Journal of Manufacturing Engineering, September 2014, Vol. 9, Issue. 3, pp 136-142

ABRASIVE WATER JET MACHINING OF COMPOSITES: A REVIEW

Dhanawade Ajit and *Kumar Shailendra

Department of Mechanical Engineering, S. V. National Institute of Technology, Surat, India.

ABSTRACT

Abrasive water jet machining (AWJM) is an emerging technology for material processing. Composite materials have gained prominent place in global manufacturing scenario. AWJM has demonstrated to be an interesting manufacturing process in the machining of composites because of its specific advantages. This paper presents a detailed literature review in the area of AWJM of composites. The available literature in the domain area is classified in three categories - cutting performance of AWJM, optimization of process parameters and modelling of AWJM process. Based on the literature review, future scope of research work in AWJM of composites is also identified.

Keywords: *Abrasive water jet machining (AWJM), Composites, Cutting performance, Optimization, Modelling.*

1. Introduction

Abrasive water jet machining (AWJM) is extensively used in various industrial applications such as cutting hard-to-cut materials, drilling and pocket milling in composite parts, cutting various materials in textile and leather industries etc. This technology is very useful for industrial applications because it has advantages such as less sensitive to material properties, no chatter, no thermal effects, minimal stresses on the work piece, high machining versatility and flexibility. Also AWJM generates surfaces of acceptable finish and of high integrity. Cutting and machining rate of AWJM is higher than conventional machining processes. In AWJM process (Fig.1) the unwanted material of work piece is removed by the combined action of high speed water and abrasive particles. The high speed jet of water transfers the kinetic energy to the abrasive particles and the mixture (water and abrasives) impinges on the workpiece material. The performance of AWJM process is dependent on erosion of material by pressurized water-abrasive mixture and mechanical properties of workpiece material along with various other process parameters [1]. It is one of the most environment-friendly material removal processes because it requires no cutting fluids and generates no fumes or harmful waste as compared to traditional machining and other non-traditional machining processes. Composites have gained prominent place in global manufacturing scenario especially where sophisticated products are required which have to be light and strong in order to withstand various loads in difficult environment. Composites have heterogeneous (non-homogeneous) nature and they consist of very strong fibres interwoven into comparatively softer matrix. Therefore, traditional machining processes are not suitable for machining of these materials. The main advantages of composites are their high strength and stiffness, combined with low density.

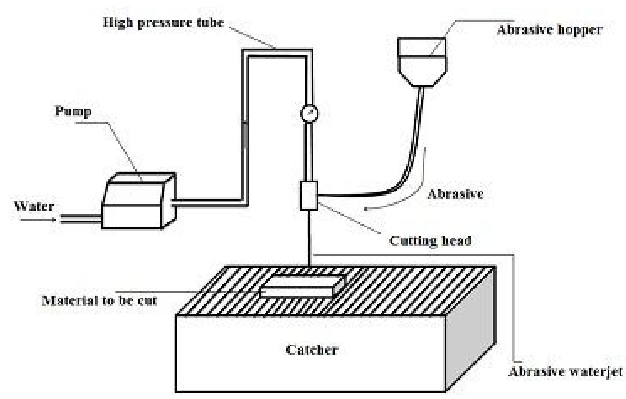

Fig. 1.Abrasive Water Jet Cutting Process [2]

Machinability of Fibre Reinforced Polymers (FRP) by conventional techniques is poor because of excessive tool wear, delamination, and excessive cutting forces and cutting temperatures. Better machinability in general is achieved by minimizing tool wear and delamination while maintaining high production rates. It is often very difficult in machining of composites by conventional means simply because of the fact that tool wear increases with an increase in cutting speed and feed rate (i.e. an increase in production rate). Applications of composites include aerospace, transportation, construction, marine goods, sporting goods, and more recently infrastructure, with

