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Review Article

A REVIEW ON THE RECENT INVESTIGATION TRENDS IN ABRASIVE WATERJET CUTTING AND TURNING OF HYBRID COMPOSITES

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ABSTRACT

Cutting with abrasive water jet is an effective method for many engineering materials. Owing to its ability providing close tolerances and dimensional accuracy as well as cutting of extremely hard materials, total using rate of abrasive water jet cutting (AWJC) in the industry rises day by day. In addition to cutting, turning of the many industrial materials can be turned into the practice with abrasive waterjet turning (AWJT) technology. In recent years, AWJC and AWJT become considerably popular cases in the machining of hybrid composite materials which consist of at least two unlike reinforcements and researches about this subject increase rapidly in order to elucidate process details and influences of input parameters. Water pressure, traverse speed, abrasive flow rate, standoff distance and abrasive particle mesh size are the most prominent parameters of the process. In this paper, abrasive waterjet cutting/turning applicability of hybrid composites was reviewed and an initiative was done to rake together the newest surveys published in the technical literature. Our purpose is to achieve detailed overview for AWJC/AWJT of hybrid composites and to emphasize feasibility of the AWJC/AWJT for them and to discuss future real application possibilities of the method.
Keywords: Water jet, abrasive, hybrid, cutting, turning.

1. INTRODUCTION

As long as the development of high-performance engineering materials continues and the total needs of them goes up, new manufacturing challenges emerge inevitably. These challenges and difficulties can't be dealt with by traditional manufacturing techniques because of their technical insufficiency for advanced components. In the fabrication of high-performance materials, machining stage plays an important role that effects on product quality significantly. On the purpose of fabricating complex shaped and perfect quality products with closed tolerances, investigators and research and development (r&d) engineers give more weight to non-traditional machining methods in recent times although they also investigate and work on conventional methods. Water jet technology is one of the most promising non-traditional method for machining operations of many kinds of materials and it is hugely open to be improved for diversified engineering applications.

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Water jet machining systems are used usually for soft materials that solely high-pressure water is enough to cut them. However, if substrate material is a metal, ceramic or difficult to cut object, some kinds of hard abrasives (garnet, aluminum oxide, silicon oxide, etc.) must be included into the high-pressure water system in order to make easier material removal. This method is dubbed abrasive water jet cutting (AWJC) in the technical literature and currently it is a remarkable alternative for traditional machining and cutting techniques and its influence area is raising day by day in the industry [1]. AWJC technology has very important and outstanding advantages of no excessive heat generation causing heat affected zones (HAZ) on cutting edges and thermally distortion, perfect material removal rate, great flexibility, small cutting forces and wide target material portfolio [2]. The process can be applied not only to metallic materials such as steel, aluminum alloys, magnesium alloys, titanium and copper but also it is very appropriate for ceramics, composites and other difficult-to-cut materials [3-9]. Recently, ultrasonic systems exploiting sound waves are integrated to the AWJC equipment to assist cutting of pretty hard sample materials without any quality setbacks [10]. After the cutting operation, closed tolerances which are particularly prominent for geometry sensitive applications and high dimensional accuracy on the substrate material are attained efficaciously in comparison with other conventional cutting and machining methods [11]. Apart from cutting, with the abrasive waterjet technology, various kinds of turning operations also can be carried out in a short duration and this method is called abrasive waterjet turning (AWJT) [12]. In other words, it is proper to express that AWJT process is a method that waterjet technology is integrated to turning equipment for high speed fabrication. This process makes use of waterjet nozzle equipment instead of cutting tools for material removal. While conventional turning methods may cause material accumulation and thermal problems owing to friction, AWJT eliminates that kinds of setbacks and provides useful solutions for different types of engineering materials [13]. AWJT is a less risky with regards to chattering and vibration than classical turning lathe in which by the reason of inappropriate clamping and problems in lathe rigidity undesired low-quality components may be seen.

A hybrid composite is defined as a composite material containing two or more different types of reinforcing components in the matrix material and it can be fabricated with hybridization techniques. The word hybrid composite is chosen to attract notice for synergetic effect of diversified features of reinforcing fibers [14]. On the other hand, the term ’hybrid’ is also often expressed for particle reinforced composites (two or more varied particle types) and some syntactic metal foams (two unlike hollow spheres or porous components) [15,16]. The main target of all these hybridization processes is notably to enhance mechanic and physical properties (density, heat resistance, strength, modulus of elasticity, etc.) of composite material. Thanks to the utilization of hybrid composites, mechanical properties of materials are not only improved seriously in the real service conditions but also production costs abate in a noteworthy manner [17]. The basic character of a hybrid composite is substantially related with reinforcing elements content, type, size, distribution, orientation and bonding states as well as matrix material [14]. Based on using place, mechanical and physical conditions, hybridization parameters may be shifted to get the best and the longest time performance. Lately, hybrid composite usage in conjunction with demands of fast-growing industry has been rising day by day and as a consequence of this stance, forming/shaping of the hybrids by utilizing machining via abrasive waterjet technology having unique properties has emerged as a bright solution. Compared to other traditional and non- traditional methods, AWJ technology possesses characteristic virtues such as flexibility, fastness, compliance with automation, environmentally cleanliness and low heat cutting. Hence, all these positive attributes are very encouraging for machining of the hybrids with AWJ technology.

