Review Article

ABRASIVE JET MACHINING- RESEARCH REVIEW

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ABSTRACT
Abrasive jet machining is an effective machining process for processing a variety of Hard and Brittle Material. And has various distinct advantages over the other non-traditional cutting technologies, such as, high machining versatility, minimum stresses on the work piece, high flexibility no thermal distortion, and small cutting forces. This paper presents an extensive review of the current state of research and development tin the abrasive jet machining process. Further challenges and scope of future development in abrasive jet machining are also projected. This review paper will help researchers, manufacturers and policy makers widely.
KEY WORDS:versatility, flexibility, nontraditional.

INTRODUCTION

Abrasive jet machining (AJM) is a processing non-traditional machine which operates materials without producing shock and heat. AJM is applied for many purposes like drilling, cutting, cleaning, and etching operation. In Abrasive jet machining abrasive particles are made to impinge on the work material at high velocity. A jet of abrasive particles is carried by carrier gas or air. The high velocity stream of abrasives is generated by converting the pressure energy of carrier gas or air to its Kinetic energy and hence the high velocity jet. Nozzles direct abrasive jet in a controlled manner onto work material. The high velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material. Machining, Drilling, Surface Finishing are the Major Processes that can be performed efficiently. The process parameters are used like variables which effect metal removal. They are carrier gas, abrasive, and velocity of abrasive, work material, and nozzle tip distance (NTD). Abrasive jet cutting is used in the cutting of materials as diverse as: Titanium, Brass, Aluminum, Stone, Any Steel, Glass, Composites etc.

BACKGROUND

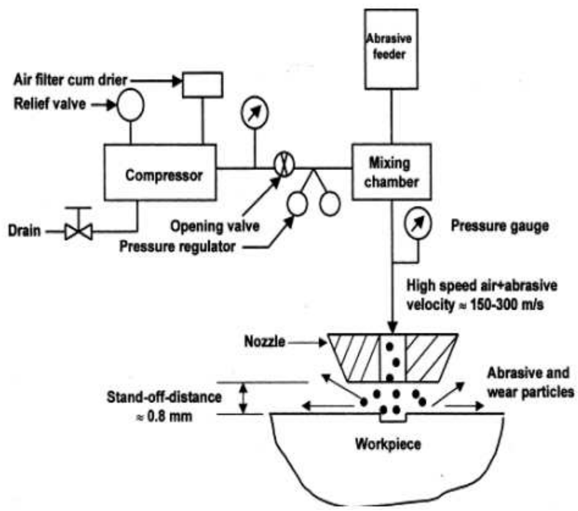


Fig 1: Schematic Diagram of AJM

This novel technology was first initiated by Franz to cut laminated paper tubes in 1968 and was first introduced as a commercial system in 1983... In the 1980s garnet abrasive was added to the water stream and the abrasive jet was born. In the early 1990s, water jet pioneer Dr. John Olsen began to explore the concept of abrasive jet cutting as a practical alternative for traditional machine shops. His end goal was to develop a system that could eliminate the noise, dust and expertise demanded by abrasive jets at that time. In the last two decades, an extensive deal of research and development in AJM is conducted.

Based on the extensive literature review of AJM Process the works on this can be classified based on the performance measure considered in to Four different categories, namely Experimental Modeling, Analytical modeling, Optimization modeling, Hybrid modeling.

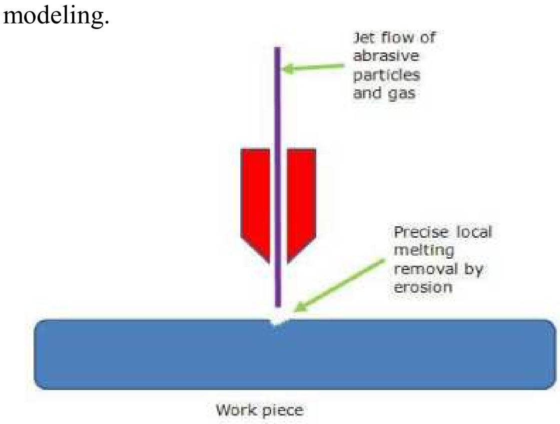


Fig 2: Metal Removal by Erosion

EXPERIMENTAL MODELLING

In this section the experimental analysis of Abrasive jet machining is discussed. The experimentations conducted by various researchers by influencing the abrasive jet machining (AJM) process parameters on material removal rate, Surface integrity, kerf are discussed. The parameters like SOD, Carrier gas, Air Pressure, Type of Abrasive, Size, Mixing Ratio etc. are focused. Various experimental models are highlighted.

