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PRIMARY RESEARCH

Development of water jet cutting and study on different parameters

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Abstract

Waterjet machining is one of the emerging technology for machining hard materials that are very hard to machine by traditional machining processes. A high-velocity jet of water with abrasive particles gives eco-friendly and relatively economical machining options for cutting, which make leading machining technology in a short span. This paper reviews the work from the start to the development of waterjet machining within the past two decades. The work also points toward the improvement of performance regarding control and monitoring of different machining parameter i-e material removing rate, standoff distance, traverse speed, kerf width & surface roughness.

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I. INTRODUCTION

Water jet machining is a non-conventional machining method which converts mechanical energy of input power source into pressure energy of the fluid. In water jet machining the abrasive particles such as aluminum oxide, garnet, silicon carbide, etc. are introduced in high-speed waterjet via mixing tube to abrade materials. In abrasive jet machining, the material removes take place with by impact of solid particles along with high-pressure water stream, meanwhile pure water jet only uses simple water. Deformation in material occurs when blitz of particles is forced on a material. The Water Jet Cutting (WJC) has achieved its attention in the world as it provides numerous economic and environmental benefits. If we correlate WJC with other traditional machining methods, one main leverage of this process is that there is no heat-affected zone during and after machining. Some other advantages which WJC provides are self-cleaning capabilities, ecologically safe, etc.

During the 60s, the study on cutting by the application of pure water jet was conducted by O. Imanaka, University of Tokyo, and by late 60's, cutting of wood using high-velocity water jets was analyze by R. Franz of the University of Michigan. The main applications of pure waterjet machining include cutting cloths, paper products, wood, plastic etc. Composites materials were introduced by the end of 1970s, providing great advantage in the field of materials such as low weight, high strength, resistance to heat, hard, etc increase its use and applications, but until 80s there was no suitable

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method to machine such materials economically. Thus by 1980s a new method was introduced using abrasive and high pressurize water named as abrasive WJC was made available in industries to machine hard to machine materials. This machining process due to use of water, which is abundant in quantity became commercially available for industrial use by the end of 1983 with various types of abrasive i.e silicon caride, aluminum oxide, glass piece etc. Adding abrasives in the water jet increase the range of cutting materials, which can be cut with a Water jet drastically. WJCM is very convenient and applicable for cutting fibrous and soft materials. The heat generation in WJCM is less than another conventional machining. Some of the key advantages of WJCM are mentioned below:

- As no heat is generated during process minimum laceration is attained
- Accelerated setup of WJCM
- Precise cutting and high accuracy cutting
- Ecofriendly way of cutting
- The capability of cutting nonmetals and soft materials like rubber, Styrofoam, plastics, etc

In this review, we will thoroughly discuss each and every idea, contributions, and development of WJCM in the light of previous past publications and developments. Moreover, the idea of the development of WJCM will be explained following identifying pertinent processing parameters. Processing parameters can be used to understand process outputs as a function of inputs.

II. ABRASIVE WATERJET CUTTING MACHINE (AWJM)

AWJM is among one of the fastest-growing non-traditional machining methods in the world. The process of material removal in AWJM is convoluted phenomena that involve diverse parameters. The performance of this AWJM is determined by these parameters i.e., surface roughness and finish, Depth of Cut (DoC), Material Removal Rate (MRR), and precision are being analyzed. We will also discuss the effects of liquid environments, material removal, and crack propagation.

Hi-pressure WJC is in development since early 19th century, they started to appear as an industrial cutting device in 1933 for paper slitting, reeling and cutting, a type of WJC was used by Papers Patents Company; these were few of the initial applications of WJC and were restricted to low pressure and soft materials i.e., paper, cardboards, etc.

A. Development of WJC

The WJC jets were introduced in quarrying applications for washing out some precious metals like platinum by excavating the soft metal-bearing rocks. Based on the idea of the carnage of shell-like structures being produced by rain particle's impact, Hoogstrate et al. [1] applied this science for the industrial use of WJC. They also researched and examine wood cutting by different jets. They mainly clicked the idea while they found a leak from the random spot, when they moved broom from there they saw a little damaged impression on a broom so it gave the idea that a high-pressure stream of water can also be utilized to cut materials. This concept started the manufacturing of first industrial WJC by Mc Cartary which was later installed in Alto Boxboard in 1972. In that era, it was the very first few days of WJC and it was used for cutting of not only soft materials like leather, wood but also materials like limestone, marbles, and some metals.

