PRODUCTION & MANUFACTURING | RESEARCH ARTICLE

Surface quality of marble machined by abrasive water jet

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Abstract: This paper presents a study conducted to examine the effect of cutting parameters, namely standoff distance, nozzle traverse speed (TS), abrasive flow rate (AFR), and material type on cutting performance for two types of marble workpieces, Carrara white and Indian green. Statistical analysis was undertaken to assess the influence of the cutting parameters on the process performances in terms of surface roughness, surface waviness, and Kerf taper ratio. The results showed that the TS and material type were the most significant factors that affected surface roughness and Kerf taper ratio. Also, although AFR was found to have significant effect on surface waviness, it had no noticeable influence on surface roughness nor Kerf taper ratio.

Subjects: Manufacturing Engineering; Manufacturing Technology; Mechanical Engineering

Keywords: abrasive water jet machining (AWJM); surface roughness (Ra); surface waviness (Wa); Kerf taper ratio (TR)

1. Introduction

Abrasive water jet machining (AWJM) is a nontraditional machining technique that uses impact erosion of abrasive particles to remove the material from the workpiece. This technique has some advantages when compared with traditional methods. In particular, no heat-affected zone appears during cutting and thus there is no need for cooling. Besides, AWJM has a unique capability to cut various types of materials with different properties. In addition, thick plates can be cut easily with...
relatively small cutting force. Also, there is no need for fixturing for most parts which in turn leads to short setup time for the operation (Shah & Patel, 2012; Sheikh-Ahmad, 2009). To obtain an effective jet, the water is pressured up to 400 Mpa and exit from a diamond orifice or nozzle with 0.4 mm diameter. Then, the abrasive particles enter into the jet and are mixed with water in a mixing chamber, and exit from the focusing tube with a velocity reaching 900 m/s that enables mechanical erosion of the material when collision occurs (Sheikh-Ahmad, 2009).

Recently, the properties of materials that are used in different engineering applications dramatically changed to higher levels of strength, hardness, and toughness which cause difficulties in machining operations by conventional methods such as turning, milling, and drilling. This development in such extreme properties causes excessive wear of the tools in the conventional techniques as well as surface quality deterioration. So, using this technique in machining these materials will be economic and allows achieving final product with high quality (Youssef & El-Hofy, 2008). In recent decades, the use of marble and granite in decoration and flooring, urban furnishing and in building works increased significantly. However, the increased demand for these stones in local and international levels increases the competition to process such material economically. These aspects chase the manufacturers to search for reliable manufacturing technique that gives high quality, in low time at low cost (Aydin, Karakurt, & Aydiner, 2011). The primitive technique such as saw can cut slabs only and cannot do contouring and complex shapes in the work part. These industrial requirements are considered challenges that need addressing and have motivated researchers to examine different unconventional methods.

In this context, abrasive water jet cutting has paid a great deal of interests due to its advantages when compared with other nontraditional techniques. In this research, some cutting outcomes, particularly surface roughness, waviness, and Kerf taper ratio have been studied when processing two types of marbles, called Carrara white and Indian green, by varying the cutting parameters (standoff distance (SOD), traverse speed (TS) and abrasive flow rate(AFR)). These experimental tests were utilized to identify the best cutting conditions that give high quality in shorter time.

2. Related work

AWJM technique significantly contributes to manufacturing development as a nontraditional method. The water jet structure consists of three regions (initial region, main region, and final region) (Shimizu, 2011). The initial region has continuous flow and the pressure in this region is called stagnation pressure. The main region has constant velocity of structure and the jet converts to intermittent flow and water lumps with pressure which is called hammer pressure. The hammer pressure at impact point for this flow is greater than stagnation pressure for continuous flow. The final region contains fine drops of water and the velocity of the jet decreases (Shimizu, 2011). Figure 1 shows different regions of the jet structure.

Due to the importance of this machining method, the key factors that dominate the process have to be taken into consideration under systematic study. Generally, the potential of any manufacturing techniques is strongly associated with surface textures that significantly affect the quality of the final product. The surface texture consists of various spatial frequencies. The high frequency is related to roughness while the medium frequency related to waviness as shown in Figure 2. (Raja, Muralikrishnan, & Fu, 2002). The following section presents previous studies on AWJM, which will cover three categories that represent the main criteria used to assess cutting performance of the process.

