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A REVIEW ON PARAMETRIC STUDY AND DEVELOPMENT IN ABRASIVE WATER JET MACHINING

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Abstract: Abrasive water jet machining (AWJM) is an emerging machining technology option for hard material parts that are extremely difficult-to-machine by conventional machining processes. A narrow stream of high velocity water mixed with abrasive particles gives relatively inexpensive and environment friendly production with reasonably high material removal rate. Because of that abrasive water jet machining has become one of the leading manufacturing technologies in a relatively short period of time. This paper reviews the research work carried out from the inception to the development and Parametric Study of AWJM within the past decade. It reports on the AWJM research relating to improving performance measures, monitoring and control of process, optimizing the process variables. A wide range of AWJM industrial applications for different category of material are reported with variations. The paper also discusses the future trend of research work in the same area.
Keyword: Abrasive water jet machining, Process parameter, Process optimization, Monitoring, Control, and Responses Parameter.

I. INTRODUCTION

Manufacturing industry is becoming ever more time conscious with regard to the global economy. The need for rapid prototyping and small production batches is increasing in modern industries. Nowadays a number of methods and technologies designed for cutting of structural material exist. New requirements related to up-to-date material and its properties are constantly being laid on these methods. [1]These trends have placed a premium on the use of new and advanced technologies for quickly processing raw materials into usable goods; with no time being required for tooling. Manufacturing industry is becoming ever more time conscious with regard to the global economy. The need for rapid prototyping and small production batches is increasing in modern industries. These trends have placed a premium on the use of new and advanced technologies for quickly processing raw materials into usable goods; with no time being required for tooling. Material cutting by abrasive water jet was first commercialized in the late 1980s as a pioneering breakthrough in the area of unconventional processing technologies. Abrasive Water jet Cutting (AWJC) has various distinct advantages over the other non-traditional cutting technologies, such as no thermal distortion, high machining versatility, minimum stresses on the work piece, high flexibility and small cutting forces and has been proven to be an effective technology for processing various engineering materials. [8] However, the cutting capacity of this technology in terms of depth of cut (or depth of jet penetration) and kerf quality is still the major obstruction that limits its applications. Considerable research and development effort has been made in recent years to develop new techniques to enhance the cutting performance of this technology such as the depth of cut and surface finish. [18]

II. AWJM APPLICATIONS AND AREAS OF AWJM RESEARCH

P. Hreha, S. Hloch, P. Monka, K. Monkova investigation of sandwich material surface created by abrasive water jet (AWJ) via vibration emission.Abrasive water jet cutting of heterogeneous "sandwich" material with different Young modulus of elasticity of the catted surface geometry by means of vibration emission.An experiment in heterogeneous material consisting of stainless steel (DIN 1.4006 / AISI 410) and alloy AlCuMg2 has been provided. A sandwich semi-product composing of two metal plates bonded together by epoxy adhesive was prepared as an experimental material. These plates were made of stainless steel with marking according to DIN 1.4006 (AISI 410) standard with thickness of 32 mm and of Al alloyAlCuMg2 with thickness of 20 mm. The sensors were placed. The first cutting the experimental material was. Oriented upwards by means of the Al alloy plate. In the second cutting the orientation of material was the opposite one. The vibration signal was scanned from a side perpendicular to the cutting direction. Time records of the scanned signal.The signals of both layers of material possess similar development due to transmission of oscillations in the material. Higher amplitudes were again recorded in the case of softer material (Al alloy). That material was placed in the zone in which the abrasive water jet lost a high amount of kinetic energy due to passing through the material with higher modulus of elasticity (stainless steel). The results of frequency analysis of scanned signals.Material with low modulus of elasticity is not capable of sufficient resistance and generates a negative to the expanded instrument shape.

When the instrument had passed into the material with higher modulus of elasticity in upward work piece orientation by means of aluminium alloy plate the mechanism of the surface generation was realized anew with the instrument which lost part of its initial energy. [1]

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A. Alberdi, A. Suárez, T. Artaza, G. A. Escobar-Palafox, K. Ridgway had worked on Composite Cutting with Abrasive Water Jet. The process parameters for each type of FRP & CFRP material which will allow AWJ trimming operations to be easily carried out on composite materials, since machine manufacturers still do not provide good databases for composite cutting. The presented work aims at studying the behavior of a machinability model in composite materials. The machinability index for various composite materials with different thicknesses was found experimentally, which showed very different results for different materials.A study of the effect of the abrasive water jet process parameters on the quality of cut taper and surface roughness was carried out.Process parameter selection is an important aspect to take into account in order to increase productivity. The taper angle may be a function of the absolute traverse feed rate more than a function of its respective percentage to the separation speed.The machinability index of different composite materials is very different, so they have to be studied separately. This index may be related to the tensile modulus and/or to the fiber content of the composite materials. [2]