In this paper, AWJC/AWJT applications of hybrid composites were reviewed in depth in the guidance of the latest developments and researches. Furthermore, literature scans were done and future occasions of the processes were interpreted in terms of both scientific and industrial aspects. Our main goal in this survey is to form a wide perspective for machining of the hybrids and to co ntribute possible new works about AWJC/AWJT of them.

2. COMPACT OUTLOOK ON HYBRIDS and AWJC/AWJT PROCESSES

2.1. Hybrids

Hybrid composites are defined as composite materials consisting of two or more different reinforcing fibers impregnated in the same matrix [18]. These novel materials are mostly denominated according to their including fibres and matrix like Carbon- Glass, Glass-Kevlar Hybrid etc. These type of combination gives an advantage of good strength at lower cost which can be used for applications that were not possible by using the classical composite materials [19-22]. According to early studies about hybrid composites, there are four general categories of hybrid composites including: (1) interply hybrids; (2) intraply hybrids; (3) interply/intraply hybrids; and (4) superhybrids [23]. The interply hybrids consist of plies from two or more unidirectional composites stacked in a specified sequence. Intraply hybrids include two or more different fibers mixed in the same ply. Interply/intraply hybrids compose of plies of intraply and interply hybrids stacked in a specified sequence. Superhybrids compose of metal foils or metal composite plies stacked in a specified sequence [20]. Nowadays, in conjunction with the need of high-performance engineering materials, total usage of hybrid composite materials has been growing from year to year. Hybrid composite materials are widely used for primary and secondary aircraft structures, at times also for critical elements. The basic criteria regarding with the selection of hybrid composites for a specific implementation is satisfactoriness of Young modulus-density and Young modulus-strength rates shown in Figure 2.1 [24].

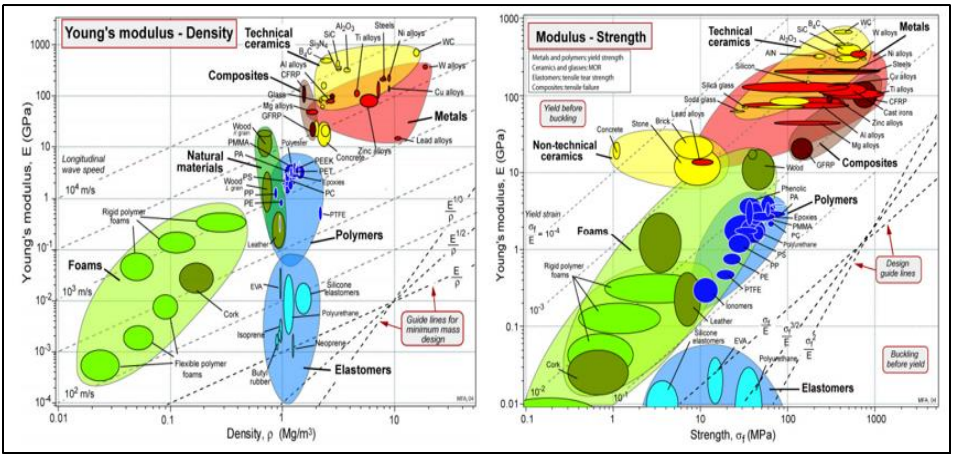

Figure 2.1. Selection guide for engineering materials [24]

They are the potential target material as, e.g., skin elements, fuselage, spars, blades, landing gear elements, stabilizers, hatches, and many more. Initially, the use of composites in aircraft structures reached several percent (military aircraft and structures). Now, the percentage of composite materials oscillates around 2030%. The leading products employing composite materials, apart from military aircraft and space industry, are Airbus A380 (with the composite percentage of a dozen or so) and Boeing 787—with the percentage of composites of over 50%. The availability of input materials, their considerable modifications, lower production costs and well-known composite production process contribute to the fact that these materials constitute a group with a strong development potential. Although metals and composites have a number of beneficial properties, they also have some disadvantages limiting their potential applications. Hybrid composites, compared to metal alloys, display high mechanical properties: static strength, high stiffness, low density, chemical and corrosive resistance, balanced thermal stability, better fatigue resistance and impact resistance, fracture toughness besides reduced notch sensitivity [25]. The disadvantages of hybrid composites include low formability, cold cracking and velocity impact resistance, moisture absorption, and relatively low operating temperature of composite materials [18].