It was a few of the early stages when various research was being done on water jet technology and due to which it led to the discovery of AWJM in the '80s. AWJM is quite similar to pure water jet machining with a small difference that in AWJM the abrasive particles are added to water stream for intensifying the effect of pressure by which range of possible machining of materials is increased.

Since many people have contributed to the research of AWJM they also researched various performance parameters and performance characteristics. The main contributors to WJC technology were mainly Russians from USSR. The Soviet scientists who worked on liquid jet cutting technology include Hoogstrate et al. [1], Chacko et al. [2].

There are several studies have been carried out to study the AWJM [3, 4, 5, 6, 7, 8]. Kovacevic [4] discovered that if we want to control the flow of AWJM impact on the material being cut; it is crucial to formulate a procedure by which we control and manage the abrasive flow according to our required need. They presented that if we increase the abrasive flow the penetration of the object will be high on the same pressure so it means we can regulate the pressure or abrasive flow according to our desired need.

[5] studied the effect of pressure on AWJM, the optimization aspects of AWJM, machining of advanced composites on AWJM, and modeling of surface waviness.

The AWJM can also be utilized to be used in the drilling of a variety of materials. One of the main advantages is there are no heat zones generated while cutting. It was identified that due to power alteration the depth and diameter of the hole can be drastically increased during continuous jet. This led to the development of the empirical model by which we can easily predict hole depths and their diameters [6].

From researches being done till now, it is evident that the cutting force of AWJM can vary by changing parameters i.e

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nozzle diameter, orifice diameter, flow rate, pressure, and standoff distance. Kovacevic [4] found that the cutting force of AWJM decreases with an increase in standoff distance while it is marginally affected by traverse rate, whereas by increasing pressure, mixing tube diameter and altering abrasive flow can increase cutting force. However, using less grit mesh size of abrasives may result in less blast lag while larger particles are favorable for this machine. The selectivity of abrasives mesh is crucial as perfect mesh size can result in prolonged blasting which will eventually result in a decrease in sidewall inclination [7].

B. Classification of Waterjets

There are various types of jets present for different types of operations i.e., turning, cutting, slitting, milling, drilling, etc but among all AWJM are mostly used by industries i.e aerospace, mining, manufacturing because one the key advantages of AWJM is the ease of maneuvering the jet nozzle. It also gives the edge to miners as it cuts down material without thermally degrading [9]. Furthermore, it reduces narrow kerf in material as the process doesn't have direct contact with the machine.

Based on the principle of generation of jets, WJC can be broadly classified into abrasive water jets and pure water jets. Abrasive jets are classified into abrasive wear suspension jets and abrasive water injection jets. On the other hand, pure water jets are classified into cavitating jets, continuous water jets, and pulsed jets.

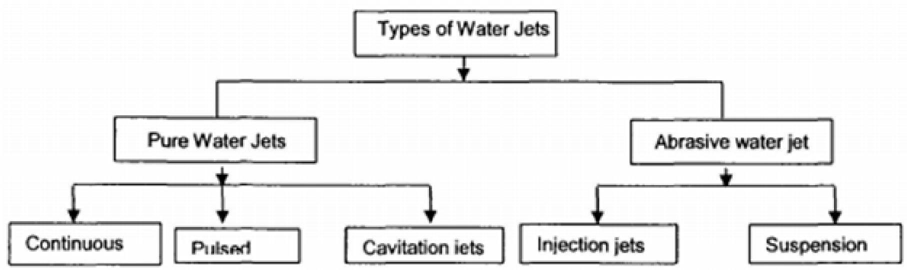

Fig. 1. Types of waterjets [10]

C. MRR

We can define the MRR as the volume of material being removed divided by the machining time. In other words, it's the instantaneous MRR at which a specified cross-sectional area of material being removed as it moves through the workpiece [11]. Several research has been carried out to study the MRR in AWJM [4, 12, 13, 14, 15, 16, 17, 18, 19].