Gokhan Aydin, Izzet Karakurt, Kerim Aydiner investigation on Prediction of the Cut Depth of Granitic Rocks Machined by Abrasive Water jet (AWJ). A variety of nine types of granitic rocks were used in the cutting experiments. The experimental data were used to assess the influence of AWJ operating variables on the cut depth. Using regression analysis, models for prediction of the cut depth from the operating variables and rock properties in AWJ machining of granitic rocks were then developed and verified. The influence of the traverse speed on the cut depth is plotted. The figure shows that the cut depths of all granites decrease with an increase in the traverse speed. The influence of the abrasive mass flow rate on the cut depth. It can be seen that the cut depth slowly increases with increasing abrasive mass flow rate. The standoff distance plays a limited role in influencing the cut depth. The standoff distance has no discernible influence on the cut depths of the granites tested. The experimental data depicted illustrate the influence of the water pressure on the cut depths. It is noticed that the cut depths increase initially in all granites when the water pressure increases. The experimental data depicted illustrate the influence of the abrasive size on the cut depths of the granites studied. It can be noted that higher cut depths were obtained by coarse-grained abrasives. [3]

Zheng Wang had an investigation on water jet machining for hardwood floors. A computer numeric control (CNC) router equipped with ultra-high pressure abrasive water jets was used to investigate the effects of wood species (density), pressure of water jet, feeding speed of wood samples and screen mesh grade of abrasives on the quality of hardwood floors. Owing to the high operational cost during the mill trial, a statistical methodology named orthogonal array testing, which reduced the number of factor combinations and exhibited maximum coverage with a minimum number of test scenarios, was employed in this study. Through both industrial scale trials and statistical analysis, it was concluded that the wood density of 0.70 g/cm3, the water pressure of 280 MPa, the feeding speed of 80 mm/min and the abrasive size of 100 screen mesh grades yielded the optimum combination for achieving the best quality during abrasive water jet machining on hardwood floors. Among the four factors, the water jet pressure had the most important impact on the surface quality, followed by the abrasive size, wood density and feeding speed. In addition, the results also demonstrated that OAT is a cost-effective method to be used for achieving optimal machining parameters in the mill environment. [4]

Izzet Karakurt, Gokhan Aydin, and Kerim Aydiner investigation on the Depth of Cut of Granite in Abrasive Water jet Cutting. It is aimed at investigating the cut ability of granite by abrasive water jet. The effect of process parameters and the textural properties of granites on the cut depth and surface quality were investigated. The design philosophy of Taguchi was followed to conduct the experiments. Analysis of variance (ANOVA) was used to evaluate the data obtained statistically. Major significant process factors affecting the cut depth of granite were determined. In the experiments, pre-sized granite samples of 30mm thickness, 200mm length, and 100mm width were cut by a water jet cutter with an operating pressure of up to 380 MPa. Its nozzle diameter and length is 1.1mm and 75 mm, respectively. In general, it was found that increasing of the traverse speed and decreasing of the abrasive size decreased the cut depths of all granites tested. The cut depths of the granites increased marginally with an increase of the abrasive flow rate, while the standoff distance did not have a discernible effect on the depth of cut. Additionally, the effect of the water pressure differs from the other control factors. It was determined that the traverse speed was statistically the most significant factor influencing the cut depth granites. [5]
Zsolt Maros have worked on Taper cut at Abrasive Water Jet Cutting of an Aluminium alloy. Taper can be different at different materials and depends on the applied technological parameters (feed rate, pressure, abrasive flow rate etc.). Cutting kerf is one of the main problems effecting on the accuracy of abrasive water jet cutting. Kerf characteristics refer to the kerf geometrical features as kerf width, kerf taper and kerf depth. Generally there are two types of kerfs, through cut and non-through cut. Cutting tests were carried out for investigation of kerf taper on AlMgSi0.5 aluminium alloy. During the cutting experiments the water pressure (p), the abrasive mass flow rate (ma) and the federate (f) were changed in different levels. In this case increasing the pressure decreases the taper angle of the kerf because of the fact that at lower federates the abrasive jet is able cut through more wide the material at the bottom side as well.
Increase of the abrasive mass flow rate decreases the taper too. By increasing the number of abrasive grains acting in the jet, increases the energy of the jet, which results a wider kerf width at the bottom side of the cut. [6]

