ANALYSIS OF KERF GEOMETRY WITH ABRASIVE WATER JET MACHINE IN MARBLE PROCESSING

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Abstract - *Marble is the most popular natural stone in the world, Rajasthan accounts for approximately 90% of all marble production in India. So, marble resources are scarce, it is critical to improve the end product's cutting and design. Abrasive water jet machine (AWJM) is a recent technology in cutting and processing unit and mechanism is the conversion of hydrostatic energy into a jet with enough kinetic energy to disintegrate the material. AWJM has a number of significant advantages over traditional procedures. In this study, Experimentation on three types of marble's cutting pattern with Abrasive water jet machine as well as evaluation of machine parameters such as water pressure, abrasive flow rate, standoff distance and nozzle geometry. Data collection and analysis for cutting parameters like as kerf width, taper angle, burr and surface roughness among other parameters. Also on minimization of taper angle and kerf width. The results are favorable and show that AWJM is far superior to other traditional methods. Furthermore, minimization of kerf width is possible by tilt-a-nozzle technique, by adjusting in machining parameters such as water pressure, abrasive flow rate etc. can effective on kerf width and taper angle, material removal rate. Burr formation, surface roughness, and edge rounding can also be adjusted. The abrasive water jet mechanism is environmentally friendly, increasing final product value while decreasing cutting costs.*

***Key Words*: Marble, Abrasive water jet machine, Kerf width, Taper angle, Minimization of kerf, Burr, Surface roughness**

1.0 INTRODUCTION

In our modern era, marble has become an integral part of our lives. The variety of colors, applications and production of marble has expanded and so has the number of mines. So mining activities that affect the environment are also increasing and putting human life at greater risk. Due to waste generation at various stages of mining activities, dimensional stone marble has contributed to the significant environmental problems. Also marble resources are scarce, it is critical to improve the end product's cutting and design.

Marble has traditionally been cut with a milling, traditional tools and diamond wire/saw cutter. A number of issues were identified during the traditional marble cutting methods, including time consuming operations, dust & noise nuisances, material wastage during cutting slots and damage of tools & clogging.

Abrasive water jet machine (AWJM) is becoming increasingly popular in recent technologies due to its advantages over other traditional methods. AWJM is a new machining technology that can be used to cut extremely difficult-to-cut hard material parts.

Water Jet Cutting Machine: Nature has long demonstrated that even the hardest materials change form and shape when exposed to water. This phenomenon can produce structures that are both efficient and attractive.

Fig.1 The Grand Canyon (cut by water flowing through stone)

A water jet is a computerized technique that can cut most materials into any shape, regardless of how brittle they are. AWJM process does not generate heat, there are no heat affected zones or residual stresses during the surface generation stage. The process's inherent feature is that it is a non-contact, dynamic cutting process. Other noticeable advantages include a narrow kerf width, a negligible heat affected zone and flexibility during material removal. AWJM cuts composite materials 10 times faster than traditional machining methods.

Variants of water jet machine:

A. Pure Water Jet Machining (PWJM)
B. Abrasive Water Jet Machining (AWJM)

Pure water jet refers to a water jet that does not use abrasives. Because they cannot cut hard materials, pure water jets are used for cutting wood or rubber. **Abrasive water jet** refers to a water jet that employs a combination of water and abrasives.

Abrasive Water Jet machining (AWJM): A narrow stream of high velocity water mixed with abrasive particles produces a low-cost, environmentally friendly product with a high material removal rate. AWJM typically employs a variety of abrasives such as garnet, olivine, aluminum oxide (Al_2O_3), silicon carbide (SiC) and others. The water acts as an accelerator for the abrasive particles, striking the material at an impact speed of 800 m/s and removing it precisely.

2.0 EXPERIMENTAL WORK

The materials used for present study are (a) Makrana generic white Marble (b) Rajnagar marble (c) Keshariyaji green marble. The marble is a brittle material and has the various applications as a building/construction material. The dimensions of these marbles were 300mm × 77mm × 22.5 mm. The Chemical composition, Mechanical and physical properties of all rock are shown in Table 3.1 and 3.2.