2.1. Surface roughness

Surface roughness is considered one of the most significant factors that influence product quality in water jet cutting, similar to the case in all other machining processes. This is due to the fact that there are some critical applications that need specific level of quality to finish the product or complete a central piece of high sensitive product. The most effective parameters to be applied to perform the machining process irrespective to the type of materials are hydraulic pressure, TS, SOD,
AFR, abrasive mesh size, and abrasive type. Although, these have been considered in great deal of publications, most of the reported work paid attention to one or few parameters which differs from one study to another.

For example, mesh size of abrasive particles was taken as a main parameter to examine its effect on surface roughness (Babu & Chetty, 2006). It is reported that single mesh provided better surface roughness than multi mesh size on aluminium material for different types of abrasives (Babu & Chetty, 2006). Also single mesh of colemanite powder was selected as abrasive material instead of garnet to assess if it can be taken as alternative to garnet type which has commercial success in this field of machining (Cosansu & Cogun, 2012). By comparing the results of surface roughness for the two types of abrasives that were applied on different materials such as AL7075, marble, glass, and composite materials, it was found that colemanite powder has shown potential to replace garnet (Cosansu & Cogun, 2012). On the other hand, hydraulic pressure and SOD were found to have significant effect on surface roughness when processing glass/epoxy composite laminate (Azmir, Ahsan, & Rahmah, 2008; Azmira & Ahsanb, 2009). It was reported that increasing the hydraulic pressure as well as decreasing TS and SOD enhanced surface quality. Different types of granite have been examined by changing the main cutting parameters as mentioned in previous section. It was concluded that AFR and hydraulic pressure had the most significant effect on surface roughness, followed by TS and SOD (Aydin et al., 2011). The developments of machining using water jet have achieved great success in stone industry, but there are no sufficient studies that discuss these types of materials.
2.2. Kerf taper ratio

Kerf taper is the most significant parameter to be studied after surface roughness which is generated due to the variation in the jet velocities and energy from the jet wall to the jet center, where the maximum velocity takes place (Wang, 1999). Kerf taper ratio is defined as the ratio between the top and the bottom of the Kerf width (Xu, 2005). Figure 3 shows the Kerf geometry (Kechagias & Petropoulos, 2012).

\[ TR = \frac{W_t}{W_b} \]

This performance criterion is a critical factor during assembly operation because the taper of the surface may cause some difficulties during the operation and lead to the failure of collection of the two parts together. In this context, Scanning electron microscopy was used as a measurement technique to study the Kerf geometry and taper angle which results from different machining parameters. It was concluded that impact angle 80° will achieve greatest depth of cut and less effect on other characteristics (Wang, 1999). Otherwise, different studies were conducted on different materials to investigate which machining parameters have significant effect on this performance. Glass epoxy composite laminate was used to study the effect of hydraulic pressure and abrasive type on Kerf ratio. It was concluded that increasing hydraulic pressure and mass flow rate enhance the cutting and reduce the taper ratio, as well as the harder abrasive provide better cutting (Azmira & Ahsanb, 2009). Meanwhile, the Kerf widths at the top, the bottom, and the ratio between them were investigated for aluminium by three single mesh size for garnet abrasive which reveals different behavior about multi size (Babu & Chetty, 2006). Also, different types of abrasive material, such as garnet, silica sand, silicon carbide, and olivine, were used to study the effect of abrasive type on the width of cut. Using silicon carbide produced greater width of cut than garnet due to its hardness and the width decrease by high feed rate. SOD caused wider slot but pressure provided small slot (Khan & Haque, 2007). Recently, colemanite powder was used as abrasive material compared with garnet type which is the most common type of abrasive in this application. The study was conducted on different materials such as AL7075, marble, glass, Ti6Al4V, and a composite material. The results showed that the amount of the colemanite powder used is higher than garnet to give same action (Cosansu & Cogun, 2012).

2.3. Surface waviness

Surface waviness or surface striation is one of surface characteristics which are generated by beam cutting methods such as jets and lasers (Chen & Siores, 2001). Although, this significant phenomenon appears on most surface texture studies, the mechanism that causes this phenomenon still not fully defined. In abrasive water jet cutting, it was noticed that abrasive particle energy distribution is the main reason for striation formation. So, laser Doppler was used to analyze this distribution. It was found that the vibration of the nozzle during cutting and fluctuations in the process parameters...
were the main reasons (Chen & Siores, 2001). Increasing the cutting depth resulted in decreasing the amount of abrasives that have high kinetic energy. The particles which have high energy cut the surface, while the others with low energy will have weak effect on cutting which produces peaks on the surface as shown in Figure 4.