S. Srinivas1 and N. RameshBabu had presented a set of

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studies performed on aluminum-silicon carbide particulate metal matrix composites prepared by adding 5, 10, 15 and 20% of SiC in aluminum alloy and processed with abrasive water jets that are formed with garnet and silicon carbide abrasives of 80 mesh size. These studies are essentially meant to assess the penetration ability of abrasive water jets on different compositions of Al-SiCp MMCs produced by stir casting method. Abrasive water jet cutting experiments were conducted on trapezoidal shaped specimens of different composites as well on the constituent materials i.e., 100% aluminum alloy and 100% SiC specimens by varying water pressure, jet traverse speed and abrasive mass flow rate, each at three different levels. The percentage contribution of individual and combined effects of process parameters on penetration ability was analyzed by means of analysis of variance. Contribution of water jet pressure and traverse speed on jet penetration in these materials are found to be more than abrasive flow rate. Among the interaction effects, water jet pressure and jet traverse speed combinations contribute more to jet penetration.Although developing the statistical models for predicting the depth of jet penetration achievable with AWJs produced by the variation of different process parameters, the study carried out in this work would help to choose the parameters carefully. For effective cutting of harder materials with AWJs, proper choice of abrasive mass flow rates and jet traverse speeds are of considerable importance over the other parameters like water jet pressure. [7]

M. Chithirai Pon Selvan, N. Mohana Sundara Raju, H. K. Sachidananda had worked on Effects of process parameters on surface roughness in abrasive water jet cutting of aluminium. This paper shows the influence of process parameters on surface roughness (Ra) which is an important cutting performance measure in abrasive water jet cutting of aluminium. Surface roughness is one of the most important criteria, which help us determine how rough a work piece material is machined. The influence of water pressure on the surface roughness is shown in Fig. 4. Jet pressure plays an important role in surface finish. As the jet pressure increases, surface becomes smoother. With increase in jet pressure, brittle abrasives break down into smaller ones. As a result of reduction of size of the abrasives the surface becomes smoother. It needs a large number of impacts per unit area under a certain pressure to overcome the bonding strength of any material with the increase in abrasive flow rate, surface roughness decreases. Traverse speed didn't show a prominent influence on surface roughness. Surface roughness increase with increase in standoff Distance. Higher standoff distance allows the jet to expand before impingement which may increase vulnerability to external drag from the surrounding environment. Therefore, increase in the standoff distance results an increased jet diameter as cutting is initiated and in turn, reduces the kinetic energy of the jet at impingement. So surface roughness increase with increase in standoff distance. [8].

Leeladhar Nagdeve, Vedansh Chaturvedi and Jyoti Vimal worked on non–traditional Abrasive Water Jet Machining to find optimum process parameter.Abrasive water jet machining is a process of removal of material by impact erosion of high pressure, high velocity of water and entrained high velocity of grit abrasives on a work piece.Experimental investigation were conducted to assess the influence of abrasive water jet machining (AWJM)Processes Parameter such as Pressure (P) MPa, Stand of Distance (S) mm, Abrasive Flow rate (A) g/s, Traverse rate (T)mm/s on MRR and surface Roughness (Ra) of aluminium. The approach was based on Taguchi's method and analysis of variance (ANOVA) to optimize the AWJM process parameter for effective machining and to predict the optimal choice for each AWJM parameter such as pressure, standoff distance, Abrasive flow rate and Traverse rate. Main effects of MRR of each factor for various level conditions are shown in figure1.MRR increases with four major parameter Pressure, Stand of Distances, Traverse rate, Abrasive flow rate. Pressure is the most significant factor on MRR during AWJM. Meanwhile standoff distance, Abrasive flow rate and Traverse rate are sub significant in influencing. The surface Roughness decreases with four major parameter Pressure, Stand of Distances, Traverse rate, Abrasive flow rate.Abrasive flow rate is most significant control factor and hence the optimum recommended parametric combination for optimum surface Roughness. [9]