Table 2.1 Chemical Composition Marble rock type tested

Elements	Weight %		
	Makrana generic white Marble	**Rajnagar marble**	**Keshariyaji green marble**
Silica (SiO2)	20-25%	16-25%	28-32%
Lime (CaO)	38-42%	30-33%	16-30%
Loss On Ignition (LOI)	30-32%	36-44%	20-30%
Other Oxides like Na. Mg	1.5to2.5%	1-7.5%	20-25%
Alumina (Al2O3)	2-4%	2-4%	1-2%

Table 2.2 Mechanical and physical properties of tested marble

Property	Value		
	Makrana generic white Marble	**Rajnagar marble**	**Keshariyaji green marble**
Hardness	3 to 4 on Moh's Scale	3 to 4 on Moh's Scale	3 to 4 on Moh's Scale
Density	2.5 to 2.65 Kg/m^3	2.80 to 2.90 Kg/cm^2	2.66 to 2.70Kg/cm^2
Water Absorption	Less than 1%(0.04)	Less than 1%(0.06)	Less than 1%(0.07)
Compressive Strength	1800 to 2100 Kg/cm^2	1000 to 1500 Kg/cm^2	1900 to 3000 Kg/cm^2
color	White	White with bands	White with bands
Porosity	Quite low	Quite low	Quite low

2.1Experimentation on marble cutting for kerf width and taper angle

2.1.1 Equipment: Cutting equipment was utilized to cut the sample flow mach 2 abrasive water jet and machine's dimension 5000 × 4800 × 3000mm with single head. Machine can control either manual or automatic after given cutting command. Water jet machine attached with all other necessary systems like Pump, gas propulsion system, abrasive storage, abrasive feed system, electricity system, computer control system and catcher.

Fig. 2.1 Flow mach 2 water jet cutting machine

Table 2.3 Specification of flow mach 2 water jet machine

Cutting table	5000x3000mm
Power	3850Bars
Weight	8500 kg
Worked hours	2500 hours
Max Operating Pressure	60,000 PSI
Abrasive Hopper Capacity	500 Lbs.
Pump	Intensifier pump (60,000 psi)
Nozzle	tungsten-carbide material
Abrasive flow system	Gravity feed type with gas propulsion system

There are number of influencing cutting parameters who affect kerf width, taper angle, depth of cut and material removal rate but large no. of cuttings runs are not viable and costly procedure. So, we take 10 cutting runs with variation of parameters like Water pressure and abrasive flow rate on three marble types.

Table 2.4 Constant parameters for experiment

Abrasive material	Garnet
Abrasive mesh size	#80
Orifice diameter	0.4 mm
Nozzle diameter	0.8 mm
Nozzle length	101.6 mm
Jet impingement angle	90°
Stand-off distance	5 mm
Cutting length each run	42 mm
Mixing tube	1.0160 mm

In total, 10 cutting runs were performed, 9 with parameter changes and one for surface roughness for each marble type. The output response parameter kerf top width, kerf bottom width and kerf taper angle has been studied in order to optimize the process parameter cutting for three marble types. Input parameters were collected using the AWJM's PC control device, while output parameters such as kerf width and taper angle, as well as material dimensions, were measured using a "digital vernier caliper". Equation 1 is used to calculate the kerf taper angle the taper angle is obtained using the formula below.

$$\boldsymbol{\theta} = \tan^{-1}\left(\frac{Wt - Wb}{2t}\right) \quad ....Eq.1$$

Where: θ = kerf taper angle (TE/KA), t = thickness of sample $\tan^{-1}$= arch tan Wt/T_{kw} = top kerf width, Wb/B_{kw} = bottom kerf width

Table 2.5 Data summary for top and bottom kerf width and taper angle for three rocks

