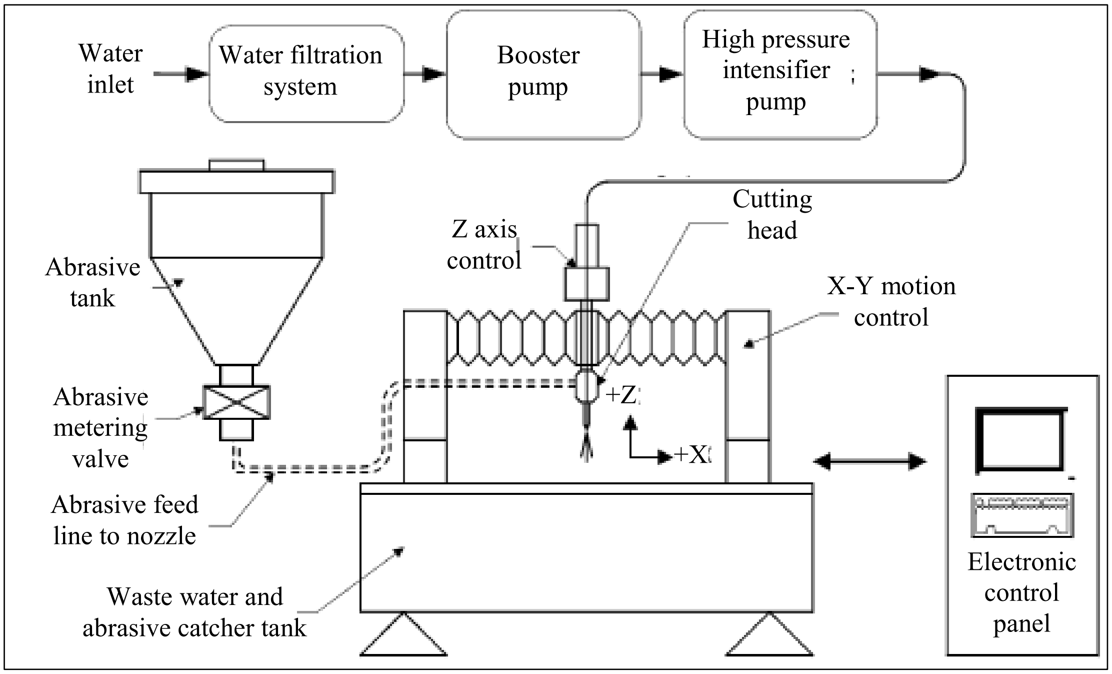


**Figure 1.** Schematic illustration of the experimental set-up (adapted from Duflou et al., 2001).

In the study, five machining parameters were considered as control factors as given in Table 2. All machining procedures were done using a single-pass cutting. Some of the machining parameters including impact angle ($90^o$), nozzle diameter and length of the nozzle were kept constant during the experiments. Surface roughness measurements of the cut surface of the samples were made using a stylus-type profilometer, Mitutoyo Surftest SJ-301. Due to the variability of surface finish data, four measurements for each specimen on each cut were made at the upper zone (smooth zone) of the cut surface and the average was taken as the final reading for the surface roughness (Ra).

Additionally, named as also the kerf wall inclination, the kerf angle for each cut is determined from the equation below (Wang and Guo, 2003).

$$\theta = \tan^{-1}\left(\frac{W_{top} - W_{bottom}}{H}\right) \quad (1)$$

where; $W_{top}$ and $W_{bottom}$ are the top and the bottom kerf widths respectively and H, the distance from the top kerf to where the cut depth is measured. In the study, four readings for top and bottom kerf widths on each sample were respectively taken and the average was taken as the final reading for the calculation of kerf angle through equation (1). Furthermore, for measuring the cut depth and cutting wear zone of the samples, four measurements for each specimen on each cut were carried out and the average was taken as the final reading for the output parameters.