Neema & Pandey (1977) proposed an equation for material removal rate by equating the kinetic energy of the particles impinging on to the work of deformation during indentation.

$$Q = k\,N\,d^3 v^{3/2} (\rho a_{/12\sigma y})$$

Where k is a constant; N is the number of abrasive particles taking quite a time; d= the size or diameter of an abrasive particle; fa= the density of the abrasive material; v= the velocity of the abrasive particle; and **σ** y, =the yield stress of the work material. [2].

Dr.A. K. Paul &P. K. Roy (1987) Carried out the effect of the carrier fluid (air) pressure on the MRR, AFR, and the material removal factor (MRF) have been investigated experimentally on an indigenous AJM set-up developed in the laboratory. Conducted Experimentation on the cutting of Porcelain with Sic abrasive particles at various Air pressures.Observed that MRR has increased with increase in grain size and increase in nozzle diameter. The dependence of MRR on standoff distance reveals that MRR increases with increase in SOD at a particular pressure. [4].

Varma & Lal (1984) explained about the effect of Nozzle Pressure on MRR and Effect of SOD on MRR for various Mixing ratios. The Variation in Pressure is clearly indicated with the help of graphs. [5].

Finnie (1960) showed that volume of Material (Q) eroded by impacting Particles of mass M carried in a stream of air can be calculated as

$$\mathbf{Q = Cf(\theta)\, M\, v^n,}$$

Where C& n are constants σ_s =Minimum flow stress of work material, θ is Impingement Angle. [6].

Sarkar & Pandey (1980) suggested a model to calculate MRR (Q) during AJM.

$$\mathbf{Q = x\, Zd^3 v^{3/2}\, (\rho/12H_{w)})^{3/4},}$$

Where Z is no of particles impacting per unit time, D is the mean diameter of Abrasive grain, P is the density, V is the velocity of abrasive particles, how is hardness of work material, X is a constant. [7].

Bhaskar Chandra Kandpal et al (2011) conducted Experimentation on machining of Glass and Ceramics with various types of Abrasives by changing pressure, nozzle tip distance on different thickness of glass plates and ceramic plates. The effect of process parameters of compared with theoretical results. The photos of the specimens Machined are shown below. [11].

Fig. 3- Samples of glass plate cut by AJM (11)

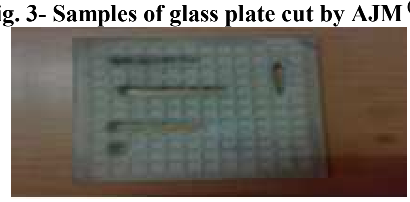


Fig. 4 - Samples of ceramic plate cut by AJM (11

El-Domiaty et al (2009) are conducted the experint on the drilling of Glass with AJM. The abrasive grits (sand) were mixed with an air stream ahead of the nozzle and the abrasive flow rate was kept constant throughout the machining process. [12].

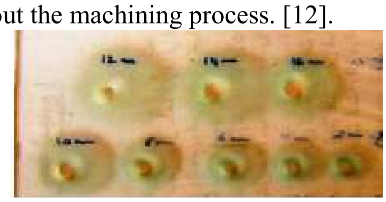


Fig 5 –Drilling of Glass at different SOD's [12]

Linden et al (2001) investigated abrasive machining characteristics of a glass-infiltrated alumina used for fabrication of all-ceramic dental crowns were investigated using a high-speed dental hand piece and diamond burs with different grit sizes. [14].

Bhaskar Chandra &Jag tarSingh (2011) carried out experimental studies to investigate the influence of process parameters like Nozzle Tip Distance, Mass flow rate, Gas pressure on Metal Removal Rate. [17].