Run no.	WP (psi)	AFR (g/min)	Kerf width(mm) for rock sample (a)			Kerf width(mm) for rock sample (b)			Kerf width(mm) for rock sample (c)		
			T_{kw}/Wt	B_{kw}/Wb	TE(°)	T_{kw}/Wt	B_{kw}/Wb	TE(°)	T_{kw}/Wt	B_{kw}/Wb	TE(°)
1.	35000	Low	1.695	NC	-------	1.783	NC	--------	1.702	NC	--------
2.	40000	Low	1.726	1.291	0.553	1.836	1.392	0.561	1.780	1.311	0.595
3.	45000	Low	1.773	1.522	0.319	1.885	1.689	0.253	1.825	1.579	0.309
4.	35000	High	2.121	1.806	0.401	2.229	1.969	0.331	2.173	1.869	0.383
5.	40000	High	1.946	1.606	0.432	2.126	1.801	0.412	2.046	1.713	0.423
6.	45000	High	2.083	1.453	0.802	2.188	1.623	0.716	2.131	1.578	0.698
7.	35000(Al)	High	2.073	1.291	0.995	2.197	1.445	0.957	2.108	1.504	0.768
8.	40000(Al)	High	2.181	1.451	0.929	2.288	1.624	0.842	2.233	1.536	0.859
9.	45000(Al)	High	2.126	1.036	1.387	2.391	1.167	1.387	2.218	1.093	1.432

2.2 Method for minimizing kerf width

We experimented with the following strategies to minimize both top and bottom kerf widths:

2.2.1 Controlling input parameters of water jet

A. **Speed/Water pressure:** We can find the optimal speed for minimum kerf widths by gradually increasing the speed. It began with a water jet pressure of 35000 to 45000 psi.

B. **Standoff distance:** The standoff distance is set to 5 cm as a constant; increasing the standoff distance will increase the kerf widths. The nozzle's X and Y axes are aligned to the sample, whereas the z-axis is perpendicular to the nozzle.

C. **Abrasive parameters:** By experimenting with a range of abrasive flow rates, the required abrasive flow rate was determined. Because the quality of the abrasives has an impact on the kerf width, we use high-grade Garnet #80 mesh size.

D. **Thickness and hardness of material:** Both factors have an impact on kerf widths. Kerf widths rise as thickness and hardness increase.

2.3 Tilting the cutting head

By computer control, command is instructed to tilt the nozzle slightly to the scraping side to reduce kerf width.

2.4 Experiment for surface roughness

For surface roughness, we cut the sample into two parts, photograph the surface roughness and compare it to the surface roughness scale (see figure 3.7).

45000 psi (WP) and high AFR

Fig. 2.2 Surface roughness

2.5 Experimentation for burr

Burrs were noted on the jet exit side (bottom kerf) on some of the cuts due to material deformation. Burr is often developed near the kerf's bottom border. For the purpose of the experiment, take note of the burr after each cutting of the sample.

2.6 Experimentation for wear nozzle

To determine the nozzle wear rate, simply compare the weight of the nozzle before and after the experiment, as well as the nozzle weight loss rate, also known as the nozzle life indicator.

3.0 RESULTS

3.1 Quantitative Results of Minimization of Taper Angle and Kerf Width: As we all know, kerf width and taper angle are inextricably linked; therefore, we precisely measured using digital vernier calliper and discovered the result.

3.1.1 Kerf width as a function of water pressure and abrasive flow rate: As shown in the graphs, the top kerf width increases as water pressure increases while the abrasive flow rate remains constant as low or high.

However, the bottom kerf width initially increases and then decreases while the water pressure continues to increase because the water pressure rises to 45000 psi, the depth of cut and material removal rate increase, resulting in a decrease in bottom kerf width. Because water pressure and abrasive particles have more time and area to impinge on the work sample, the top kerf width increases in comparison to the bottom kerf width. Between the three marble types tested (a) Makrana generic white marble (b) Rajnagar marble (c) Keshariyaji green marble, marble type (a) has less kerf width in all experiments because the hardness of marble (a) is lower than the hardness of both other marble types. Similarly, marble type (c) has a lower hardness than marble type (b) as shown in graphs (fig. 3.1).