*Corresponding Author - E- mail: skbudhwar@med.svnit.ac.in

construction and transportation being the largest and hence AWJM technology has received considerable attention from these industries [3]. As far as AWJM of composites is concerned, the type of abrasives, hydraulic pressure, and traverse rate are more significant process parameters as compared to other process parameters such as stand-off distance, abrasive mass flow rate, and cutting orientation to achieve good surface finish. But in the cutting of composites especially laminated composites, delamination is major composite defect. While AWJM of composites, abrasive water jet (AWJ) creates shock wave impact on material because of which crack tips are generated in the workpiece material at initial cutting stage. Now the pressurized AWJ penetrates into the crack tips which tend to water-wedging and abrasive embedment [2].

Worldwide researchers have investigated in the domain of AWJM of composites. A detailed literature review in this area is described in next section of the paper.

2. Literature Review on AWJM of Composites

The efforts applied by worldwide researchers in the area of AWJM of composites are broadly classified into three categories - cutting performance of AWJM process, optimization of process parameters and modelling of AWJM process. Major research work in these categories is described as under.

2.1 Cutting Performance of AWJM process

Most of the researchers have investigated the cutting performance of AWJM of composites through cutting performance measures such as surface finish, kerf properties, material removal rate, etc. For example, Ramulu and Arola [4] carried out an experimental investigation to determine the influence of cutting parameters on the surface roughness and kerf taper of an abrasive water jet machined graphite/epoxy laminate. Arola and Ramulu [5] investigated kerf geometry, kerf wall features and cutting front characteristics of graphite epoxy laminates machined by abrasive water jet. But the major cutting performance measure i.e. material removal rate is not taken into consideration. The machining of continuous fibre-reinforced advanced ceramic composite materials was investigated by Ramulu et al. [6] to evaluate topology and morphology of machined surface. But in this work, evaluation of kerf characteristics was not considered. Komanduri [7] studied various issues involved in machining (conventional and nonconventional) of fiber-reinforced composites. An experimental investigation on AWJM for machinability and kerf characteristics of polymer matrix composite sheets was carried out by Wang [8]. But in this experimental work only major and easy to adjustable process parameters were considered which may lead to improper results. Zeng et al. [9] studied abrasive water jet technology as a precision metal cutting tool. The operating principles, equipment and control, physical parameters of the process, metal removal rate, dimensional control, corner radii, taper, surface finish, possible surface damage, as well as health, safety, and environmental issues were studied. Ramulu [10] studied the mechanism of AWJM of Advanced continuous fibre-reinforced ceramic composite for evaluation of cutting forces, surface microstructure, and retained tensile behaviours. An experimental work on cutting of glass fibre reinforced polymer composite materials with abrasive water jet cutting with head oscillation was carried out by Lemma et al. [11]. The whole study was concentrated on cutting head oscillation but finally the improvements in surface quality was found much higher with increase in the angle of oscillation than with increase in frequency of oscillation. Shanmugan et al. [12] have done the comparative study of jetting technologies and lesser machining techniques. The study was concentrated on machining of composite materials like epoxy graphite fabric and fibre reinforced plastic materials which are used in aerospace industries. Machining of composites was carried out with traditional machining but compared with jetting and laser technologies. Arola and Williams [13] examined influence of machined surface texture on the fatigue strength of a Graphite/Bismaleimide (Gr/Bmi) laminate. The investigation on the influence of hole quality on the mechanical behaviour of fibre reinforced laminates was performed by Arola and Mccain [14]. The work has limited applications and also researchers have used both conventional as well as non-conventional processes to machine the specimen. Wang and Liu [15] carried out experimental investigation on various cutting performance measures such as kerf taper and depth of cut in profile cutting of alumina ceramics by abrasive water jet. Azmir and Ahsan [16] conducted experimental investigation to assess the influence of AWJM process parameters on surface roughness of glass fibre reinforced epoxy composites using Taguchi's method and analysis of variance approach to optimize process parameters for effective machining. But the researchers have made their conclusions only on the basis of surface roughness achieved whereas some important measures such as material removal rate and kerf geometry properties were not considered. Prisco and D'Onofrio [17] carried out a computational fluid dynamics (CFD) simulation of the formation and discharge process of an air-water flow in an abrasive water jet head. The study on surface roughness and kerf taper ratio characteristics of an abrasive water jet machined glass/epoxy composite laminate was carried out by Azmir and Ahsan [18]. The effects of machining parameters on surface roughness and kerf taper ratio were investigated using Taguchi's design of experiments and analysis of variance. But the cutting performance is measured only on the basis of surface roughness achieved and kerf taper ratio generated. Rao et al. [19] studied the importance of the water jet cutting process for composite tooling, space structure fabrication and ceramic test coupon generation. Sadat [20] used ring-shaped test samples having outside and inside diameters of 65mm and 52.5 mm respectively of aluminum metal matrix composite material. George et al. [21] investigated the effect of various process parameters in AWJM of composite materials. Cenac et al. [22] adapted the experimental protocol of abrasive water jet milling of aluminum to composite materials. A comparative study of various processes for cutting cotton fibre polyester composite by maintaining unidirectional reinforcement was carried out by Sheikh and Jain [23]. Srinivas and Ramesh Babu [24] performed set of studies on aluminum-silicon carbide particulate metal matrix composites processed with abrasive water jet. But the range of process parameters varied in this experiment is very small. Patel and Shaikh [25] evaluated the performance of abrasive water jet cutting of cotton fibre reinforced plastics through investigation on the effect of jet impact angle on kerf characteristics. Alberdi et al. [26] studied the machining of two different composites each having different thicknesses to investigate the machinability index. Machining of composite material by water jet and abrasive water jet cutting processes was performed by Miron et al. [27] to measure cutting performance. In their work, only surface roughness is considered as measure of quality of product whereas some other measures such as kerf characteristics and material removal rate were not considered. Nedelcu et al. [28] carried out a concise analysis on composites' machining (conventional and non-conventional machining). Devadula and Nicolescu [29] studied various issues observed in AWJM of carbon and glass fibre skin based aluminum sandwich composite materials, and the limitations of AWJM in processing these exotic materials. The research work from the inception to the development of AWJM within the past decade is reviewed by Korat and Acharya [30].