H. Gateau et al (2007) measured the fundamental erosion rate of polymethylmethacrylate (PMMA) with a stream of 25um Al2O3 particles as a function of impact angle. The erosion rate was maximum at around 25◦ relative to the surface, suggesting a ductile erosion mechanism. [18].

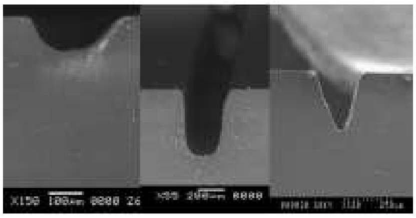


Fig 6 –Cross-sectional Profiles of Masked surfaces at different Passes [18]

Wakuda Manabu et al (2001) described an elementary approach to the characterization of fundamental AJM properties for silicon nitride. In dimpling of the Si3N4 surface, the material removed was identified by mild wear within the grain particles in a manner resembling ductile behavior. [20].

Ghobeity, H. Gateau et al (2007) Explained Poor repeatability of the erosion rate in a pressure feed AJM system was traced to uncontrolled variation in the abrasive particle mass flux caused by particle packing and local cavity formation in the reservoir. [21].

V. C. Venkatesh (1984) was Performed Parametric Studies on Abrasive Jet Machining and explained the effect of feed rate, pressure, abrasive grit size, spray angle, nozzle tip to work distance, and metal removal rate are reported. [23].

V. C. Venkatesh, T. N. Goh et al (1989) reported a study of the results of machining under various conditions. A commercial AJM machine was used, with nozzles of diameter ranging from 0.45 to 0.65 mm, the nozzle materials being either tungsten carbide or sapphire, both of which have high tool lives. Silicon carbide and aluminum oxide were the two abrasives used. The materials machined were glass, ceramics, and electro-discharge machined (EDM) dies steel. [24].

Manabu Wakuda, Yukihiko et al (2003) presented a paper attempts to identify the material response of alumina ceramics to the abrasive particle impact in the AJM process. They used three kinds of commercial abrasive particles to dimple the sintered alumina samples, aluminum oxide (WA), silicon carbide (GC) abrasive, and synthetic diamond (SD) abrasive. [25].

T Burzynski and M Papini (2011) The spatial distribution of particles within the jet was found by using a direct particle capture technique, and was found to depend on the nozzle diameter, following either a Weibull or a piecewise Weibull distribution [27].

D.S. Robinson Smart (2011) designed and fabricated a set up in order to investigate the effect of Standoff Distance (SOD), horizontal and vertical angle between the work piece and abrasive jet nozzle and the exit diameter of abrasive jet nozzle on coating removal rate. [28].

Shanmugam and Masood (2009) presented an investigation on the kerf taper angle generated by abrasive water jet (AWJ) technique to machine two types of composites: epoxy pre-impregnated graphite woven fabric and glass epoxy. Comprehensive factorial design of experiments was carried out in varying the traverse speed, abrasive flow rate, standoff distance and water pressure. [30].

Shanmugam et al. (2008) An experimental investigation was carried out by tominimize or eliminate the kerf taper in AWJC of alumina ceramics by using a kerf-taper compensation technique. [31].

A. Ghobeity et al (2008) presented model predictions and experimental data related to the abrasive jet micromachining of masked and unmasked channels in glass. The spatial and velocity distributions of particles in the jet of an abrasive jet micromachining (AJM) setup were measured using a novel technique. [33].

R. H. M. Jafar et al (2013) presented experimental data on the effect of particle size, velocity, and angle of attack on the Surface roughness of unmasked channels machined in borosilicate glass using AJM. Single impact experiments were conducted to quantify the damage due to the individual alumina particles. Based on these observations, the assumed location of lateral crack initiation in a relatively simple analytical model from the literature was modified, and used to predict the roughness and erosion rate. [38].

Stephen Wan et al. (2010) present simple deterministic process models for the prediction of the evolution of the cross-sectional profile of the glass channels generated by erosive wear in micro air abrasive jet machining using a round nozzle. Experiments were carried out on soda lime and borosilicate glass to verify the process models. Predicted model results show fairly good agreement with experimental results. [51].

N. S. Pawar et al (2013) presented Experimental analysis of AJM with sea sand as abrasive material and considering Silicon Carbide, mild steel as nozzle material with a vibrating cylindrical mixing chamber. The experimentis conductedon glass sheet by varying the pressure &Sod. Graphs are plotted with variation in parameters. [57].