In more recent times, researchers have focused on new methods besides conventional ways for machining of hybrid composites which have unique material properties as a combine of different materials in order to have better quality product. In the light of these interests, many studies have been conducted about machining ability and methods of hybrid composites [26-31]. Also, in Figure 2.2, machining investigations on hybrid composites can be seen with one example study which includes investigation area, used process parameters and output parameters. By these example studies of machining processes of hybrid composites, the relation between process and output parameters can be understood easier. Besides traditional hybrid machining process like drilling, milling and turning, new trend nontraditional machining processes play an important role in this manufacturing area. Electrical discharge machining (EDM) is one of the non-traditional machining methods which can machine any electrically conductive materials regardless of their hardness with its removal mechanism of melting and evaporating of workpiece materials; what is more, by using EDM, the materials can be machined precisely into complicated shapes with low cutting force [32]. To minimize the tool wear rate and to improve the machining process, selection of the process parameters is a significantly complicated process. In order to find out the effects of input parameters, several investigations [33-35] were carried out. In similar to EDM, wire electrical discharge machining (WEDM) is a thermal erosion process whereby a desired shape and size can be acquired through using sparks. Material is removed from conductive material immersed in dielectric by a series of arbitrarily recurring sparks between wire tool and the workpiece [36]. WEDM is such a technique that can be successfully applied to machining of single-phase ceramics, cermet and ceramic matrix composites. An important feature to remember with WEDM is that it will only work with materials that are electrically conductive. For healthy machining via discharge technology, electrical resistivity of the sample material should be lower than 100-300 cm. In comparison with conventional machining techniques, WEDM achieves higher removal rates for these materials with respect of surface integrity and tolerances of below 1 mm have been achieved as well [37]. On the other hand, difficulties also arise with respect to the surface finish conditions the corrosion of these materials during machining and the influence the machining parameters in the surface damage, i. e. cracks produced within the thermally affected zone (recast layer and adjacent regions) beneath the shaped surface [38-40]. Because of these difficulties and limited material usage range like electrically conductive materials, researchers have been focused on one of another non-traditional machining method AWJM which has larger material usage scale and many advantages that are mentioned on coming papers.