2.2. Optimization of AWJM Process Parameters

For better performance of AWJM of composites, selection of proper process parameters is very necessary and therefore some researchers have optimized the process parameters of AWJM process. Geiger et al. [31] proposed a fuzzy-logic theory to build up a knowledge base for the water jet cutting of composite materials. For the necessary experiments composite material made of aluminium was used. They also developed an expert system according to the given design parameters. The expert system determines the optimal cutting speed for the desired cutting contour. Azmir et al. [32] carried out experimental investigation to assess the influence of AWJM process parameters on surface roughness and kerf taper ratio of aramid fibre reinforced plastics (AFRP) composite. They [33] also made an effort to optimize the AWJM process parameters with multiple performance characteristics based on the orthogonal array with the grey relational analysis. In this research work AWJM of Kevler composite laminate was performed. During machining, four process parameters namely hydraulic pressure, abrasive mass flow rate, stand-off distance and traverse rate were considered. Optimization of these four parameters with consideration of multiple performance characteristics was carried out. Shaikh and Ambardekar [34] investigated the effects of process parameters such as abrasive water pressure, stand-off distance and traverse rate on the depth of cut in abrasive water jet cutting of metal-polymer-metal laminate. Based on analysis of variance it was found that abrasive water jet pressure and traverse rate are most significant over stand-off distance. Later on, a predictive model was developed using regression analysis technique.