S. Ally, J. K. Spelt, M. Papini had investigation on Surface evolution models have been used in the past to accurately predict the cross-sectional profile of micro-channels resulting from the abrasive jet micro-machining (AJM) of glass and polymeric substrates. In the present paper, the models are suitably modified and applied for the first time to the AJM of metallic substrates. The dependence of erosion rate on abrasive jet inclination angle was measured for aluminum 6061-T6, Ti–6Al–4V alloy, and 316L stainless steel using 50 mm Al2O3 abrasive powder launched at an average velocity of 106 m/s. For all three systems the peak erosion rate was found to occur when the jet was inclined between 201 and 351 relative to the surface. The AJM etch rate was found to be much lower than that found in glass and polymers, and it was found that a significant amount of particle embedding occurred in the 316L stainless steel. When the erosion data were used in an AJM surface evolution model, the resulting predicted cross-sectional profiles of unmasked and masked channels were in reasonable agreement with the measured profiles up to an aspect ratio (channel depth/width) of 1.25. The results demonstrate that surface evolution during the abrasive jet micro-machining of metals can be predicted using existing models, originally developed for glass and polymers. The angular dependencies of the erosion of aluminum 6061-T6, 316L stainless steel and Ti–6Al–4V were measured by machining channels usinganabrasivejetof50 mm aluminum oxide powder. As expected for ductile materials, the maximum erosion rate occurred betweenimpactanglesof201–301. In the case of the symmetric channels, the predicted profiles matched them ensured cross- section shape accurately. In the case of the

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asymmetric channels, the use of an angular coordinate transformation to fit the first or third-pass profile produced reasonable agreement in both the shape and depth, with a maximum error in the center depth of approximately 4%atanaspectratioapproaching0.1.Thesurface evolution model was also applied to masked channels for aluminum 6061T6,316LstainlesssteelandTi–6Al–4Valloyat901. The center-line depths were quite accurately predicted up to an aspect ratioofapproximately1.25, with a small discrepancies caused by a first order erosive efficacy approximation. [10]

Gokhan Aydin, Izzet Karakurt and Kerim Aydiner had an investigation on surface roughness of granite machined by abrasive water jet. In the experiments, pre-dimensioned granite specimens of 30 mm thickness, 200 mm length and 100 mm width were cut by a KMT international water jet Cutting. Design of experiments (DOE) is the process of planning the experiments considering the process parameters at different levels. Experimental design using Taguchi's method provides a simple, efficient and systematic approach for an optimal design of experiments to assess the performance, quality and cost. An increase in abrasive flow rate means a proportional increase in the cut depth. When the abrasive flow rate is increased, the cut surface becomes smoother and low surface rough nesses are expected due to the more number of impacts and cutting edges available per unit area.The water pressure and the abrasive flow rate were statistically found to be the most significant factor influencing the surface roughness of the granites, followed by the traverse speed and the stand-off distance with respect to the granite.The grain size of the granites and boundaries between grains play an important role in abrasive water jet cutting for surface roughness. [11]

FarhadKolahan, A. Hamid Khajavi have worked on Modeling and Optimization of Abrasive Water Jet Parameter using Regression Analysis.To model the process a set of experimental data has been used to evaluate the effects of various parameter settings in cutting 6063-T6 aluminum alloy.The process variables considered here include nozzle diameter, jet traverse rate, jet pressure and abrasive flow rate. Depth of cut, as one of the most important output characteristics. The Taguchi method and regression modeling are used in order to establish the relationships between input and output parameters. The adequacy of the model is evaluated using analysis of variance (ANOVA) technique the response surface for h in terms of water pressure and focusing nozzle diameter. From this figure it can be observed that h increases with an increase in water pressure. However, the increasing the diameter of focusing nozzle would increase the depth of cut until 1.2 and then has a reverse effect on h since behind this diameter the cutting energy would decrease. Response surface of h versus jet traverse rate and abrasive flow rate. High jet traverse rate and abrasive flow rate combination leads to high h. Similarly, it can be observed that high h is obtained at high water pressure and high jet traverse rate combination. High values of water pressure and jet traverse rate lead to an efficient cutting energy which improves the h.Statistical regression analysis have been employed to develop mathematical models relating such process parameters as water pressure, jet traverse rate, abrasive flow rate and diameter of focusing nozzle to the depth of cut. A set of experimental data, based on Taguchi method, has been used for model development. Various functions were fitted on the data among which the second order model was found to be the best one to represent relationship between input process parameters and depth of cut. The adequacy of the proposed model was then investigated using ANOVA technique. The results of ANOVA indicate that the proposed model has very good conformability to the real process. Computational results have proven that the proposed SA method can efficiently and accurately determine cutting parameters so as a desired depth of cut is obtained. [12]