ANALYTICAL MODELLING

Analytical modelling of Abrasive jet machining involves the Study Investigations on Effect of different types of Process parameters on the performance measures. This study highlights different types of empirical equations, analysis of the areas like surface roughness, impingement angle, variation in MRR, kerf geometry, etc., in which the AJM process can be effectively applied.

Ingulli.C. N (1967) wasthe first Person Explained in detailed about Abrasive Jet Machining and Highlighted Varies parameters effect on Material Removal and Variation in MRR with change in Abrasive flow rate. [1].

Pandey, et al (1980) and Bhattacharya (1976) studied the effects of abrasive flow rate {AFR) and standoff distance on the material removal rate (MRR). They observed that MRR reaches an optimum value with the increase in AFR and SOD, and then falls with the increase in these parameters. [3].

R. Balasubramaniam et al (1999) Explained Deburring of cross-drilled holes by secondary erosion of an abrasive jet wasperformedand the parameters effect on drilling were identified. [8].

R. Balasubramaniam et al (2000) studied the generation of edge radius by using the abrasive jet external deburring... [9].

N. Jaganath et al (2012) combining abrasive and hot air to form an abrasive hot air jet. Abrasive hot air jet machining. The effect of air temperature on the material removal rate applied to the process of glass etching and grooving is discussed in this article. The roughness of machined surface are also analyzed. It is found that the Material Removal Rate (MRR) increases as the temperature of carrier media (air) is increased [16].

Matthew W. Chastagner Explained about the edge with a consistent and precise shape is important for highly stressed mechanical components. This study investigates the generation, measurement, and definition of edges. Abrasive jet machining, a flexible process ideal for difficult-to-reach areas, is applied for edge generation. The SEM micrographs AJM and edges are established as shown in Figure [19].

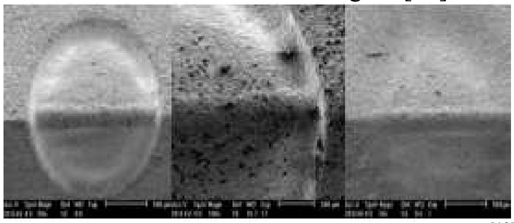


Fig 7- SEM micrographs AJM Region and edges [19]

Srinivasu et al. (2009) investigated the influence of key kinematic operating parameters (i.e. α-jet impingement angle and v-jet feed rate) on the kerf geometry and its dimensional characteristics. [29].

R. Balasubramaniam et al (2002) Studied on the shape of the surface generated by Abrasive jet machining. They developed a semi empirical equation to obtain the shape of Abrasive jet machined surfaces, Effect of Various AJM input parameters on the generation of shapes, deburred edge radius are focused... [32].T Burzynski etal (2010) Presented The time-dependent evolution of an abrasive jet micro-machined surface and described by a partial differential equation which is difficult to solve using traditional analytical or numerical techniques... [37].

R. H. M. Jafar et al (2013) presented experimental data on the effect of particle size, velocity, and angle of attack on the Surface roughness of unmasked channels machined in borosilicate glass using AJM. Single impact experiments were conducted to quantify the damage due to the individual alumina particles. Based on these observations, the assumed location of lateral crack initiation in a relatively simple analytical model from the literature was modified, and used to predict the roughness and erosion rate. [38].

Li et al (2008) investigated the process that combined grinding with abrasive jet finishing, the material removal rate (MRR) model in abrasive jet precision finishes with grinding wheel as restraint was investigated. The material removal rate model was found to give a good description of the experimental results. [41]

J. B. Byiringiro et al (2012) presented a novel fabrication technique of a photo-resist mask onto 3D curved wafer for micro-abrasive jet machining (AJM) process. In this study, the developed modelling algorithm for planar and non-planar mask models assisted in two ways.Design. Optimization and significantly reduces the time required for experimental investigations. [46].

P. M. Khodke et al. Discussed about the work samples eroded by AJM shows that, for brittle materials, material removal is due to an intersection and propagation of cracks produced by adjacent impacting particles on the target surface. An analytical model d based on the above observations for predicting the material removal in abrasive jet machining process. [49].