2.3. Modelling of AWJM Process

For the prediction of some of the important factors in AWJM of composites such as delamination, depth of jet penetration, kerf properties etc. some researchers have developed various models. For example, Cheng [35] developed an analytical approach to study the delamination during drilling by water jet piercing. This model predicts an optimal water jet pressure for no delamination as a function of hole depth and material parameters (opening-mode delamination fracture toughness and modulus of elasticity). Good agreement was achieved with data obtained from water jet drilling of graphite epoxy laminate. Wang [36] investigated the cutting performance and erosion process in AWJM of polymer matrix composites. A mathematical model was developed for the total depth of cut and verified together with empirical models for the other kerf geometrical features. Wang and Guo [37] developed a semi-empirical model for prediction of the depth of jet penetration in abrasive water jet cutting of polymer matrix composites. Deam et al. [38] proposed a model for predicting shape of cut profile in industrial cutting processes and applied to abrasive water jet cutting. Two versions of this model were developed.

The model predicts a constant radius of curvature for the cut profile but this is done with jet angle less than about 60^0. Orbanic and Junkar [39] carried out an experimental study of drilling small and deep holes with AWJM. Drilling tests on different materials were performed and hole depth and diameter at different machining times were observed. An empirical model for predicting hole depths and diameters at different drilling times was developed. Wang and Liu [40] developed predictive models for the important cutting performance measures, such as kerf taper, depth of cut for straight slit cutting and profile cutting by AWJM. Shanmugan et al. [41] carried out experimental investigation to explore the delamination mechanism in graphite/epoxy composites under AWJM. A semi-analytical model based on energy conservation to predict the maximum delamination length was developed. Ramulu et al. [42] assessed the machining characteristics in terms of delamination and hole defects. A systematic study of the parametric effects contributing to the surface quality and damage induced in cutting, drilling of CFRP and hybrid composites using water jet and abrasive water jet technologies was conducted.

3. Comments on Reviewed Literature

The work done by worldwide researchers in area of cutting performance, optimization and modelling of AWJM process of composites is summarized respectively in Table 1, 2 and 3. From last four decades, AWJM process is being used to machine and cut composites. Research over the last two decades in this area shows some improvement in the use of AWJM technique as a cutting tool for machining and cutting of composites. Most of the researchers have applied their efforts to investigate cutting performance of AWJM of composites through the cutting performance measures such as surface finish, kerf properties, material removal rate, etc. Researchers also worked and studied the effect of various process parameters on surface roughness, kerf properties and material removal rate. But very few researchers have applied efforts to investigate material removal rate in AWJM of composites. Even though AWJM is widely used in the machining of composites, very less work has been found on the optimization of AWJM process parameters for effective use of AWJM technique. Few researchers worked on optimization of process parameters. But they optimized few (one or two) process parameters of AWJM. It is also found that very less research efforts have been applied in modelling of AWJM of composites. Few researchers have successfully tried to develop predictive models for delamination, depth of jet penetration and depth of cut. Further, very less effort has been applied to investigate AWJM of carbon fibre and epoxy resin composites. Therefore, there is future scope of applying research efforts in these identified areas.

Table 1: Summary of Literature Review on Cutting Performance of AWJM of Composites

Researcher (s)	Investigation	Material	Scope of further work
Arola and Ramulu (1996)	Kerf geometry, kerf wall features and cutting front characteristics	Graphite epoxy laminates	Investigation on cutting performance through MRR
Ramulu et al. (1997)	surface characteristics	continuous fibre-reinforced advanced ceramic composite	Evaluation of kerf characteristics
Wang (1999)	Machinability and kerf characteristics	Polymer matrix composite	Investigation on all process parameters
Lemma et al. (2002)	Comparative study of the oscillation and normal (without oscillation) cutting	Glass fibre reinforced polymer composite	Investigation on cutting head oscillation with impact angle
Wang and Liu (2006)	Kerf taper and depth of cut	Alumina ceramics	Investigation on all process parameters
Azmir and Ahsan (2008)	Influence of process parameters on surface roughness	Glass fibre reinforced epoxy composites.	Investigation on MRR and kerf properties
Azmir and Ahsan (2009)	Surface roughness and kerf taper ratio characteristics	Glass/epoxy composite laminate	Consideration of MRR as cutting performance measure
Srinivasan et al. (2012)	Effects of cutting speed, feed and depth of cut on surface roughness, and cutting force	Homogenized Al metal matrix composite	Must include materials other than MMCs
Sheikh and Jain (2012)	Comparative study of various processes	Cotton fibre polyester composite	Other non-traditional processes should be considered for comparison