The behavior of machined material vigorously depends on the optimum/maximum process parameter especially flowrate of abrasive being used. The cuts developed by AWJM are mostly conical or tapered. As the process of removing material in AWJM is a blended mixture between inter-granular and trans-granular fractures. The bottom region is characterized by inter-granular fracture while the upper region is characterized by trans-granular fracture. These observations and researches are explained by continual loss in the kinetic energy of the AWJM model [13].

It is considered to be a highly localized process while cutting multiphase materials with high-pressure WJC. During this type of loading scenario, the distribution of material properties holds a crucial significance in the condition of a pressure range up to 30x the UTS (ultimate tensile strength) of material. The material properties may characterize the partial-rupture behavior of a material when the pressure level is exceeded. Further, we use Gaussian distribution for the width of generated rupture over the laden area. The fracture/rupture experiments have previously been done on multiphase WJC [12].

To determine the effects of different input parameters on MRR, surface finish, and to explain many destruction mechanisms several types of research have been done so far. Various researchers have suggested different material removal mechanism performed on different materials. Bitter [14] researched that the deformation wear is responsible for crack propagation while spalling of the object causes the material to remove, while Finnie [15] described that the plastic deformation and fracture are responsible for material removal in ductile materials. Tilly [16] the material is extruded to form a lip and the lip is been detached by fragmented particles. Researches by Hutchings [17] describe the rupture is the result of lip detachment and Kovacevic [4] investigated that the material removal of ductile materials is mainly caused by platelet mechanism.

Ramachandran [18] researched that in AWJM many more parameters can be defined since much of analytical work is yet to be conducted on the effects of particle distribution in AWJM mixture stream and particle combination.

Simultaneously, several researchers have researched to investigate and explain the material removal due to the erosive action of AWJM for different materials [12, 13, 14, 15,

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16, 17]. They all concluded similar results as ductile materials are removed mostly as a result of plastic strain, deformation wear, cutting wear, and plastic deformation. Meanwhile, brittle materials may be removed as a result of radical cracking or surface rupture, elastic-plastic deformation, or rupture due to indentation.

It is also observed by experiments that MRR may be increased by increasing the diameter of the nozzle and grain size. It is also observed that in some particular cases MRR increases on an increased of standoff pressure up to some extent but there might be rough cuts observed on the surface. However, from the research of Verma [19], it is observed that MRR remains constant for minor changes in standoff distance if further increased then pressure drops.

D. Stand-Off Distance (SOD)

SOD can be defined as the distance between the working surface of work and the face of the nozzle. SOD is had a considerable effect not only on MRR but on accuracy and precision too. Poor accuracy may be a result of large SOD which usually due to flaring up of jet.

The concept and effect of SOD on penetration rate and MRR of material have been discussed and reported by many authors [19, 20, 21, 22, 23, 24, 25, 26, 27]. All studies indicate the SOD increases penetration rate and MRR up to some optimum limit value afterward they start decreasing.

Due to a reduction in nozzle pressure(s) with the decreasing distance, we observe small MRR at low SOD, whereas due to a reduction in velocity of the jet with the increasing distance we observe a drop in MRR at large SOD [23].

Within a limited range value of SOD, the process was the removal of burr was found. SOD was found to be a significant factor in the size of the radius produced at the boundary edges [24]. It is also explained that SOD and nozzle diameter are the most crucial parameters which can affect the percentage variation on the side diameter of the work-piece while the nozzle diameter parameter is the most crucial parameter in which can affect the percentage variation on the exit side of workpiece diameter [25].

Pandey et al. [20], Misra [26] [27], researched about the flowrate of abrasive(AFR) and SOD on MRR. They observed that MRR reaches an optimum limit value when AFR and SOD are increased then decline suddenly as we further increase in these parameters.

E. Influence of Machining Parameters

Since we know that a large number of parameters are involved in AWJM and the crucial tasks include the optimization of performance to a multitude of machining requirements [28]. There are numerous studies been carried out previously to study machining parameters of AWJM [28, 29, 30].

Figure 2 shows different parameters which generally influence AWJM, these parameters can be distinguished into target parameters and process parameters. The target parameters include DoC, MRR, surface roughness, kerf taper, quality of cut, kerf width, and energy scattered into the workpiece. While various process parameters are classified into mixing, cutting, abrasive and hydraulic parameters. The jet separator is basically influenced by different jet pressure, water flow rate, and hydraulic parameters [28]. MRR, DoC, and smooth cuts are produced when water pressure increases, and cutting is further enhanced with an increase in abrasive flowrates [29].