Izzet Karakurt, Gokhan Aydin and Kerim Aydiner had investigation onAbrasive water jet (AWJ) cutting is one of the fastest growing machining processes which can machine almost any engineering material. However, the cutting capability of AWJ in terms of kerf quality is one of the major obstructions limiting its applications. Kerf angle, an important cutting performance measure, is a special geometrical feature inherent to AWJ machining and its high values are undesirable. It reflects the inclination of the kerf wall from the top surface to the bottom of the kerf. In this study, effects of process parameters and the material properties (i.e. textural properties) of the granites on the kerf angle are experimentally investigated. The design philosophy of Taguchi was followed to conduct experiments. Analysis of variance (ANOVA) was used to evaluate data obtained to determine the major significant process factors statistically affecting the kerf angle of the granites. The results revealed that the grains and their boundaries, the uniaxial compressive strength as well as the mineral compositions (especially feldspar and quartz) play the most important role for the kerf angles in the granites as material properties. Additionally, the most significant process factors influencing the kerf angle of the granites are statistically determined as the traverse speed, and the standoff distance. In general, it can be disclosed that increasing of the traverse speed, the standoff distance and the water pressure increased the kerf angle of granites, while an increase in the abrasive flow rate did not have discernible effect on the kerf angle of the granites. On the other hand, fine-grained abrasives led to obtain higher kerf angles in all granites tested. [13]

M.A. Azmira, A.K. Ahsanbat al investigation on Surface roughness (Ra) and kerf taper ratio (TR) characteristics of an abrasive water jet machined surfaces of glass/epoxy composite laminate. Taguchi's design of experiments and analysis of variance were used to determine the effect of machining parameters on Ra and TR. It was found that higher hardness of abrasive material which was aluminium oxide gave better surface finish compared to lower hardness of abrasive material such as garnet.Consequently, the surface of cuts became smoother. In case of hydraulic pressure, a

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higher hydraulic pressure increases the kinetic energy of the abrasive particles and enhances their capability for material removal. As a result, the surface roughness decreases.It is desirable to have a lower standoff distance which may produce a smoother surface due to increased kinetic energy. However, the roughness increases with an increase in abrasive mass flow rate up to a certain limit and beyond that limit it was found to decrease. In this case, a lower traverse rate is desirable to produce a better surface finish. Consequently, the kerf taper ratio calculated as the ratio of top to the bottom width is reduced with further increase of supply hydraulic pressure due to the more rapidly increasing of top kerf width compared to the bottom kerf width.The kerf taper ratio increases with the increase in standoff distance. Increase in abrasive mass flow rate consequently the kerf taper ratio is approaching to 1 as the penetration capability increases. The effect of traverse rate on the kerf taper was also found to be similar to that observed on the surface roughness. Increasing the kinetic energy of abrasive water jet machining (AWJM) process may produce a better quality of cuts. [14]

M. A. Azmir and A. K. Ahsana and A. Rahmah had investigation on Effect of abrasive water jet machining parameters on aramid fiber reinforced plastics composite. This paper presents a study on the effect of abrasive water jet machining (AWJM) process parameters on surface roughness (Ra) and kerf taper ratio (TR) of aramid fiber reinforced plastics (AFRP) composite. Taguchi's design of experiment was used as the experimental approach. Through analysis of variance (ANOVA), it was found that the traverse rate was considered to be the most significant factor in both Ra and TR quality criteria. Ra and TR were reduced as increasing the hydraulic pressure and reducing the standoff distance and traverse rate. However, there was no clear pattern for abrasive mass flow rate on both Ra and TR. Therefore, it was confirmed that increasing the kinetic energy of water jet may produce a better quality of cuts. Mathematical models were also developed using multiple linear regression analysis to predict the performance of Ra and TR in terms of AWJM process parameters. [15]

L.M. Hlava, I.M. Hlavacat have investigation on the declination angle for a prediction and control of the abrasive water jet cutting quality. The presented results of tests are promising for a development of the software for prediction and control of the cutting parameters and quality. The up-to-date correspondence with the previous work results in the assignment of the maximum values of the declination angles to the five zones of quality on the kerf walls. The maximum angles allocated for the first four quality zones were assigned as 4◦, 10◦, 18◦ and 32◦ respectively. The declination angle between the tangent to the striation and the impinging abrasive water jet axis was measured and used for the calculation of the required values of the material thickness, the traverse speed or the tilting angle of the cutting head. The procedure of the experimental determination of the declination angle was presented and the experimental data were used for the prediction of cutting variables—the thickness of material cut for a selected traverse speed or the traverse speed for the required material thickness. The power of the model was demonstrated in comparison with experimental results and it was proved that it is usable for the calculation of the cutting head tilting respective to the traverse speeds and their changes. [16]