**Table 1.** Some properties of the samples

| Granite | Uniaxial compressive strength (MPa) | Mean grain size (mm) | Mineralogical composition (%) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Alkali feldspar | Quartz | Plagioclase | Biotite | Others |
| Rosa Minho | 110 | 13.16 | 54 | 29 | 10 | 5 | 2 |
| Baltic Brown | 94 | 11.97 | 57 | 21 | 15 | 3 | 4 |
| Carmen Red | 105 | 15.1 | 47 | 37 | 10 | 5 | 1 |
| Giresun Vizon | 98 | 7.97 | 52 | 14 | 24 | 4 | 6 |
| Aksaray Yaylak | 112 | 6.36 | 26 | 22 | 40 | 7 | 5 |
| Azul Platino | 115 | 6.89 | 57 | 25 | 10 | 6 | 2 |
| Balaban Green | 135 | 2.88 | 52 | 23 | 13 | 8 | 4 |
| Multicolor Red | 138.5 | 2.33 | 51 | 36 | 5 | 6 | 2 |
| Bergama Grey | 145 | 2.8 | 52 | 23 | 13 | 8 | 4 |

**Table 2.** Machining factors and their levels considered for the experimentation

| Factors | Symbols | Units | Levels |
|---|---|---|---|
| Traverse speed | T | mm/min | 100 |
| Abrasive flow rate | M | g/min | 150 |
| Standoff distance | D | mm | 2 |
| Water pressure | P | MPa | 200 |
| Abrasive size | S | mesh | 80 |

## 3. RESULTS and DISCUSSON

The results of the study were collectively given in Table 3. It was observed that higher cut depths were surprisingly obtained in the granites having high uniaxial compressive strength. In other words, the cut depths increased when the uniaxial compressive strength of the rocks increased. This observed phenomenon was also illustrated in Fig. 2. Similarly, a consistent correlation between uniaxial compressive strength and cutting wear zone was found (Fig.3a). That is, increasing of uniaxial compressive strength increased the cutting wear zone of the granites.

**Table 3**. Results of the experiments

| Granite | Cut depth (mm) | Cutting wear zone (mm) | Kerf angle (degree) | Surface roughness (μm) |
|---|---|---|---|---|
| Rosa Minho | 20.45 | 9.72 | 11.80 | 5.84 |
| Baltic Brown | 19.52 | 9.79 | 12.87 | 5.78 |
| Carmen Red | 19.56 | 10.13 | 10.22 | 5.98 |
| Giresun Vizon | 23.31 | 12.25 | 7.38 | 6.26 |
| Aksaray Yaylak | 21.43 | 11.89 | 8.21 | 6.40 |
| Azul Platino | 23.33 | 13.30 | 6.05 | 6.29 |
| Balaban Green | 23.75 | 13.21 | 6.24 | 6.26 |
| Multicolor Red | 24.63 | 16.17 | 6.63 | 6.55 |
| Bergama Grey | 25.09 | 16.49 | 5.24 | 6.67 |

Uniaxial compressive strength (UCS) of a rock is one of the most important parameters representing the bearing capacity of rock mass. Its variation is explained by a number of factors including mineral composition. It can be also defined as the threshold value for a rock and/or any other material to be failure under the external forces. On the other hand, it is known the fact that the jet cuts the material by a rapid erosion process when its force exceeds the compressive strength of the material (e.g. granite) in abrasive waterjet cutting. And, it is normally expected that the lower cut depths and cutting wear zone could be obtained in the granites having lower compressive strength. However, the micro fractures, grain boundaries, mineral cleavages and twinning planes also have effects on the strength of the granites as well as their behavior to cutting since the microstructure of a rock is known to influence its strength characteristics.