Srinivas and Ramesh Babu (2012)	Penetration ability	Aluminum-silicon carbide particulate metal matrix composites	Range of varied process parameters must be increased
Miron et al (2013)	Quality of the surfaces, delamination, dimensional accuracy	Fibre epoxy matrix	Kerf characteristics and MRR must be considered to measure cutting performance
Devadula and Nicolescu (2013)	Various issues observed in AWJ machining	Carbon- and glass-fibre skin based, aluminum sandwich structure composite	Process parameters must be varied instead of keeping constant

Table 2. Summary of Literature Review on Optimization of Process Parameters

Researcher(s)	Parameters optimized	Material	Scope of further work
Geiger et al. (2003)	Cutting speed	Light weight composites of aluminium	Parameters must be optimized for heavy composites also
Azmir et al. (2007)	Traverse rate	Aramid fibre reinforced plastics	Impact angle should also be considered
Shaikh and Ambardekar (2013)	Water jet pressure and traverse rate	Metal-polymer-metal laminate	Stand-off distance and impact angle should be considered

4. Conclusion

Research work on AWJM of composites done by worldwide researchers over the last two decades is reviewed in this paper. The available literature in the domain is classified into three main areas- (i) cutting performance of AWJM process, (ii) optimization of process parameters, and (iii) modelling of AWJM process. Major research work in these three areas has been summarized in tabular form and scope of further work has been identified. It has been found that more research efforts are required to study geometric accuracy and surface hardness of machined composites, surface errors, nozzle wears, and defects like fiber pull out in AWJM of composites. Further, there is scope of experimental investigation on AWJM of carbon fiber and epoxy resin composites. The effects of various process parameters, optimization of process parameters, kerf characteristics, surface roughness, material removal rate, machinability, mechanism of delamination and other defects in AWJM of carbon fiber and epoxy resin composites are required to be investigated.

Table 3. Summary of Literature Review on Modeling of Process

Researcher(s)	Development of Model	Material	Scope of further work
Wang (1999)	For the total depth of cut	Polymer matrix composites	MRR should be considered in the study
Wang and Guo (2002)	To predict the depth of jet penetration	Polymer matrix composites	Process parameters range should be increased
Deam et al. (2004)	To predict the shape of the cut profile	--	Impact angle range should be increased above 60^0
Orbanic and Junkar (2004)	To predict the hole depths and diameters	--	Parameters which affect depth and diameter of hole should be considered
Wang and Liu (2006)	To predict kerf taper, depth of cut for straight slit cutting and profile cutting	Alumina ceramics	MRR should also be considered in the study

References

1. *Hascalik A., Caydas U., Gurun H., 2007. Effect of traverse speed on abrasive water jet machining of Ti-6Al-4V alloy, Materials and Design, vol. 28, 1953-1957.*

2. *Shanmugam D. K., Nguyen T., Wang J., 2008, A study of delamination on graphite/epoxy composites in abrasive water jet machining, Composites Part A: Applied Science and Manufacturing, 396, 923–929.*

3. *Sheikh-Ahmad J. Y., 2009, Conventional Machining of FRPs, Machining of Polymer Composites, Springer Science + Business Media, 143-231.*

4. *Ramulu M., Arola D., 1994, The Influence Of Abrasive Water jet Cutting Conditions On The Surface Quality Of Graphite/Epoxy Laminates, Int. J. Mach. Tools Manufact., 343, 295–313.*

5. *Arola D, Ramulu M, 1996, A study of kerf characteristics in abrasive water jet machining of Graphite/Epoxy composite, Journal of Engineering materials and Technology, 1182, 256-265.*