It is also noticed that the jet pressure follows an almost linear trend with some variations of DoC. The AFR and traverse rate influence the DoC differently [30].

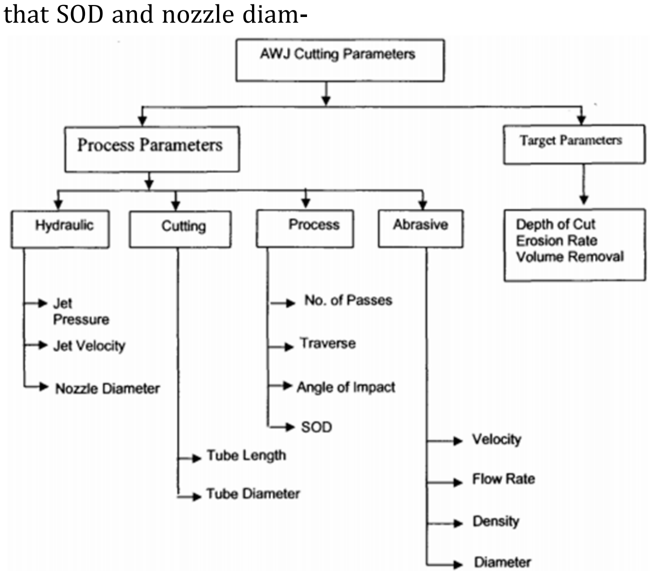

Fig. 2. Parameters that influence AWJ cutting [30]

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F. AWJ Cut Surface Structure

Several studies have been carried out to study the Cut Surface Structure of Abrasive waterjet [23, 31, 32, 33, 34]. With the help of conventional machining processes, cut surfaces can be machined easily; this may be impossible in the case where material properties are being affected by particle embedment [31].

The cutting process in AWJC is relatively cool and clean as no heat zones are generated during the process and there are fewer deformation stresses. WJC is quite amenable to Computer Numerical Control (CNC) which ensures repeatability and accuracy. The costs of components are the major cost in AWJC, the major cost includes the capital cost of machine and cost of nozzles, power source, and abrasive garnet material [23].

Certain parameters characterize the geometry of cut, irrespective type of material being cut with AWJM. The geometry of cut is dependent on the energy that is being utilized for cutting materials, but the energy is somehow, in turn, depends on AWJM parameters. It is essential to carefully select the cutting parameters for obtaining the desired quality of the surface being cut [32].

Higher AFR of abrasives may reduce the convergence taper, withal the taper switches from divergent to convergent taper if certain abrasive diameter may be increased [33]. Furthermore, the taper also depends on SOD, the taper gets reduced as this parameter is minimized. [35] observed that the taper reduces with an increase in pressure in brittle materials. Moreover, it was observed that the taper increases for high traverse rate and low-pressure application while taper is lesser when its high pressure and low traverse rate employed. Therefore, the traverse rate is considered to be the most influential aspect in governing taper of cut.

Apart from this, the excess waviness known as striation existed on the surface of the generated sidewall which is considered to be one of the main deficiencies of AWJM. Moreover, the surface which is being cut topography usually varies from top to bottom of the cut. We can divide the entire region into 3, i.e Rough Zone, Transition Zone, and Smooth Zone. By increasing the velocity of jet or by reducing traverse rate we can increase the smooth zone region but somehow it results in a reduction of productivity. So for the precision cutting applications, it is necessary to obtain a smooth region and one has to select process parameters where AWJ cutting is maximum and optimum.

The surface quality can be improved by adequately improving the mixture of abrasives and water to form a slurry jet of water-abrasive with uniformly distributed particles. Improving the particle mixing with water is also a difficult task unless the slurry jet is been used at high pressure as directly driven WJC. To improve the uniformity of the distribution of energy across the WJC and to improve the quality of cut, more study is currently being required for a better understanding of the dynamic characteristics of WJC [35].