Some researches demonstrated that the TS has significant effect on waviness irrespective of the other parameters taken into consideration and the materials that were used to be machined. Increasing the TS results in the decrease in surface waviness for titanium alloy and the shape factor of the abrasive particles has no significant effect on the waviness (Fowler, Pashby, & Shipway, 2009). However, increasing TS caused increase in surface waviness with colemanite powder which used as abrasive material and increasing AFR reduced this waviness (Cosansu & Cogun, 2012).

3. Experimental work

3.1. Materials and methods

In this paper, two types of marble specimens which are called Carrara white and Indian green were cut by abrasive water jet machine. These types of marble materials are the most common in industrial environment. Figure 5 shows the two types of marble. Indian green has higher hardness than Carrara white. The specimens have dimensions of 70 mm length, 30 mm width, and 20 mm thickness. The experimental work is carried out on a two-dimensional abrasive water jet machine Italiano 2003 as shown in Figure 6. The machine has a work table dimensions as follow x-axis 1.6 m, y-axis 3 m, and z-axis has discrete motion. The TS of the nozzle can reach to maximum value of 400 mm/min. The maximum value of intensifier pump (WSI 60 HP) pressure is 380 MPa was used.
3.2. Design of experiments
The experimental work included four machining parameters, namely SOD, TS, AFR, and material type. Each parameter has different levels that were selected based on some previous studies in AWJM. The parameters were divided into constant and variable one. The constant parameters are pressure, abrasive type, abrasive size, orifice diameter, focusing tube diameter and length as shown in Table 1. SOD, TS, AFR, and material type were considered to be variable parameters as shown in Table 2. Four levels were taken for each parameter. When changing one parameter the remaining parameters kept constant. There are 12 runs for each sample material as shown in Table 3. These runs were recommended by the machining experts to cut these two types of marbles according to the experience in this field and the possibilities of the machine. Especially it is not possible to change the pressure to compensate the energy loss during the cutting operation when changing the other parameters. However, it is worth stating that initially some experiments were conducted by varying the applied parameters, but the cutting operation could not be completed and the obtained surface was unsatisfied, and thus these results were excluded.

3.3. Cutting performance assessment
The surface textures consist of various spatial frequencies. The high frequency is related to roughness while the medium frequency related to waviness as shown in Figure 2. At first, surface
roughness measurements of the cut surfaces of the marble specimens were carried out using a Surtronic 3 + stylus profilometer. The surface roughness was taken in the smooth region at 1 mm below the top of the specimen to prevent any distortion made by jet entry. All measurements were carried out at 0.8 mm cut-off length (Azmira & Ahsanb, 2009). Surface waviness was the second performance measure that has been undertaken. The coordinates of the points on the wavy surface were calculated using Axiom Too Coordinate measuring machine (CMM) as shown in Figure 7. The CMM probe was used to measure the height (hi) of the wavy surface from the machine’s table surface that was taken as a reference plane, as shown in Figure 8. One hundred points were taken along
the length of the specimen at the bottom to cover the whole region then the average deviation for these heights was calculated using Microsoft excel to get the waviness of the specimen (Cao, Lin, & Zhang, 2013).

Kerf taper was the third performance measurement that has been assessed. Ten mm length of the slot was machined into the marble specimen to assess the Kerf taper ratio (TR) which is defined as a ratio between the top and the bottom of the Kerf width as shown in Figure 3 (Xu, 2005). The surface tapers that were generated after machining were measured by taking photos to the Kerf geometry using Sony digital camera with high resolution as shown in Figure 9. Then, image processing tool box in MATLAB 2013 software was used for helping in measurement of top and bottom width of the Kerf.