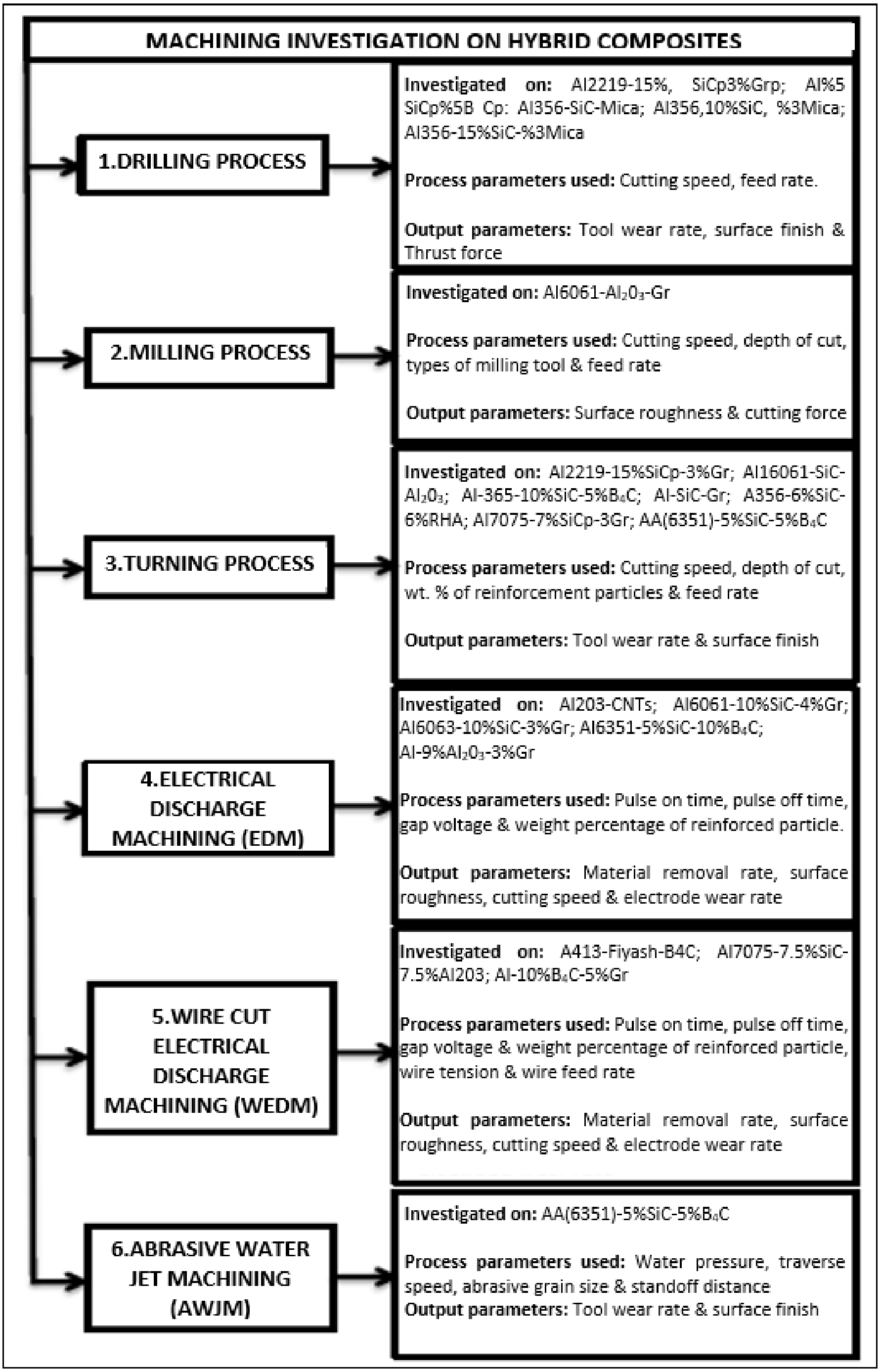

Figure 2.2. Different machining methods and investigations on hybrid composites

2.2. AWJC/AWJT Technology and Major Applications

Water jet machining (WJM) process works majorly on the main principle of material removal from the subject surface with high water pressure. However, in abrasive waterjet machining (AWJM) system, a high speed well concentrated water and hard abrasive particles are mixed to cut work-piece material efficaciously. AWJM systems exploit kinetic energy of water and abrasive particles to wear and erode the sample part at localized contact surface. A traditional abrasive water jet system normally comprises of five primary sections. These are an intensifier pump which is responsible for supplying high-pressure water, an abrasive particle adding module, a cutting head providing mixture for waterjet nozzles, a computer programmed head controller unit which directs the head to desired coordinates and a work table [41]. Figure 2.3 and Figure 2.4 illustrate main components of the AWJC/AWJT installation in detail by benefiting from real set-up while Figure 2.5 shows schematic views of the both processes basically [42-45].

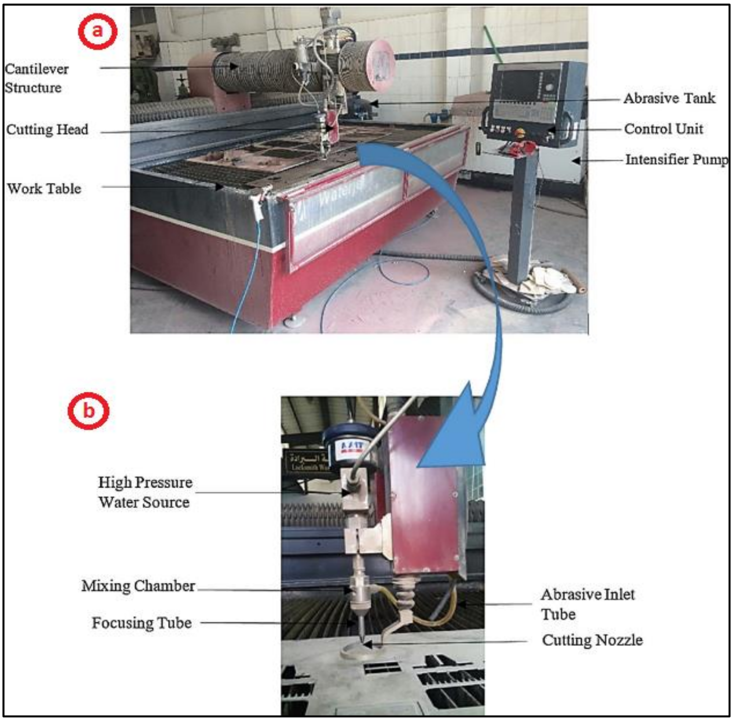

Figure 2.3. Real setup of an abrasive waterjet cutting (a) and cutting head (b) [42]

In general, in order to enhance performance of the process, abrasive particle grains of garnet are added to water jet system, which help seriously the cutting of extremely hard materials. Apart from garnet, there are many different types of abrasives illustrated in Figure 2.6 in industrial usage but garnet is the most common material owing to its positive effects on the cutting performance [47].