Slikkerveer et al. [1999] proposed an analytical model to predict the evolving cross sectional profile of abrasive jet machined features. Their model relates the instantaneous surface slope to the local erosion rate through the normal component of the particle velocity vector. The model was developed in brittle materials and assumes, therefore, that only the surface-normal velocity component contributes to erosion [52].

OPTIMIATION MODELING

Modelling is a tool that is more capable of Explaining the effect of various process parameters on the efficiency of Abrasive Jet cutting process. In this review various authors are identified and established different Optimization models like Simulation models, Idea diagrams, Taguchi etc.

Alireza Moridi et al (2010) study presented on the micro-grooving of quartz crystals using an abrasive air jet. Predictive models are then developed for quantitatively estimating the machining performance. The models are finally verified by an experiment. [40].

R. Haj Mohammad Jafar et al (2013)A numerical model was developed to simulate the brittle erosion process leading to the creation of unmasked channels as a function of particle size, velocity, dose, impact angle and target material properties. Erosion was simulated using models of two damage mechanisms: The Experimental data are compared with the simulated model and Analyzed. [43].

Alina Oancea et al (2012) The study of the solutions corresponding to the sand blasting gun highlighted some possibilities to modify the nozzle and the subsystem for clamping the nozzle. An ideas diagram was used in order to identify some constructive solutions able to satisfy the formulated objectives. Different Versions of Ideas diagrams are established and compared by using tables. [45].

D Ciampini and M Papini (2010) A cellular automaton simulation for the prediction of the size and shape of masked features resulting from the abrasive jet micro-machining (AJM) of brittle targets was presented. The simulation allowed the prediction of complex phenomena such as mask under-etch, mask ricochet, spatial hindering and second-strike effects, which cannot be readily modelled using analytical techniques. [47].

A Ghobeity et al (2007) Models are presented to predict the shape and size of masked and unmasked holes machined in glass and polymethymethacrylate (PMMA) using abrasive jet micromachining (AJM). The modified model predicts whole profiles that agree well with both experiments and a computer simulation. [48]

Li, HZ (2012) presented an analysis of the AJM Process for brittle materials. The analysis is based on a fundamental erosion model of the solid particle impact for brittle materials, and a recently developed model for the particle velocity in micro-abrasive jet, to form a mathematical basis for AJM process modelling and optimization. [50]

Jiuan-Hung Ke et al (2012) presented a novel hybrid method that self-made magnetic, abrasive with elasticity was utilized to investigate machining characteristics in abrasive jet machining. They Experimented with Magnetic abrasives and used Taguchi method and analyzed that flexible magnetic abrasive is adopted in abrasive jet machining. [53].

Chang He Li et al (2006) In this Paper the Metal Removal Model is investigated in abrasive jet precision finishing (AJPF) with the wheel as restraint. In the study, the material removal rate model was established according to machining mechanisms and machining modes from two-body to three-body process transition condition, and active number of particles in grinding zone were calculated and simulated. [54].

R. Balasubramaniam et al (1998) experimental investigation has been conducted to identify the abrasive jet deburring process parameters and the edge quality of abrasive jet deburred components. Result of the edge quality measurements supplemented with the visual inspection were analyzed by the ANOVA method of Taguchi is used to designate deburring quality by employing the software STATGRAPHICS. [55].

U. D. Gulhane et al (2013)Conducted experiments and Analyzed the influence of process parameters on MRR and Kerf width.The results of experiments are Analyzed by Taguchi, Characterized the influence of Factors on MRR and Kerf by Analysis of Variance (ANOVA) [56].

Fig-8-drilling of ceramic tile at diff pressure, sod, nozzle dia [56]

HYDRID MODELLING

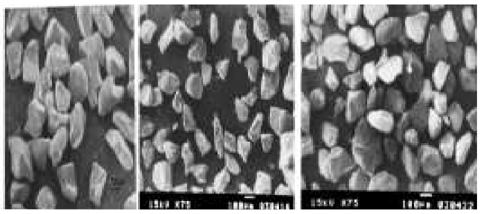
In this section of the review the combination of unconventional machining processes like ECM, EDM with AJM, Recycling of Abrasive particles, micro grooving, masking etc. are discussed.