G. Parameters Influencing Accuracy

Some of the studies have been carried out to study parameters influencing accuracy in AWJM. [36, 37] The abrasive grit size is one of the key factors which affect the accuracy of AWJM. One of the main factors which affect the hole oversize during the machining process is grain size [36]. Komaraiah[37] over cut be 1 1/2 time mean grit size. The various researchers mentioned in references [36] observed and suggested several investigations and rules for clearance which is related to distribution, size, and geometry of abrasives. The unavoidable conicity at exit is due the oversize holes are greater in the amount at entry than exit. Conicity is reduced with the use of finer abrasives [36, 37]. Injection of slurry into zone being machined decreases conicity while increasing precision. The conicity can also be eliminated by re-passing fine abrasives. Out-off-roundness is due to micro-chipping of work material at exit and inaccuracy in feed motion at entry.

As mentioned above by Adithan [36] accuracy of machining is mostly dependent on the abrasive grit size. If we observed theoretically the hole oversize is twice the mean size of grain diameter yet the holes produced are generally always greater than theoretical oversize. The accuracy of holes machined can be increased if finer abrasive is being used due to which it will result in reduced oversize of holes and oversize usually varies with machining time. So we can conclude that oversize holes produce decreases with an increase in machining time of abrasive slurry. The reduction in mean abrasive size is one of the main reasons for the decrease in oversize.

The conclusions which we can extract from the above observations is that the abrasive grain size is one of major influence which affects the oversize of the hole.

H. Surface Finish

Numerous studies have been carried out to study surface finish obtained by AWJM [24, 38, 39, 40, 41, 42, 43, 44]. The surface finish of a workpiece is directly related to the cutting force. The finish will be rougher if force is higher. It can be easily detected by a change in cutting force in case if the problem persists [38].

The development of striation marks that emerge below

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an area of relativity which results in smooth surface finish shows a typical characteristic of surface finish by WJC. When the cutting efficiency of the machine decreases these striation marks/lines usually appear or it could happen in many other ways. The possible reasons may include; if water pressure is too slow/low, the material is too thick to penetrate, inappropriate use of abrasives or excess abrasive quantity, or if the cutting speed is too fast. If we control these parameters an excellent surface finish could be achieved with enhanced quality cut throughout the entire DoC [38].

The surface roughness of components in the machining process usually depends on the physio-mechanical properties of components which are being machined, size, and concentration of abrasives in suspension [41]. It is also observed that if we increase the cutting speed of WJC the SOD also increases, withal there are round edges displayed at the surface of the material after cutting [41].

We can only attain a desirable surface finish when the depth of the smooth zone is more than the thickness of the workpiece. Due to restrictions of WJC pressures from current pumping methods, the minimization of striations without sacrificing cutting speed and increasing the depth of the smooth region would create an improvement in AWJM [40].

Unlike the features which are result by the use of traditional machine tools, the characteristics of the surface resulting from AWJM are different and maybe dissimilar as a function of jet energy and DoC [41].

The researches on black granite in terms of surface roughness with AWJM indicated two different regions a rough cut region beyond 30mm and a smooth zone up to 30mm. On the other hand, the observations from kerf geometry studies show the presence of three regions irregular kerf zone, uniform kerf zone, and tapered kerf zone. Since many parameters are influencing forces in different ways, it is essential to select appropriate parameters for achieving appropriate results, in AWJM cutting of granite is currently being found to be important [42].

The action of abrasives against the surface is observed to both cut acrimonies into the surface and to displace materials. Usually, different sapience profiles are achieved by using tiny abrasives during the machining, and the finishing surface is a result of abrasive marks superimposed on an altered profile. Therefore machining changes in the internal surface of the workpiece while the tube roughness decreases [43].

It was observed that the burrs from the specimens weren't removed when the SOD parameter was changed beyond 8mm. It was also found that a particular length after deburring the surface finish value at the top surface also changed [24].

Through various research, works have been done so far in the development of AWJM but Ramulu and Arola [44] is one of finest in surface finish, their research and experiments helps to determine the influence of cutting parameters on kerf taper and surface roughness which they observed while machining graphite/epoxy laminate. Experimental studies were carried out to measure the influence of cutting parameters on the specimen of kerf taper of laminate and surface roughness.