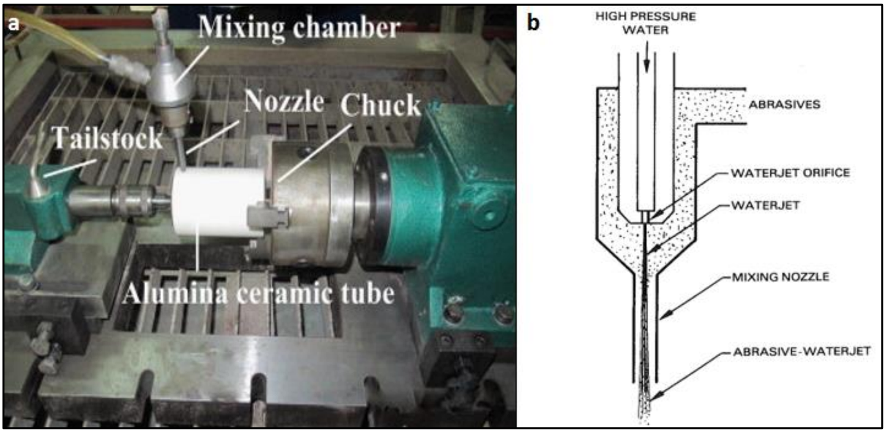

Figure 2.4. A real setup example of AWJT system (a) and nozzle system (b) [44]

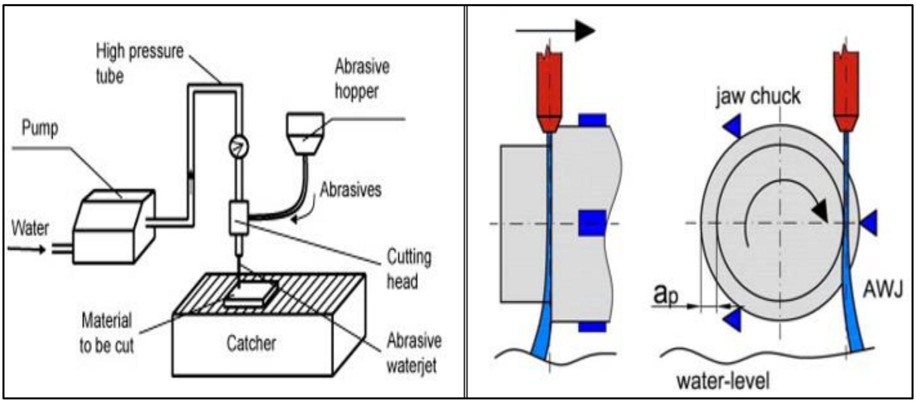

Figure 2.5. Schematic view of AWJC (left) and AWJT (right) processes [43], [46]

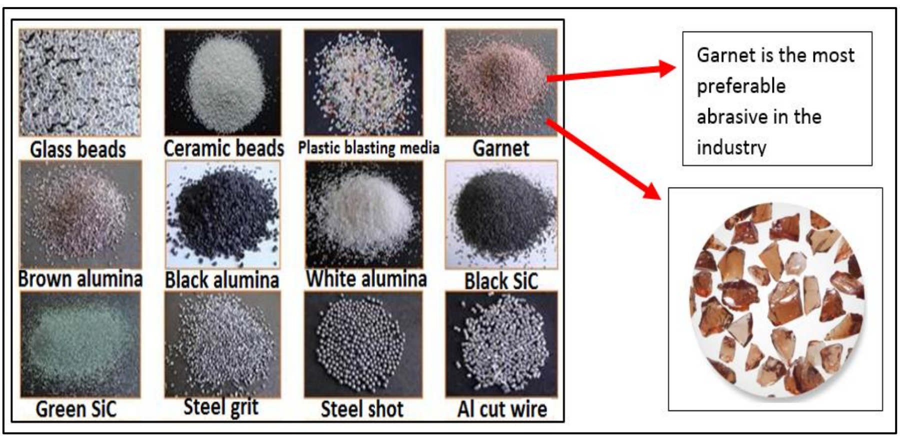

Figure 2.6. Abrasive types for AWJC/AWJT applications and close view of garnet grains [47]

Provided that AWJC and AWJT techniques are compared to other classical methods, some significant virtues listed below can be expressed concisely;

- AWJC and AWJT usually automated by CNC or robots to manipulate nozzle ways. As a result of this, closed tolerance parts and rapid manufacturing properties come comfortably together.
- No heat generated on part surface (As opposed to laser cutting, AWJC generates less heat than laser systems on material surface and it means that probability of any metallurgical changes on cutting edges can be decreased notably.)
- During AWJC and AWJT processes, no environmental problems are present. Their environmental friendliness feature is very remarkable for the future applications of the process, since in today's industry, trend of clean manufacturing and sensitiveness for nature go up day by day.
- AWJC has a multidirectional cutting capacity and the burr produced is minimal.
- Range of the suitable materials to be cut or turned (from different grades of steels to light alloys, rocklike materials, ceramics and composites) is considerably wide.
- By means of AWJC and AWJT, plain and complex geometries as well as hollow structures can be machined perfectly without any setbacks.