V. K. Jain et al (2002) combined the performances of AJM and ECM, termed a name ECSAD. Experiments have been conducted using abrasive cutting tools, with a view to enhance the capabilities of the process. [13].

V. S. Rajashekhar et al (2012) presented a paper on reusing the Discarded Abrasive Particles from Abrasive Water Jet Machining for Drilling Holes in Glass Sheet by Abrasive Jet Machining. The abrasive grains used in AWJM are reused and tested with AJM for drilling Glass. The process of Recycling can perform in two cases at Nozzle entry, exit and after cutting in three recycling stages. [15].

Alireza Moridi et al (2010) presented a study on the micro-grooving of quartz crystals using an abrasive air jet. The effect of the various process on the major machining performance measures are analyzed to provide a deep understanding of this micro-machining process. Predictive models are then developed for quantitatively estimating the machining performance. The models are finally verified by an experiment. [22].

M. Kantha Babu, O.V. Krishnaiah Chetty (2003) Discussed about the Recycling of Abrasive Particles with different sizes. Recycling leads to further disintegration. The role of fine abrasives in reduction of cutting is well established. Hence recycling leads to the decreased depth of cut. [26].



(a) Fresh Abrasives (b) Abrasives (After Cut) (c) Recycled Abrasives

Fig 9-SEM Photographs of Abrasives (Garnet) [26]

Y.L.HOU et al (2009) Experiments were performed with plane grinder M7120 and workpiece material 40Cr steel which was ground with the surface roughness mean values of Ra=0. 6µm. [34].

T Burzynski et al (2012) Explained that this model permits the prediction of the surface evolution of both the mask and the target simultaneously, by representing them as a hybrid and continuous mask–target surface. [35].

J-H Keet al (2011) studies on fabrication of a new composite, abrasive by replacing the regular Abrasive particles like sic, Al_20_3 can achieve better machining and improved surface roughness on hard brittle materials. Application of the new composite abrasive to AJM achieves enhancement in surface roughness. [36].

Yan-Cherng LIN et al (2012) Explained about the combination of AJM and EDM as Hybrid machining. Studied about A novel hybrid process combined material removal mechanisms of AJM and EDM was developed initially, and then a series of experiments were performed to determine the effects of the machining parameters on the machining characteristics for machining SKD 61 steels. [42].

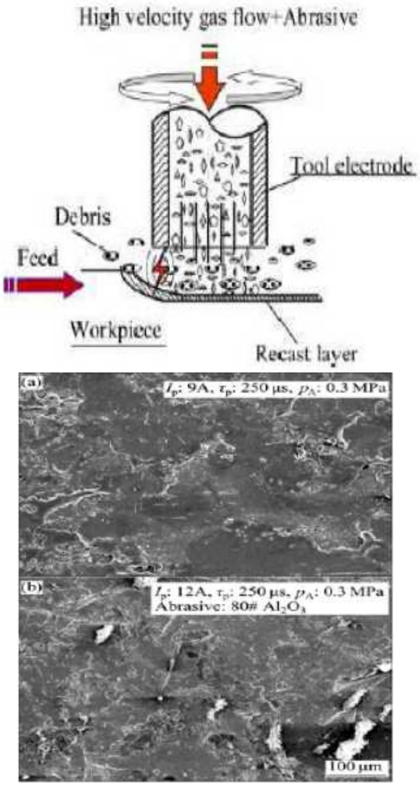


Fig10--Details of Actions in Hybrid process of AJM, EDM& Surface Integrity [42]

Dong-Sam Park et al (2004) Established a Paper on Micro grooving of Glass using Ajm.In the Micro grooving process the Material undergoes into three processes 1) Masking 2) Abrasive Jet Machining 3) Mask removing and cleaning process. An optical microscope is used to investigate masking results and analyze machined shapes of the groove. Necessary images are captured and processed using a CCD camera and image processing board (DT3153, Data translation) installed in the PC. [44].