III. CONCLUSION

The work presented above is an overview of recent developments of waterjet machining, from the above discussion it can be concluded that:

1. The waterjet machining process is getting more and more attention in the machining areas particularly for hard-to-cut materials. Its unique benefits over other traditional and non-traditional methods make it a new alternative in the machining industry.

2. Limited literature available shows that the standoff distance at the optimal value during the waterjet machining by monitoring and control. This type of work has not been done for any other parameters so, research work is required to be done in this area.

3. In most research work, waterjet pressure, standoff distance, traverse speed, abrasive grit size, and abrasive flow rate have been done. Very little work has been done on the effect of nozzle and orifice diameter.

4. Most of the optimization work has been carried out on process parameters for improvement of a quality characteristic such as DOC, MRR, surface roughness, kerf geometry, and nozzle wear. There is no work found based on the optimization for the dimension accuracy, power consumption, and multi-objective optimization of the waterjet machining process. So, this area is still open for research work.

REFERENCES

[1] A. Hoogstrate, B. Karpuschewski, C. Van Luttervelt, and H. Kals, ``Modelling of high velocity, loose abrasive machining processes,'' *Cirp Annals*, vol. 51, no. 1, pp. 263-266, 2002. doi: https://doi.org/10.1016/S0007-8506(07)61513-3

[2] S. Chacko, A. Gupta, and D. Summers, ``Comparative performance study of polyacrylamide and xanthum polymer in abrasive slurry jet,'' in *Proceedings of American Water Jet Conference,* New York, NY, 2003.

[3] T. M. Mahmoud, ``The effect of different types of soils on the germination rate of the watercress seeds (nasturtium officinal),'' *International Journal of Applied and Physical Sciences*, vol. 2, no. 1, pp. 21-32, 2016. doi: https://doi.org/10.20469/ijaps.2.50004-1

[4] R. Kovacevic, ``Monitoring the depth of abrasive waterjet penetration,'' *International Journal of Machine Tools and Manufacture*, vol. 32, no. 5, pp. 725-736, 1992. doi: https://doi.org/10.1016/0890-6955(92)90026-D

[5] M. Hashish, ``Observations of wear of abrasive-waterjet nozzle materials,'' *Journal of Tribology*, vol. 116, no. 3, pp. 439-444, 1994. doi: https://doi.org/10.1115/1.2928861

[6] H. Orbanic and M. Junkar, ``An experimental study of drilling small and deep blind holes with an abrasive water jet,'' *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 218, no. 5, pp. 503-508, 2004. doi: https://doi.org/10.1177/095440540421800504

[7] H. Wensink and M. C. Elwenspoek, ``Reduction of sidewall inclination and blast lag of powder blasted channels,'' *Sensors and Actuators A: Physical*, vol. 102, no. 1-2, pp. 157-164, 2002. doi: https://doi.org/10.1016/S0924-4247(02)00301-1

[8] Y. X. Lee and Z. W. Zhong, ``A study of the relationship between adverse weather conditions and flight delay,'' *Journal of Advances in Technology and Engineering Research*, vol. 2, no. 4, pp. 113-117, 2016. doi: https://doi.org/10.20474/jater-2.4.2

[9] J. Olsen and J. Zeng, ``the state-of-the-art of precision abrasive waterjet cutting,'' in *Proceedings of the 8th Pacific Rim International Conference on Water Jet Technolog,* California, CA, 2006.

[10] K. H. Orbanic, ``Water jet and abrasive water jet machining classification,'' *Classification High Stream Jet*, vol. 4, no. 6, pp. 123-145, 1975.

[11] R. A. K. E. Paul Degarmo and J. T. Black, ``Fundamentals of machining,'' 2001. [Online]. Available: https://bit.ly/37A9xIG

[12] A. Momber and R. Kovacevic, ``Statistical character of the failure of multiphase materials due to high pressure water jet impingement,'' *International Journal of Fracture*, vol. 71, no. 1, pp. 1-14, 1995. doi: https://doi.org/10.1007/BF00019338

[13] A. Momber, I. Eusch, and R. Kovacevic, ``Machining refractory ceramics with abrasive water jets,'' *Journal of Materials Science*, vol. 31, no. 24, pp. 6485-6493, 1996. doi: https://doi.org/10.1007/BF00356252

[14] J. G. A. Bitter, ``A study of erosion phenomena,'' *Wear*, vol. 6, no. 1, pp. 1-92, 1963.