In today's industrial world, productivity, efficiency and economic competition are very determinant in terms of sectorial success and eligibility for all manufacturers. Because of its capability of cutting/turning of the difficult-to-cut materials and ability of machining complex 2D and 3D geometries in a short time, AWJC and AWJT processes offer several advantages to manufacturers serving in many different industrial areas. In Figure 2.7, the most common sectors experiencing AWJC and AWJT are illustrated [48], [49]. Especially, particular industrial areas like aerospace, defence and automotive requiring dimensional accuracy and perfect finish surfaces prefer these techniques owing to their high potential and flexibility. In addition to the applications demonstrated in Figure 2.7, abrasive waterjet process is also utilized for micro-electro-mechanical systems (MEMS). For instance, micro-module production for semiconductors is possible with AWJC method [47]. Furthermore, in glass industry, abrasive waterjet applications such as cutting, milling, piercing and turning become an important solution nowadays and provides new alternatives for producers and research and development engineers [50-52].

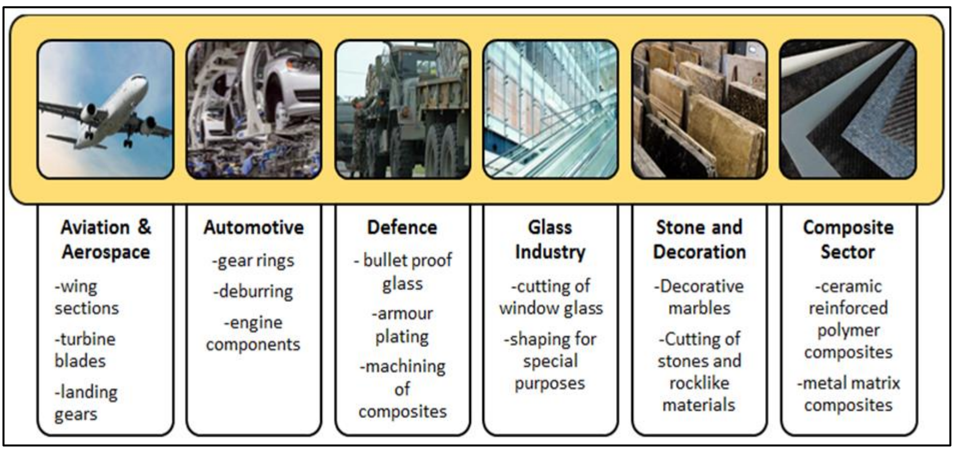

Figure 2.7. The most common industrial areas benefiting from AWJ systems [48], [49]

With nontraditional machining like AWJC and AWJT, same materials such as ceramics (polycrystalline ceramics, alumina ceramics), metals (Ti6Al4V, Inconel 718, AISI D2 tool steel), alloys (aluminum alloy 7075, aluminum 6061, aluminum 2219, Al-6082 T6 alloy, AZ91 magnesium alloy), composites (aluminum/tungsten carbide, carbon fiber reinforced polymer, carbon fiber fabrics, metal matrix composite) and hybrids (aluminum-based hybrid, Al/Ticp/Gr hybrid, A359 aluminum matrix/B4C and Al2O3 particles), glass (borosilicate glass) can be machined with less damage, more complex shapes are able to made, low rigidity structures can be produced, micro-machined components with tight tolerances and perfect surface quality with low cost can be obtained. Recently, the amount of AWJ works performed on various kinds of substrate materials are increasing rapidly in the literature and many industries are using them to enhance component performances. If it is taken a glance at some new works briefly, for generic composites, Kumar et al. examined a study about optimizing the AWJM parameters when machining aluminum/tungsten carbide (WC) composites. Their investigations were carried on with 2, 4, 6, 8 and 10 wt% tungsten carbide reinforced composite specimens fabricated by stir casting technique and the optimum parameter maximizing the material removal rate and minimizing the surface roughness is standoff distance of 4.22 mm, transverse speed of 223.28 mm/min, and percentage WC of 2.10% [53]. Also, an experimental study and statistical analysis for cutting 2 lay-up configurations of multidirectional CFRP laminates was carried out by a group of researchers. They have focused on different conditions including jet pressure, feed rate and standoff distance by using full factorial design of experiments and machining process responses such as top and bottom kerf width, kerf taper, machinability and surface characteristics have been evaluated using analysis of variance (ANOVA) technique [54]. Voit et al. conducted an experimental study on AWJC of unidirectional carbon fiber fabrics and the obtained results showed that the best cutting-edge quality and the lowest water absorption for all tested fabrics were achieved by high forward speed and low nozzle distance [55].