4. Results

4.1. Analysis of variance (ANOVA)

The effects of machining parameters on cutting performance were examined by ANOVA. Table 4 shows the ANOVA and F-ratio values for surface roughness, surface waviness, and Kerf taper ratio that were conducted at 95% confidence level. After applying this analysis, It was found that AFR and the TS have no significant effect on surface roughness, while SOD and material type have the most effect. Surface waviness dramatically affected AFR followed by material type. Meanwhile, SOD and TS have no effect on waviness. TS show most significant effect on Kerf ratio followed by material type. Meanwhile, SOD and TS are insignificant factors.

4.2. Effect of process parameters on surface roughness

In case of SOD, increasing SOD caused an increase in the surface roughness for both types of materials as shown in Figure 10(a). The increase in SOD led the jet divergence at the exit of the nozzle near to the impact region which caused an increase in the jet diameter and reduction in the kinetic energy of the jet at this region which caused high surface roughness (Aydin et al., 2011; Azmira & Ahsan, 2009). In Figure 10(b), it was noticed that the roughness increased by faster motion of the nozzle. The main cause of this is the small number of abrasive particles that hit the impact region. These small numbers reduced the kinetic energy of the jet that had great effect on all cutting performance...
(roughness, waviness, and Kerf ratio). Consequently, the increase in TS resulted in reduced kinetic energy and rougher surface (Aydin et al., 2011). The surface roughness decreased for Indian green marble by increasing AFR as shown in Figure 10(c), but the roughness of Carrara white marble decreased with the increase in abrasive mass flow rate up to specified limit. However, behind that limit the roughness increased again because Carrara marble has less hardness than the Indian green which means that Carrara required less energy to be cut compared with Indian green. However, increasing the AFR more than a certain level of energy to provide smooth surface will cause inter-collision between the particles themselves (Aydin et al., 2011). This collision will lead to loss in energy of the jet and provide rough surface while the increasing the abrasive amount during machining Indian green will increase jet energy and the force of cut. Thus, to maintain the energy at the sufficient level to cut, the largest level of abrasive is applied, which in turn allows obtaining low surface roughness.

4.3. Effect of process parameters on surface waviness

It was found that the surface waviness decreased with an increase in SOD up to a specified limit, and above this limit it was observed that the waviness for the two types of marbles increased again as illustrated in Figure 11(a). This is because the increase in SOD increased the jet diameter and altered from continuous flow to droplet flow. In this region, the hammer pressure is much greater than stagnation pressure of continuous flow region (Shimizu, 2011). This transformation in jet flow caused an increase in energy and compensated any loss of energy for some particles and thus reduced waviness. For more increase in SOD the final region with low energy became responsible for cutting so waviness increased again. Figure 11(b) illustrates that the increase in TS caused an increase in surface waviness for both marble types. Since increasing TS eliminates overlapping machining action and the abrasive particles which hit the surface was low which caused high waviness in the surface (Azmir et al., 2008). AFR was found to have significant influence on surface waviness formation due to the kinetic energy distribution of the abrasive particles related to the machined surface as well as some external effects such as fluctuations in process parameters, vibration of the nozzle or the part during cutting. The cutting occurs when the particle kinetic energy is greater than the destruction energy of the part material. At the beginning of cutting, the first amount of particles cut the part, followed by some weak particles that are unable to do like the first amount (Chen & Siores, 2001). So the striation is formed as shown in Figure 4. An increase in the abrasive mass flow rate substantially reduced the surface waviness for the both types of materials as shown in Figure 11(c) due to increase in jet energy and compensated the loss energy for some particles during machining operation.

4.4. Effect of process parameters on Kerf taper ratio

Figure 12(a) clearly shows that the Kerf taper ratio increased by increasing SOD. This is owed to the jet divergence that increased by increasing SOD which led to energy loss as well as the loss of jet
momentum during cutting. So the bottom width was much smaller than the top width and produced high Kerf ratio (Azmira & Ahsanb, 2009). Faster movement of the nozzle caused the Kerf ratio to increase as illustrated in Figure 12(b). The main reason of this behavior was due to the few number of particles which struck the impact region or the less exposure time for the jet (Azmira & Ahsanb, 2009). Figure 12(c) illustrates that an increasing AFR caused decrease in Kerf ratio because the amount of particle added to the jet increased its energy making it more sufficient to penetrate to the bottom of the part and the bottom width become nearby from the top width which leads to small Kerf ratio (Azmira & Ahsanb, 2009).
5. Conclusions
This paper reports on an experimental investigation of the abrasive water jet process. In particular, the effects of the process parameters, namely the SOD, TS, and AFR on the achievable surface roughness, resultant waviness, and Kerf taper ratio have been examined. Based on the undertaken study and the results obtained, specific conclusions can be made as follows:

The TS and material type were the most significant factors that affected surface roughness and Kerf taper ratio. However, the SOD was found to be the second effective parameter influencing the obtainable surface roughness but had no effect on the surface waviness and Kerf taper ratio.
Although, AFR had significant effect on surface waviness, it slightly influenced the surface roughness and Kerf taper ratio.