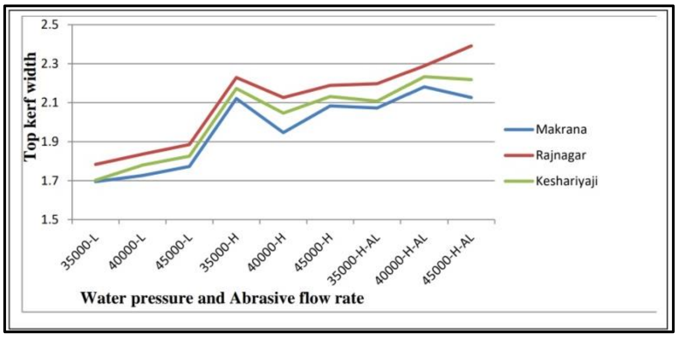

Fig 3.1 Water pressure and abrasive flow rate vs. top kerf width

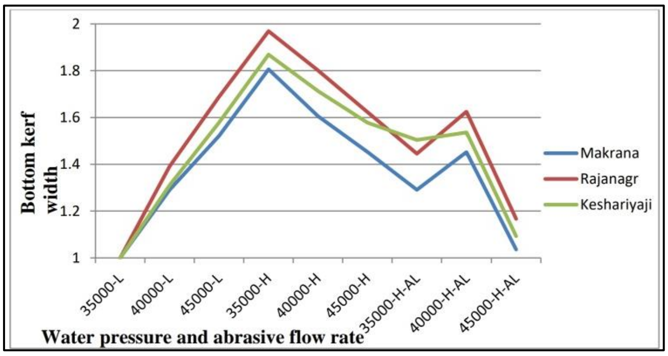

Fig.3.2 Water pressure and abrasive flow rate vs. bottom kerf widths

The graph shows the relationship between kerf width and abrasive flow rate. As the abrasive flow rate increases, so does the kerf width due to the increased imping rate of particals.

3.1.2 Taper angle function with water pressure and abrasive flow rate

The taper angle is defined as the difference between the top kerf width (T_{kw}) and the bottom kerf width (B_{kw}) and their arctangent over half of the thickness, so it is entirely dependent on kerf width. As shown in the graph, as water pressure rises, the taper angle rises as well, reaching a maximum of nearly 1.2 degree. As well as abrasive flow rate increases taper angle also increases.

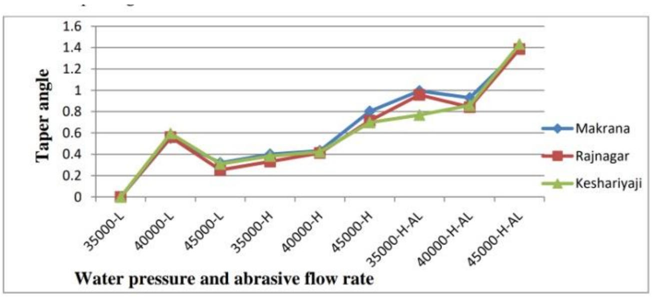

Fig.3.3 Water pressures and abrasive flow rate vs. taper angle

3.2 Minimization of kerf width and taper angle

Through experimentations and knowledge gained during experiments, we discovered some of the techniques for minimizing kerf width and taper angle. These are:

a) **Speed of water jet cutting:** Speed of water jet directly affect kerf width and taper angle. By controlling the speed of the water jet, we can minimize both the kerf width and the taper angle. High speeds are used to cut thin materials, whereas low speeds are used to cut thick materials. Thin materials may taper more than thicker materials. Taper can be eliminated only by slowing down the cut speed if a water jet with taper compensation is not provided. V-shaped taper is produced by higher cut speeds, while less taper is produced by lower cut rates. Cut speeds that are too slow can cause reverse taper.

b) **Amount of nozzle standoff:** The jet stream can spread if the nozzle is too far away from the material, resulting in tapered cut faces and severe erosion on the cut's top edge. The less taper you have, the lower you can get the nozzle to the substance. In most cases, a nozzle standoff of 5cm is sufficient.

c) In both the X and Y-axis directions, make sure the Z-axis is perpendicular to the material.

d) **Quality of cutting stream:** Less taper is produced by nozzles that are more focused. The cutting stream loses its symmetry and coherence if the orifice and nozzle are worn or broken.