With regards to metals, nowadays, efforts of AWJC and AWJT process of Al, Mg, Ti alloys and super-alloys continues and deepens. On the other hand, researches regarding with ceramic and steel substrates also are not be ruled out due to spread using of those. In this context, Ahmed et al. presented a work to understand the effect AWJC parameters (traverse speed, water pressure and standoff distance) on surface roughness for the cutting process of aluminum alloy 7075 which is used widely in space and aviation applications [42]. The results showed that an improvement of the surface roughness can be achieved by increasing the water pressure at low traverse speed or decreasing the pressure at high traverse speed, or decreasing the standoff distance at low traverse speed. In another study, Prabhuswamy et al. studied about the project aiming to investigate the cutting ability of abrasive water jet on aluminum 6061 [56]. The effect of dynamic input parameters such as abrasive mass flow rate, water jet pressure and traverse speed of jet on depth of cut of was investigated. Also, Niranjan et al. performed out the influence of input parameters on depth of penetration and surface topography in AWJC of AZ91 magnesium alloy and it was observed that, depth of penetration was a function of water pressure whose influence was more than that of traverse speed [57]. At another study, Kartal et al. studied about the effects of AWJT parameters on the surface roughness and macro surface characteristics when machining Al-6082 T6 alloy [58]. The material removal tests were conducted for different parameters of nozzle feed rate, abrasive flow rate, spindle speed and standoff distance. It was found that increased spindle speed, decreased nozzle feed rate, increased abrasive flow rate and lower standoff distance resulted in smoother surfaces and best results were obtained when spindle speed and abrasive flow rate were increased. Furthermore, Gnanavelbabu et al. reported a research study about machining of biocompatible material Ti-6Al-4V by using AWJM under different process parameters such as mesh size, abrasive flow rate, pressure and traverse speed [59]. The experimental results pointed out that high pressure, low traverse speed, low abrasive mesh size and high abrasive flow rate were resulted in lower surface roughness. And it was found that high pressure, high mesh size led to minimum kerf taper ratio and whereas high traverse speed produced a maximum kerf taper. AWJ technology has unique properties which provides some superiorities for machining of super alloys which are used in aerospace and high temperature applications frequently over other non-traditional methods like laser beam machining and EDM. Likewise, a latest survey about machinability of Inconel 718 carried out by Holmberg et al. asserted that in terms of surface quality and integrity machining with AWJ technology was more effective than EDM and laser [60].

Tool steels are difficult to machine materials but at the same time, their machining operations require dimensional accuracy, closed tolerances and quality surfaces. Yuvaraj and Kumar dig out influences of the process parameters on AWJC performance of AISI D2 tool steel and revealed that jet pressure and jet impingement angle were the most significant factors affecting the performance [3]. Dumbhare et al. tried to optimize surface roughness and kerf taper in the process of AWJC of mild steel. The study showed that traverse speed was major parameter changing output features [61]. Tiwari et al. analyzed effects of input variables on AWJC of alumina ceramic by taking advantage of response surface model and stated that water pressure made an affirmative effect on surface roughness while traverse speed and abrasive flow rate dropped it [62]. Also, Hlavac et al. checked up on kerf taper issue during AWJC process for rocklike materials. They compared results with metals in order to find out discrepancy truly [63].

2.3. Process Parameters

There are several influential parameters in this advanced machining technology. In this context, it is true to say that input parameters and their effects on output properties are hugely significant for researchers and engineers. Generally, input parameters of AWJC and AWJT processes are technological factors (stand-off distance, traverse speed, traverse direction, sample material, impact angle, speed and direction of rotation and number of passes for AWJT), water system components (water pressure, nozzle type, orifice diameter) and factors regarding with abrasives (abrasive material, abrasive particle grain size and shape, feed rate) [47], [64-69]. Figure 2.8 shows distribution of the process parameters and output features in depth.

Surface roughness and material removal rate are the most common output parameters and they are followed by factors of depth of cut and waviness. Due to the fact that surface quality and process time are related strongly to roughness and removal rate respectively, these parameters come into the frontline compared to others. In the presence of hybrid composites, the situation is almost same with general applications for output factors (in terms of laminate hybrids, delamination issue can be added as an extra output, [70]) whereas input parameters may increase by the reason of the structural nature of the hybrids. Reinforcement and matrix types, fiber or particle amount and matrix/reinforcement bonding state are additive inputs which might influence result variables. Depending on reinforcement type and amount, micro cracks, craters, void and other irregularities might be noticed in substrate machined surface and these circumstances culminate in poor surfaces.