D.K. Shanmugam, J. Wang, H. Liu has carried out work on minimization of kerf tapers in abrasive water jet machining of alumina ceramics using a compensation technique. In this study, an experimental investigation is carried out to minimize or eliminate the kerf taper in AWJ cutting of alumina ceramics by using a kerf-taper compensation technique. Among the cutting parameters studied, kerf-taper compensation angle is found to have the most significant effect on the kerf taper and the kerf taper angle varies almost linearly with this compensation angle. It shows that with this technique, it is possible to achieve a zero kerf taper angle without compromising the nozzle traverse speed or cutting rate. Depending on the other cutting parameters considered in this study, it is found that a kerf-taper compensation angle in the range of 4–51 can minimize the kerf taper angle to around zero. There are five major process parameter which include water pressure, standoff distance and jet traverse speed, each at four levels, abrasive mass flow rate at three levels, and kerf taper compensation angle at six levels. So getting a two typical kerf profiles for cutting with a normal cutting and a 51 kerf-taper compensation angle, respectively. It shows that the overall profile produced by cutting with a kerf-taper compensation angle is similar to that by normal cutting, i.e. the kerfs are typified by a wider entrance on the top and the width decreases downwards, so that a kerf taper is formed. It has been shown that the kerf-taper compensation angle is the most significant parameter affecting the kerf taper. The kerf taper angle on the compensated kerf wall decreases almost linearly with an increase in the kerf-taper compensation angle, but increases on other kerf wall. Similarly, an increase in water pressure and abrasive mass flow rate results in a decrease in the kerf taper angle, while a reverse trend applies for nozzle traverse speed and standoff distance. [17]

A.A. Khan, M.M. Hague had worked on Performance of different types of abrasive materials like garnet, aluminum oxide and silicon carbide during abrasive water jet machining of glass. They have used varying parameter as Abrasive flow rate (gm/min), work feed rate (mm/min), SOD (mm) and analyze for Taper of cut and average width of cut with different abrasive materials. The taper of cut increases with SOD with abrasive materials like garnet, aluminum oxide and silicon carbide. As SOD is increased, the jet focus area also increases resulting increase in the width of cut. The relationship between work feed rate and taper of cut during AWJM using different abrasive materials the average width of cut increases with increase in SOD which is due to the divergence shape of the jet. It was found that SiC produced the widest slot followed by Al2O3 and garnet. Average

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width of cut decreases with increase in work feed rate since with increase in feed rate the work is exposed to the jet for a shorter period. It was found that in all the cases the average width of cut produced by SiC was higher than those produced by Al2O3 and garnet abrasives. As a result they found that taper of cut increases with increase in SOD. Garnet abrasives produce a larger taper of cut followed by Al2O3 and SiC. Taper of cut increases with increase in work feed rate. SiC is harder than Al2O3 and garnet. As a result, its cutting ability is also higher than that of Al2O3 and garnet. Therefore, the average width of cut produced by SiC is higher than those produced by Al2O3 and garnet. [18]

Manabu Wakuda, Yukihiko Yamauchi, Shuzo Kanzaki had work on material response to particle impact during abrasive jet of alumina ceramic. Than to identify the material response of alumina ceramics to the abrasive particle impact in the AJM process. Three kinds of commercial abrasive particles were utilized to dimple the sintered alumina samples, and it was found that the material response to particle impact depends drastically on the employed abrasives. The employed cutting media were aluminum oxide (WA) and silicon carbide (GC), which are the most common abrasives in the application of the AJM process. In addition, synthetic diamond (SD) was also utilized to investigate the effect of the abrasive hardness on the material response. And the work piece materials tested were four kinds of alumina ceramics. Which should be #1 to #4? Material removal rates for various machining sets were calculated using the measured values of the removed volume and the result is shown in Fig. High repeatability was obtained for all the machining sets with less than 5% deviation from the mean value of the material removal rate shown in the figure. In the case of both WA and GC, differences in mechanical properties among the tested alumina samples, such as hardness and fracture toughness, did not strongly affect the material removal rate. The machinability was rather dominated by the employed abrasive, although in the case of SD, there was a significant difference in MRR between samples. The material removal rate achieved with WA abrasive was less than 5% of that for SD, and that with GC at most 10%. SD The use of SD abrasive is a possible choice if high machining efficiency is desired. [19]