[15] I. Finnie, ``Some observations on the erosion of ductile metals,'' *wear*, vol. 19, no. 1, pp. 81-90, 1972. doi: https://doi.org/10.1016/0043-1648(72)90444-9

[16] G. Tilly, ``A two stage mechanism of ductile erosion,'' *Wear*, vol. 23, no. 1, pp. 87-96, 1973. doi: https://doi.org/10.1016/0043-1648(73)90044-6

[17] I. Hutchings and A. Levy, ``Thermal effects in the erosion of ductile metals,'' *Wear*, vol. 131, no. 1, pp. 105-121, 1989. doi: https://doi.org/10.1016/0043-1648(89)90248-2

[18] N. Ramachandran and N. Ramakrishnan, ``A review of abrasive jet machining,'' *Journal of Materials Processing Technology*, vol. 39, no. 1-2, pp. 21-31, 1993. doi: https://doi.org/10.1016/0924-0136(93)90005-Q

[19] A. Verma and G. Lal, ``An experimental study of abrasive jet machining,'' *International Journal of Machine Tool Design and Research*, vol. 24, no. 1, pp. 19-29, 1984. doi: https://doi.org/10.1016/0020-7357(84)90043-X

[20] N. Pandey, V. Pal, and J. K. Katiyar, ``Investigation of drilling time v/s material thickness using abrasive waterjet machining,'' *International Journal of Advances in Engineering & Technology*, vol. 4, no. 1, p. 672, 2012.

[21] V. Venkatesh, T. Goh, K. Wong, and M. Lim, ``An empirical study of parameters in abrasive jet machining,'' *International Journal of Machine Tools and Manufacture*, vol. 29, no. 4, pp. 471-479, 1989. doi: https://doi.org/10.1016/0890-6955(89)90065-5

[22] R. Balasubramaniam, J. Krishnan, and N. Ramakrishnan, ``A study on the shape of the surface generated by abrasive jet machining,'' *Journal of Materials Processing Technology*, vol. 121, no. 1, pp. 102-106, 2002. doi: https://doi.org/10.1016/S0924-0136(01)01209-2

[23] H. Shan and P. Pande, *Modern Machining Process*. California, CA: Tata McGraw-Hill Education Pvt, 1980.

[24] Z. M. Hou, W. Xia, D. H. Deng, and Q. H. Wang, ``An experimental study of abrasive waterjet for deburring,'' *Advanced Materials Research*, vol. 411, no. 6, pp. 311--314, 2012. doi: https://doi.org/10.4028/www.scientific.net/AMR.411.311

[25] R. Balasubramaniam, J. Krishnan, and N. Ramakrishnan, ``An empirical study on the generation of an edge radius in Abrasive Jet External Deburring (AJED),'' *Journal of Materials Processing Technology*, vol. 99, no. 1-3, pp. 49-53, 2000.