e) **Quality of abrasive used:** By combining an abrasive with a supersonic water stream, water jets cut. At the same cutting speed, a higher-quality abrasive such as crushed garnet cuts more aggressively, resulting in better cut quality and less taper.

f) **Thickness and hardness of material:** The thickness and hardness of the sample have a direct effect on the kerf width/taper angle; as the thickness and hardness of the work piece increase, so does the taper angle/kerf width.

g) **Tilting the cutting head:** Taper angle/kerf width can also be minimized by using an articulated tilting nozzle to tilt the cutting head in the opposite direction of the cutting. Using a predictive model to determine taper in the kerf at each segment of a cutting path, the system directs the nozzle head to tilt in line with the component edge, resulting in taper on the scrap side of the material and square, taper-free edges on your product.

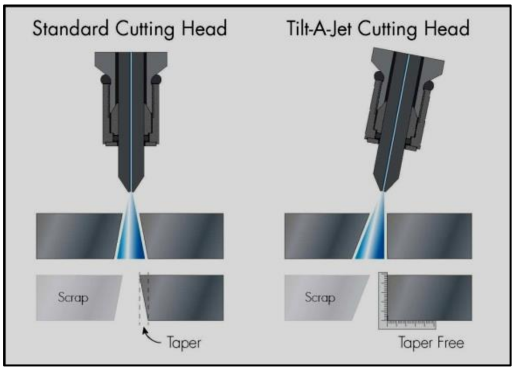

Fig.3.4 Tilt-A-Jet Cutting Head

3.3 Analysis for Surface Roughness

Surface roughness increases when water pressure rises, although abrasive flow rate has only a minor impact. Surface roughness or surface striation is influenced by traverse speed. The surface roughness of the sample as determined by the quality factor (Zeng and Kim, 1993) is **Q2** (though cut-fine). Cutting results for three types of marble are optimized when water pressure is 40000-45000 Psi and the abrasive flow rate is high, resulting in high surface roughness.

3.4 Analysis for Burr

As results, if a burr is produced in marble stone, it is either not formed if it is generated and erased by water and It's also impossible to measure (photogrammetric result).

Fig.3.5 Burr

3.5 Analysis for Wear of Nozzle

Nozzle life is approximately 12-13 hours and we can increase nozzle life through wear prevention. The approach of using porous lubricated nozzles was developed as a solution to prevent the nozzle from wearing out. To extend nozzle life and reduce wear, a novel nozzle made of tungsten carbide-based material has been created. Wear can also be decreased by using soft abrasive materials or hard material nozzles.

As a result, nozzle weights are

Weight before experiment = 50 gram

Weight after experiment = 49.98 gram

Table 3.1 Comprehensive results of experiments

PARAMETERS	Water pressure ↑	Standoff distance ↑	Abrasive flow rate ↑
Kerf width	↑	↑	↑
Taper angle	↓	↑	#
Surface roughness	↑	↑	↓
Material removal rate	↑	↓	↑
Depth of cut	↑	↓	↑

Where ↑= increasing, ↓=decreasing, #=not significant

4. CONCLUSIONS

The following conclusions were reached based on the results:

1) Abrasive water jet machine (AWJM) is far superior to other traditional methods due to numerous advantages and processes such as no dust generated, no heat affect zone (HAZ), no material distortion, easy process and water availability. And flow mach 2 machine used and having better configuration.

2) In the mining industry, marble is widely used in every industry and (a) Makrana generic white marble (b) Rajnagar marble (c) Keshariyaji green marble as their physicochemical properties are studied and tested all are respectively different features and identity.

3) Experiment result shows that minimization of kerf width/taper angle are possible by controlling input parameters and use tilt-a-nozzle technique.

4) Experiment result shows that by adjusting machining parameters such as water pressure, stand-off distance, traverse rate and abrasive flow

rate, we can optimize cutting parameters such as depth of cut, material removal rate, kerf width and surface roughness.

5) The results show that cutting three types of marble at high water pressure with a high abrasive flow rate produces better results in terms of depth of cut, material removal rate but as well as increases kerf width and surface roughness. Burr and edge rounding is very mi-nute or negligible. The wear of nozzle problem is serious concern.

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