E. Badisch, C. Mittererhad worked on high speed steels: Influence of abrasive particles and primary carbides on wear resistance on Abrasive Jet Machining. Three different abrasives, SiC, Al2O3 and ZrO2 were used. Wear mechanisms were investigated by scanning electron microscopy (SEM). A good correlation between the hardness of the abrasives and the abrasive wear coefficient was found. Higher abrasive wear resistance was determined for steels containing coarser primary carbides compared to those without or with smaller carbides.The ball cratering method has been used to determine the abrasive wear resistance of the different high speed steels investigated. Target material is 100Cr6 steel sphere is rotating against a high speed steel sample (Ø 30 × 10 mm) in the presence of an aqueous suspension of abrasive particles. The abrasive wear coefficient K is derived from the increasing wear volume V depending on sliding distance S and normal force FN during the testing process using Eq. (1) , and (2).

$$K = \frac{V}{F_N S} \quad \text{(1)}$$

$$V = \frac{\pi d^4}{64R} \quad \text{(2)}$$

The microstructure of the three different high speed steels investigated in this study, which is an HS10-2-5-8 type. The abrasive wear coefficients obtained for the three different high speed steels tested with SiC, Al2O3 and ZrO2 abrasives, respectively. The highest wear coefficient of 1.45 × 10 – 12 m2/N was measured for steel 1, tested against SiC. The small increase in wear resistance of steel 2 compared to steel 1 is in good agreement to the coarse primary carbides in steel 2. Finally, it can be concluded that the ball cratering test can only be used to compare composite materials of different abrasion resistance when the abrasive medium is properly chosen with respect to the mechanical properties of the individual phases. [20]

R. Balasubramaniam, J. Krishnan, N. Ramakrishnan had worked on the shape of surface generation by abrasive jet machining, debarring, which includes the edge conditioning/shaping, offers a potential application area for AJM. They did derive the equation of semi-empirical in order to obtain the shape of surface which is generated in AJM. With the help of this equation, it is shown that the abrasive jet machined surface is reverse bell mouthed in shape with an edge radius at the entry side of the target surface The experimental work carried out by the authors on Plaster-of-Paris specimens to study the effect of various abrasive jet input parameters on the size of the edge radius generated and on the entry side diameter indicated that the parameter stand-off-distance significantly affects the size of the edge radius generated; the parameters stand-off-distance and the nozzle diameter significantly affects the percentage variation in the entry side diameter The maximum MRR for brittle and ductile materials are obtained at different impingement angles. For brittle materials, normal impingement results maximum MRR and for ductile materials, an impingement angle of 15˚-20˚ results in maximum MRR. As the abrasive grit size and mixing ratio increase, the MRR and penetration rate increase but the surface finish value which is measured in Ra decreases. The shape of the profiles obtained with this analysis and the actual profile obtained with AJM are compared qualitatively. This relationship is obtained based on analysis carried out on the abrasive particles using the 'Malvern make Master Sizer Laser Particle Analyer' as per analysis to obtain the shape of the surface generated by abrasive jet gives reverse bell mouthed shape and it matches with e experimental result.as particle size increase, the MRR at the center line of the jet drastically increase; but the increase in the MRR nearer to the periphery is very less. As the standoff distance increase, the entry side edge radius also increase. Increasing standoff distance also increases the MRR. [21]

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M. Wakuda, Y. Yamauchi, S. Kanzaki had investigation on the machinability during the AJM process is compared to that given by the established models of solid particle erosion, in which the material removal is assumed to originate in the ideal crack formation system. When a brittle material is loaded by a sharp indenter, a plastic zone is formed beneath the indent, and a radial crack may propagate downwards from the base of the zone at a threshold load. The target materials used in the test were four kinds of well-known engineering ceramics, ZrO2, Si3N4, Al2O3, and SiC. In order to measure the removed volume by AJM, a laser scanning microscope (OLS-1100, Olympus Co. Ltd., Japan) was employed. The instrument was capable of analyzing geometrical characteristics over a small area ranging from 0.1 to 1 mm. Abrasive Jet Machine was performed on four ceramic materials using three different abrasives under constant machining conditions. When WA abrasive was used for the hard ceramics such as Al2O3 and SiC in particular, slight surface roughening occurred, but no dimpling. For the other combinations of abrasive and work piece, smooth dimples with an inverted dome shape could be generated, and few obvious defects such as cracks and chipping were observed on the newborn faces. The fracture toughness and hardness are critical parameter affecting the target material removal rate in AJM. [22]