6. *Ramulu M., Prasad E. N., Malakondaiah G., Guo Z., 1997, Secondary Processing Effects And Damage Mechanisms In Continuous-Fibre Ceramic Composites, ASM International, 274–288.*

7. *Komanduri R., 1997, Machining of Fibre- Reinforced Composites, Machining Science and Technology, vol. 11, 113–152.*

8. *Wang, J., 1999, A machinability study of polymer matrix composites using abrasive water jet cutting technology, Journal of Materials Processing Technology, 941, 30–35.*

9. *Zeng J, Olsen J, Olsen C, 1999, Abrasive Water jet as a Precision Metal Cutting Tool, 10th American Water jet conference, Houston, Texas, paper No. 65.*

10. *Ramulu, R., 2001, Abrasive Water Jet Machining Mechanisms in Continuous-Fibre Ceramic Composites, American Society for Testing and Materials ASTM, 82–91.*

11. *Lemma E., Chen L., Siores E., Wang J., 2002, Study of cutting fibre-reinforced composites by using abrasive water-jet with cutting head oscillation, Composite Structures, vol. 571-4, 297–303.*

12. *Shanmugam D. K., Nguyen T., Wang J., 2008, A study of delamination on graphite/epoxy composites in abrasive water jet machining, Composites Part A: Applied Science and Manufacturing, 396, 923–929.*

13. *Arola D., & Williams C. L., 2002, Surface Texture, Fatigue, and the Reduction in Stiffness of Fiber Reinforced Plastics, Journal of Engineering Materials and Technology, 1242, 160-166.*

14. *Arola D., McCain M. L., 2003, Surface Texture and the Stress Concentration Factor for FRP Components with Holes, Journal of Composite Materials, 37, 1439-1460.*

15. *Wang J, Liu H., 2006, Profile cutting on alumina ceramics by abrasive water jet Part 2 : cutting performance models, Proceedings of the Institution of Mechanical Engineers, 2205, 715-725.*

16. *Azmir M., & Ahsan A., 2008, Investigation on glass/epoxy composite surfaces machined by abrasive water jet machining, Journal of Materials Processing Technology, 198, 122–128.*

17. *Prisco U., D'Onofrio M. C., 2008, Three- Dimensional CFD Simulation of Two-Phase Flow Inside the Abrasive Water Jet Cutting Head, International Journal for Computational Methods in Engineering Science and Mechanics, 95, 300–319.*

18. *Azmir M. A., & Ahsan A. K., 2009, A study of abrasive water jet machining process on glass/epoxy composite laminate, Journal of Materials Processing Technology, 209(20), 6168–6173.*

19. *Rao D. B., Baskey, D., Rawat, R. S., 2009, Water Jet Cutter : An Efficient Tool for Composite Product Development, National Conference on Scientific Achievements of SC & ST Scientists & Technologists 14–16 April 2009, National Aerospace Laboratories, Bangalore, 104–107.*

20. *Sadat A. B., 2009, On The Quality Of Machined Surface Region When Turning Al / Sic Metal Matrix Composites, Machining Science and Technology, 133, 338–355.*

21. *George J, Shah D, Jivani R, Gupta, D., 2011, Abrasive Water Jet Machining - A Review, National Conference on Recent Trends in Engineering & Technology, V. Nagar, Gujarat, India.*

22. *Cenac F., Collombet F., Zitoune R., 2011, Composite milling Abrasive Water-Jet, Comptes Rendus des JNC 17 - Poitiers 2011, 1–10.*

23. *Shaikh A., Jain P., 2012, Experimental Study of Various Technologies for Cutting Polymer matrix composites, International Journal of Advanced Engineering Technology, 21, 81-88.*

24. *Srinivas S., Babu N. R., 2012, Penetration Ability of Abrasive Water jets in Cutting of Aluminum-Silicon Carbide Particulate Metal Matrix Composites, Machining Science and Technology, 163, 337–354.*