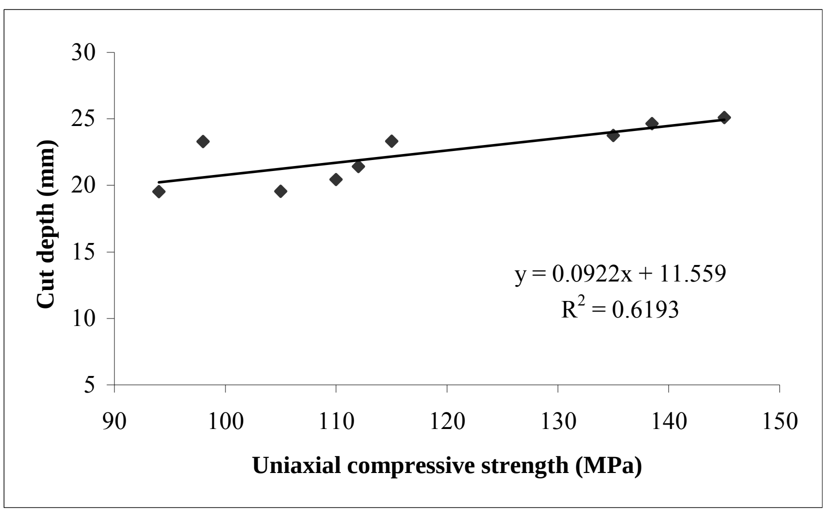


**Figure 2.** The correlation between the UCS and cut depth of the granites

On the other hand; Eberhardt et al. (1999) stated that the strength of a rock increases when the grain size of rock-forming mineral decreases. With decreases in the size f the rock-forming minerals, the possibility of weaknesses such as microstructures, mineral cleavages inside the minerals increases. In other words, these weaknesses may control the direction in which failure of rock occurs and they may act in favour of getting deeper cut depths in parallel with increases of cutting wear zone. This is also probably a consequence of the relatively weak bonding material(s) which presumably has/have a greater negative effect upon the brittleness of the rock through grains along the cutting line. These findings suggest that the effect of individual grain or grain boundary is less significant; rather, the union of several individual grain or grain boundaries may function actively on the cut depth and cutting wear zone.

From the results, it can be noted that the surface roughness of the granites was also affected by UCS. In addition, the cutting wear zone where the surface roughness measurements were carried out has similar correlation with the correlation of surface roughness. However, the power of the correlation for cutting wear zone ($r^2$=0.74) is more than the correlation for surface roughness ($r^2$=54). These correlations were shown in Fig.3. Furthermore, it was observed that kerf angle of the granites having higher UCS were smaller than the kerf angle of the granites having relatively low UCS (Table 1 and 4). Figure 4 shows the correlation between the UCS and kerf angle of the granites despite the fact that the weak correlation ($r^2$= 0.52). When jointly considering, it can briefly be concluded that the UCS of a rock is much more related to cuttability than the surface finish in AWJ cutting of granite.