YukihikoYamauchi, and Shuzo Kanzaki had worked on Alumina ceramics material to finding a surface finishing by Abrasive jet machining. Producing the desired dimensions and surface finish of ceramic components is most commonly conducted by grinding with a diamond wheel. However, diamond grinding tools often produce unreliable and uneconomical machining results. Abrasive jet machining (AJM) as a new method for the finishing of ceramic components. The technique is a specialized form of shot blasting, featuring the use of fine, hard abrasive particles at an extremely high velocity. The material removal during AJM is identified as erosive wear, resulting from the propagation and intersection of cracks produced by impacting particles. The surface of the samples following both the grinding and AJM processes. For the ground sample, grain boundary cracking, or interanular fracture, was the predominant material removal behavior. Results of the residual stress measurements at the sample surfaces.Where positive and negative values indicate tensile and compressive stresses respectively. The material removal behavior and mechanical properties were assessed and compared with conventional finishing methods. Processing of the ceramic by AJM resulted in significant improvements in surface finish and strength improvements of 15% over ground and lapped samples, as a consequence of an induced surface compressive stress. It was verified that AJM has a high potential for the surface finishing of brittle ceramic materials. [23]

Jun Wang had an experimental investigation of the machinability and kerf characteristics of polymer matrix composite sheets under abrasive water jets is presented. It shows that this unique 'cold' cutting technology is a viable and effective alternative for polymer matrix composite processing, with good productivity and kerf quality. Plausible trends of kerf quality with respect to the input parameters are discussed, from which recommendations are made for process control and optimization. Kerf geometry is a characteristic of major interest in abrasive water jet cutting. Increasing the traverse speed reduces the kerf widths but increases the surface roughness and striations. In addition, the traverse speed is directly proportional to the productivity and should be selected as high as possible, unless the surface roughness is a primary concern. By contrast, an increase in the water pressure will yield increased kerf width, kerf taper and cut surface roughness (and striations). However, a greater water pressure will allow a greater traverse speed to be used for through-cuts. [24]

III. FUTURE DIRECTION OF AWJM RESEARCH

The AWJM process is a suitable machining option in meeting the demands of today's modern applications. The AWJM of the modern composite, glass and advanced ceramic materials, which is showing a growing trend in many engineering applications, has also been experimented. It has replaced the conventional means of machining hard and difficult to cut material, namely the ultrasonic machining, laser beam machining and electro discharge machining, which are not only slow to machining but damage the surface integrity of the material. In addition, the AWJM process has sought the benefits of combining with other material removal methods to further expand its applications and improve the machining characteristics. The optimization of process variables is a major area of research in AWJM.

Researchers have excluded many important factors such as nozzle size and orifice diameter during study which otherwise would affect the performance characteristics differently. Most of the literature available in this area shows that researchers have concentrated on a single quality characteristic as objective during optimization of AWJM. Optimum value of process parameters for one quality characteristic may deteriorate other quality characteristics and hence the overall quality. No literature is available on multi-objective optimization of AWJM process and present authors found it as the main direction of future research. Also, various experimental tools used for optimization (such as Taguchi method and RSM) can be integrated together to incorporate the advantages of both simultaneously. No literature available so far for multi response optimization of process variables and more work is required to be done in this area.

Several monitoring and control algorithms based on the explicit mathematical models, expert's knowledge or intelligent systems have been reported to reduce the inaccuracy caused by the variation in orifice and focusing tube bore.

Very little literature available so far shows the standoff distance at the optimal value during the AWJ cutting process using the generated sound monitoring and not for any other

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parameters. So, more work is required to be done in this area.

IV. CONCLUSIONS

1. It was shown that AWJM process is receiving more and more attention in the machining areas particularly for the processing of difficult-to-cut materials**.**
2. AWJM is also suitable for precise machining such as polishing, drilling, turning and milling. The AWJM process has sought the benefits of combining with other material removal methods to further expand its applications.
3. Very little literature available so far shows the standoff distance at the optimal value during the AWJ cutting process by monitoring and control.
4. In most of research work, mainly traverse speed, water jet pressure, standoff distance, abrasive grit size and abrasive flow rate have been taken into account. Very little work has been reported on effect of nozzle size and orifice diameter.
5. Most of the research on optimization work has been carried out on process parameters for improvement of a single quality characteristic such as depth of cut, surface roughness, material removal rate, kerf geometry and nozzle wear. There is no any research paper found based on the optimization for the power consumption, dimension accuracy and multi-objective optimization of AWJM process. So, this area is still open for future research work.

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