For both types of marbles, the surface roughness increased by increasing SOD and TS. One can conclude that, for Carrara white workpiece, surface roughness reduced by increasing AFR up to a certain value. Then, the relationship trend was inversed, where the roughness increased with the higher values of AFR. The surface waviness decreased by increasing the AFR and SOD. However, increasing SOD beyond a certain limit caused an increase in the surface waviness. High TS resulted in an increase in the surface waviness. The Kerf taper ratio increased by increasing SOD and TS, while it decreased with the increase in AFR.
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References
Aydin, G., Karakurt, I., & Aydiner, K. (2011). An investigation on surface roughness of granite machined by abrasive waterjet. Bulletin of Materials Science, 34, 985–992. http://dx.doi.org/10.1007/s12034-011-0226-x
Azmir, M. A., Ahsan, A. K., & Rahmah, A. (2008). Effect of abrasive water jet machining parameters on aramid fibre reinforced plastics composite. International Journal of Material Forming, 2, 37–44.
Azmir, M. A., & Ahsan, A. K. (2009). A study of abrasive water jet machining process on glass/epoxy composite laminate. Journal of Materials Processing Technology, 209, 6168–6173.
Babu, M. K., & Chetty, K. (2006). A study on the use of single mesh size abrasives in abrasive waterjet machining. The International Journal of Advanced Manufacturing Technology, 29, 532–540.
Cao, X., Lin, B., & Zhang, X. (2013). A study on grinding surface waviness of woven ceramic matrix composites. Applied Surface Science, 270, 503–512.
Chen, F. L., & Siros, E., (2003). The effect of cutting jet variation on striation formation in abrasive water jet cutting. International Journal of Machine Tools & Manufacture, 41, 1479–1486.
Cosansu, G., & Cogun, C. (2012). An investigation on use of colemanite powder as abrasive in abrasive waterjet cutting. Journal of Mechanical Science and Technology, 26, 2371–2380.
Fowler, G., Poshy, I. R., & Shipway, P. H. (2009). The effect of particle hardness and shape when abrasive water jet milling titanium alloy Ti6Al4V. Wear, 266, 613–620.
Kechagias, J., & Petropoulos, G. (2012). Application of Taguchi design for quality characterization of abrasive water jet machining of TRIP sheet steels. The International Journal of Advanced Manufacturing Technology, 62, 635–643.
Khan, A. A., & Haque, M. M. (2007). Performance of different abrasive materials during abrasive water jet machining of glass. Journal of Materials Processing Technology, 191, 404–407.
Roja, J., Muralikrishnan, B., & Fu, S. (2002). Recent advances in separation of roughness, waviness and form. Journal of the International Societies for Precision Engineering and Nanotechnology, 26, 222–235.
Shah, R. V., & Patel, D. M. (2012). Abrasive water jet machining – The review. International Journal of Engineering Research and Applications, 2, 803–806.
Sheikh-Ahmad, J. (2009). Nontraditional machining of FRPs. In Machining of polymer composites (pp. 237–291). New York, NY: Springer Science + Business Media LLC.
Shimizu, S. (2011). Tribology in water jet processes. In New tribological ways (pp. 153–164). Retrieved from www.intechopen.com.
Wang, J. (1999). Abrasive waterjet machining of polymer matrix composites – cutting performance, erosive process and predictive models. The International Journal of Advanced Manufacturing Technology, 15, 757–768. http://dx.doi.org/10.1007/s001700050129
Xu, S. (2005). Modelling the cutting process and cutting performance in AWJM with controlled nozzle oscillation. Brisbane: Queensland University of Technology.
Yousef, H. A., & El-Hofy, H. (2008). Machining technology: Machine tools and operations. Boca Raton, FL: CRC Press.