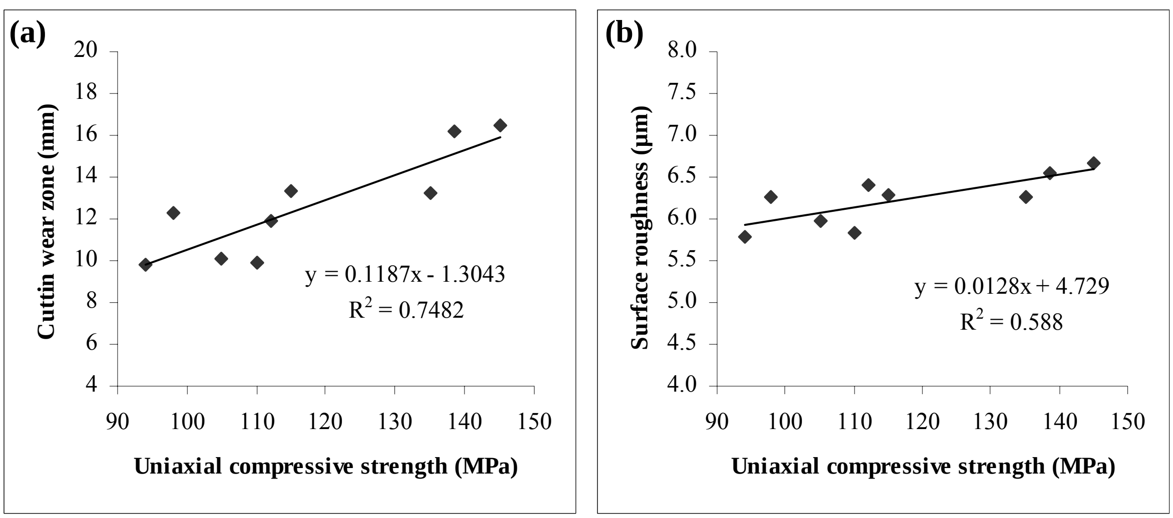


**Figure 3.** The correlation between (a) the UCS and cutting wear zone and (b) surface roughness of the granites

From the view point of kerf angle, it was seen that the differences between up and bottom of the kerf in relatively coarse-grained granites were much more than the differences in fine-grained granites. This may be attributed to the amount of grains and their boundaries with the surrounding grains. In coarse-grained granites, there are relatively less amount of grains and boundaries per unit area and/or through cutting line. The abrasive added jet, therefore, has to cut the granite through grain or grains in coarse-grained granites. That means, the abrasive waterjet exposures one or a few grains through cutting line. This would lead to irregular cuts in both up and bottom of the kerf.

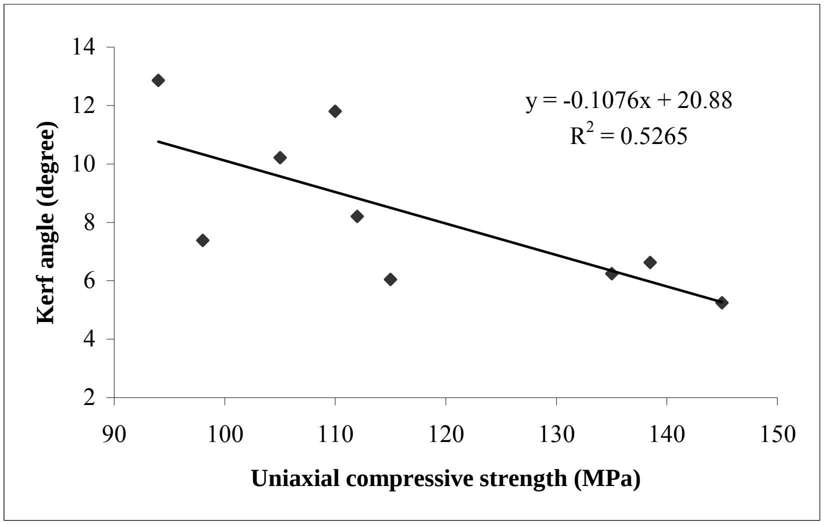


**Figure 4.** The correlation between the UCS and kerf angle of the granites

These irregularities may cause to obtain bigger kerf angles as is in the current study. However; in fine-grained granites there are more grains and grain boundaries through cutting line and/or per unit area. When the abrasive added jet begins to cut, it has to exposure more grains and grain boundaries through cutting line. This would cause to obtain small differences between up and bottom of the kerf. Hence, small kerf angles may be obtained in these kinds of granites.

## 4. CONCLUSIONS

On the basis of the experimental results, the following conclusions could be drawn:

i. It was found that increases in UCS increased the cut depths of the granites tested. A consistent correlation ($r^2$=0.62) was built between the UCS and cut depths. It can be concluded that the kinds and amounts of weaknesses control the direction of failure in rock having high UCS in AWJ cutting. Similar findings between cut depths and UCS, were obtained for the cutting wear zones of the granites.

ii. It was determined that the cut surfaces of the granites having high UCS were rougher than the cut surfaces of the granites having low UCS. However, it can be stated that the effect of the UCS on the surface quality is not as much as the other output parameters tested.

iii. It was observed that the kerf angles of the granites were higher in the granites having low UCS. It can be concluded that the amounts of grains and their boundaries with the surrounding grains may affect the kerf angles.

## 5. ACKNOWLEGDEMENTS

The authors would like to express their sincere thanks and appreciation for the financial support to TÜBİTAK (The Scientific and Technological Research Council of Turkey) (Project No: 108M370).

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