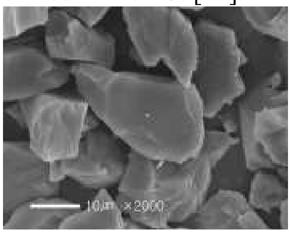


Fig-11-SEM Diagram of WA#800 abrasives (2000X) [44]

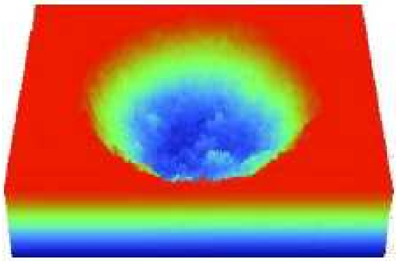


Fig-12-Hole- type groove formed after masking [44]

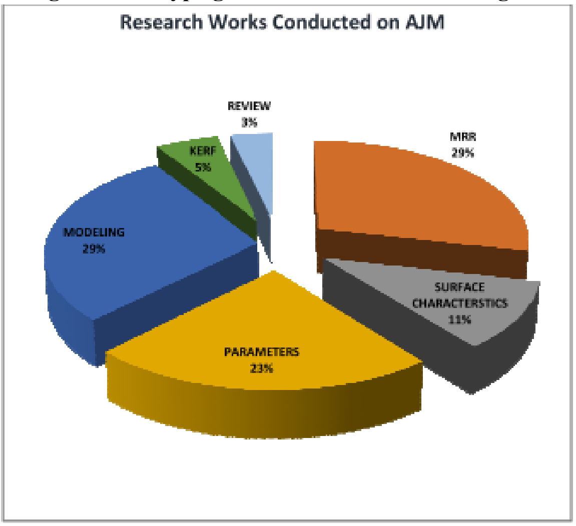


Fig 13: Pi-Chart indicates the areas of Researches performed on Abrasive jet machining.

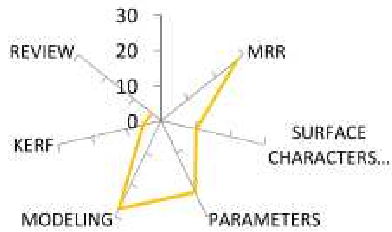


Fig 14: Radar-Chart indicates the areas of Researches performed on Abrasive jet machining.

CONCLUSION

An extensive review of the research and development in the AJM has been conducted in this paper. It was shown that AJM process is receiving more and more attention in the machining areas, particularly for the processing of difficult-to-cut materials. Its unique advantages over other conventional and un-conventional methods make it a new choice in the machining industry.

A brief review of the Experimental modelling was conducted in the fourth section of this paper. It was followed by the Analysis of various parameters on MRR, analytical modelling are reviewed in detail. The Optimization modelling, Hydride modelling are discussed later. While these investigations show a good understanding of the cutting performance and the associated science, most of the results are for particular cutting conditions and materials. The new technologies for modelling like Simulation, Taguchi approach, etc. are discussed. To enhance the cutting performance, number of new techniques have been explored. These models were developed using an AJM erosion mechanism, fracture mechanics and energy conversation approach. Most of these models are limited to particular cutting conditions and target materials. Also, they have a complex mathematical expression which is difficult for practical use. Some of them include unknown factors needed to be determined by other research. It is concluded that more experimental work is required to fully understand the relationship between important AJM parameters, namely Air pressure, nozzle size and shape, abrasive mass flow rates and process output in greater detail for aluminum, brass, cast iron, ceramics, copper, composites, granite, mild steel, stainless steel and titanium as the right choice of process parameters is very important for good cutting performance. As the Analyzing and modelling of effect of process parameters are not projected completely with complete optimization by advanced optimization techniques. Extended research works are required to study, experimentation and modelling of various parameters by advanced Analysis and Modelling techniques, the effect of parameters on AJM, Kerf characteristics. In order to correctly select the process parameters, reliable predictive mathematical models can be developed for the depth of cut in the AJM process of Various Metals.

There is much scope of research in the AJM which can be performed by changing the nozzle design, nozzle pressure, SOD, etc. and Comparing the effect of various parameters on MRR on various metals like composites, ceramics, by improving the Kerf Characteristics, Integration of AJM with CNC, Model comparison, etc. The Optimized models can be developed by using various optimization techniques, and also the surface characteristic measurements are yet to be performed.

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