25. *Patel S. R., Shaikh A. A., 2013, A Review on Machining of Fiber Reinforced Plastic using Abrasive Water jet, International Journal of Innovative Technology & Adaptive Management (IJITAM) ISSN: 2347-3622, Vol. 1 (3).*

26. *Alberdi A., Suarez A., Artaza T., Escobar-Palafox G., Ridgway K., 2013, Composite cutting with abrasive water jet, Procedia Engineering, 63, 421–429.*

27. *Miron A. V., Balc N., Popan A., Stefana C., Bere P. 2013, Studies On Water Jet Cutting of 2d Parts Made From Carbon Fibre Composite Materials, Academic Journal Of Manufacturing Engineering, vol. 112, 87–92.*

28. *Nedelcu R., Mihaila-Andres M., & Giboin P., 2013, A Concise Analysis on Composites Machining Technologies, International Conference Of Scientific Paper, Brasov, 23-25 May 2013.*

29. *Devadula S., Nicolescu M., 2013, Issues In Machining Of Hollow Core Honeycomb Sandwich Structures By Abrasive Water jet Machining, Journal of Machine Engineering, 13 1.*

30. *Korat M. M., Acharya G. D., 2014, A Review on Current Research and Development in Abrasive Water jet Machining, Int. Journal of Engineering Research and Applications, 41, 423–432.*

31. *Geiger M., Kach A., Hohenstein R., Maros Z., 2003, Fuzzy-Logic Based Knowledge Representation for Water Jet Cutting of Light-Weight Composites, Machining Science and Technology, 73, 349–360.*

32. *Azmir M., & Ahsan A., Rahmah A., Islamic I, 2007, Investigation On Abrasive Water jet Machining Of Kevlar Reinforced Phenolic Composite Using Taguchi Approach, Proceedings of the International Conference on Mechanical Engineering 2007 ICME2007) 29- 31 December 2007, Dhaka, Bangladesh.*

33. *Azmir M, Ahsan A, Rahmah A, Noor M, Aziz A, 2007, Optimization Of Abrasive Water jet Machining Process Parameters Using Orthogonal Array With Grey Relational Analysis, Regional Conference on Engineering Mathematics, Mechanics, Manufacturing & Architecture EM3ARC, pp 21-30.*

34. *Shaikh A. A., Ambardekar V. S., 2013, Predictive Depth of Cut Model for Abrasive Water jet Cutting of Metal-Polymer-Metal*

Laminate, International Journal of Emerging Technology and Advanced Engineering, 3 (6).

35. *Cheng H., 1990, A Failure Analysis Of Water Jet Drilling In Composite Laminates, Int. J. Mach. Tools Manufac, 303, 423–429.*

36. *Wang, J., 1999, Abrasive water jet machining of polymer matrix composites - cutting performance, erosive process and predictive models, The International Journal of Advanced Manufacturing Technology, 1510, 757–768.*

37. *Wang J., & Guo D., 2002, A predictive depth of penetration model for abrasive water jet cutting of polymer matrix composites, Journal of Materials Processing Technology, 121 (2-3), 390-394.*

38. *Deam R.T., Lemma E., Ahmed D.H. (2004), Modelling of the abrasive water jet cutting process, Wear, 257, 877–891.*

39. *Orbanic H, Junkar M., 2004, 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, 218, 503-508.*

40. *Wang J, Liu H., 2006, Profile cutting on alumina ceramics by abrasive water jet , Part 2: Cutting Performance Models, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 5, 715-725*

41. *Shanmugam D. K., Nguyen T., Wang J., 2008, A study of delamination on graphite/epoxy composites in abrasive water jet machining, Composites Part A: Applied Science and Manufacturing, 396, 923–929.*

42. *Ramulu M., Hwang I., Isvilanonda V., 2009, Quality issues associated with abrasive water jet cutting and drilling of advanced composites, American WJTA Conference, August 18-20, 2009, Houston, Texas.*