doi: https://doi.org/10.1016/S0924-0136(99)00350-7
[26] V. Misra, ``Prehistoric human colonization of India,'' *Journal of Biosciences*, vol. 26, no. 4, pp. 491-531, 2001. doi: https://doi.org/10.1007/BF02704749
[27] D. Srikanth and M. SreenivasaRao, ``Metal removal and kerf analysis in abrasive jet drilling of glass sheets,'' *Procedia Materials Science*, vol. 6, pp. 1303-1311, 2014. doi: https://doi.org/10.1016/j.mspro.2014.07.109
[28] M. Hashish, ``Optimization factors in abrasive-waterjet machining,'' *Journal of Engineering for Industry*, vol. 113, no. 1, pp. 29-37, 1991. doi: https://doi.org/10.1115/1.2899619
[29] M. Hashish, ``Pressure effects in Abrasive-Waterjet (AWJ) machining,'' *The Journal of Engineering Materials and Technology*, vol. 111, no. 3, pp. 221-228, 1989. doi: https://doi.org/10.1115/1.3226458
[30] L. M. Hlaváč, B. Strnadel, J. Kaličinskỳ, and L. Gembalová, ``The model of product distortion in AWJ cutting,'' *The International Journal of Advanced Manufacturing Technology*, vol. 62, no. 1-4, pp. 157-166, 2012. doi: https://doi.org/10.1007/s00170-011-3788-2
[31] A. Mohd Ali, A. A. Khan, and M. Y. Ali, ``Effect of process parameters on abrasive contamination during water abrasive jet machining of mild steel,'' *Advanced Materials Research*, vol. 264, pp. 1015-1020, 2011. doi: https://doi.org/10.4028/www.scientific.net/AMR.264-265.1015
[32] S. Dehkhoda and N. Bourne, ``Production of a high-velocity water slug using an impacting technique,'' *Review of Scientific Instruments*, vol. 85, no. 2, pp. 19-25, 2014. doi: https://doi.org/10.1063/1.4865402
[33] A. Momber, R. Kovacevic, and H. Kwak, ``Alternative method for the evaluation of the abrasive water-jet cutting of grey cast iron,'' *Journal of Materials Processing Technology*, vol. 65, no. 1-3, pp. 65-72, 1997. doi: https://doi.org/10.1016/0924-0136(95)02243-0
[34] M. Ramulu and D. Arola, ``Water jet and abrasive water jet cutting of unidirectional graphite/epoxy composite,'' *Composites*, vol. 24, no. 4, pp. 299-308, 1993. doi: https://doi.org/10.1016/0010-4361(93)90040-F
[35] D. Arola, M. McCain, S. Kunaporn, and M. Ramulu, ``Waterjet and abrasive waterjet surface treatment of titanium: A comparison of surface texture and residual stress,'' *Wear*, vol. 249, no. 10-11, pp. 943-950, 2001. doi: https://doi.org/10.1016/S0043-1648(01)00826-2
[36] M. Adithan and V. Venkatesh, ``Production accuracy of holes in ultrasonic drilling,'' *Wear*, vol. 40, no. 3, pp. 309-318, 1976. doi: https://doi.org/10.1016/0043-1648(76)90122-8
[37] M. Komaraiah, M. Manan, P. N. Reddy, and S. Victor, ``Investigation of surface roughness and accuracy in ultrasonic machining,'' *Precision Engineering*, vol. 10, no. 2, pp. 59-65, 1988. doi: https://doi.org/10.1016/0141-6359(88)90001-3
[38] D. Hunt, C. Burnham, and T. Kim, ``Surface finish characterization in machining advanced ceramics by abrasive waterjet,'' in *Proceedings of the Fourth U.S. Water Jet Conference,* California, CA, 1987.
[39] M. Vestnik, ``Surface quality of small components after ultrasonic abrasive machining,'' *Russian Physics Journal*, vol. 56, no. 4, pp. 56-70, 1976.
[40] F. Chen, E. Siores, and K. Patel, ``Improving the cut surface qualities using different controlled nozzle oscillation techniques,'' *International Journal of Machine Tools and Manufacture*, vol. 42, no. 6, pp. 717-722, 2002. doi: https://doi.org/10.1016/S0890-6955(01)00161-4
[41] D. Arola and M. Ramulu, ``Material removal in abrasive waterjet machining of metals a residual stress analysis,'' *Wear*, vol. 211, no. 2, pp. 302-310, 1997. doi: https://doi.org/10.1016/S0043-1648(97)00131-2
[42] P. Sitarama Chakravarthy and N. Ramesh Babu, ``A new approach for selection of optimal process parameters in abrasive water jet cutting,'' *Materials and Manufacturing Processes*, vol. 14, no. 4, pp. 581-600, 1999. doi: https://doi.org/10.1080/10426919908914851
[43] M. Barletta and V. Tagliaferri, ``Development of an abrasive jet machining system assisted by two fluidized beds for internal polishing of circular tubes,'' *International Journal of Machine Tools and Manufacture*, vol. 46, no. 3-4, pp. 271-283, 2006. doi: https://doi.org/10.1016/j.ijmachtools.2005.05.014
[44] M. Ramulu and D. Arola, ``The influence of abrasive waterjet cutting conditions on the surface quality of graphite/epoxy laminates,'' *International Journal of Machine Tools and Manufacture*, vol. 34, no. 3, pp. 295-313, 1994. doi: https://doi.org/10.1016/0890-6955(94)90001-9