Abrasive water jet system possesses nearly has no application limitations. Intricate and simple parts are machined with AWJC/AWJT comfortably. For quality design and high process efficiency, optimum adjustment of the process parameters and sensitive control of the system are very critical and in recent years, many researchers focus on some experimental design techniques which are basically related to statistical approaches such as Taguchi design, factorial design and response surface methods [71], [72]. By applying to these statistical approaches, engineers working on AWJC and AWJT systems and researchers can easefully found optimal levels of process parameters as well as effects of their interactions on the machining performance, so they can assess the whole case correctly and rapidly. Moreover, when using experimental design techniques, true decision of parameter levels and ranges are highly critical and which can be done with detailed literature scan. By means of correct determination of input parameter levels, meaningful and sufficient results are achieved with lesser experiment and lower cost.

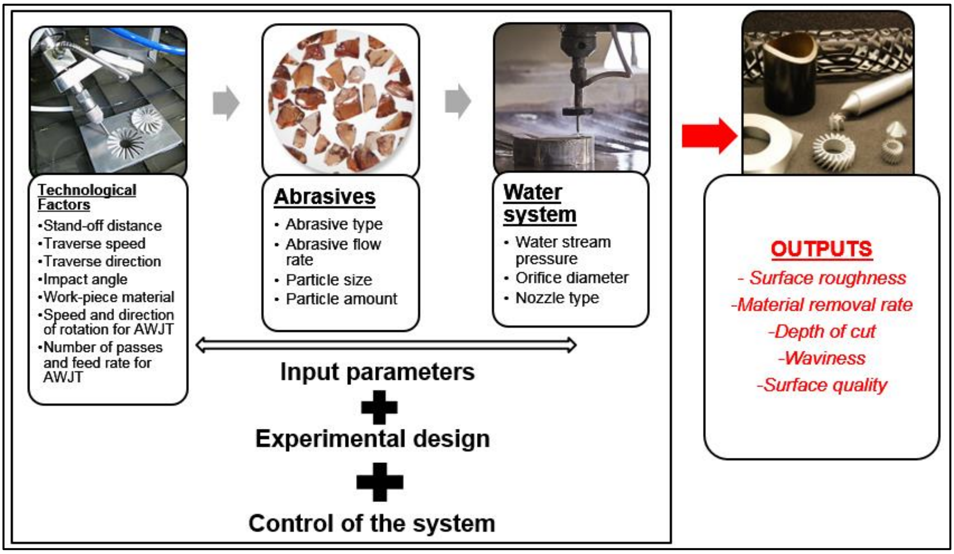

Figure 2.8. Input and output factors for AWJC and AWJT processes [47], [52], [64-69], [72]

3. AWJC and AWJT OF HYBRID COMPOSITES

3.1. Latest Research Trends and Newest Investigations

Abrasive waterjet machining technology has been used for several engineering materials since 1980's. It is also applied successfully to composite materials whose machining operations are more complex and difficult with conventional machining methods than that of the others [73], [74]. According to surveys regarding with generic composites in the last decades, abrasive water technology is really suitable way to machine them and depending upon the matrix/reinforcement combinations, some output properties (surface roughness, dimensional accuracy, kerf geometry, waviness, etc.) can be properly controlled by optimizing the input parameters [43], [74-76]. Nevertheless, in recent times, due to their mechanical/physical properties and synergetic reinforcement features, general interest in the hybrid composites has been growing and as a result of that forming/shaping of these materials has become an important issue. In this context, the topic of abrasive water jet machining of hybrid composites has come to the forefront in academic studies and manufacturing industry. In order to comprehend deeply the abrasive waterjet machinability of the hybrids, academicians and engineers has intensively concentrated on both technological developments in the process and optimization of input factors.

Metal matrix composites (MMC) are notably popular in recent years due to their unique properties but they are also very hard to machine with traditional techniques. If conventional cutting methods are applied to them, risks of some undesired tool wear problems and high cutting temperatures may come to exist. Gnanavelbabu et al. studied AWJC quality characteristics of hybrid aluminum metal matrix composites (AMMCs) due to their usage in nuclear such as control rods and automotive industry for brakes. As a substrate material, B4C and solid lubricant hexagonal BN particles reinforced AA6061 aluminum matrix composite was selected. Particle percentages were altered in three different mixtures which can be seen in Figure 3.1. According to researchers, it is clearly understood that quality control during AWJC process was more difficult for metal matrix hybrids than metals and as the percentages of boron carbide goes up, top kerf width and surface roughness increase. Moreover, it was found that traverse speed and abrasive flow rate have affirmative effects on surface roughness [16].

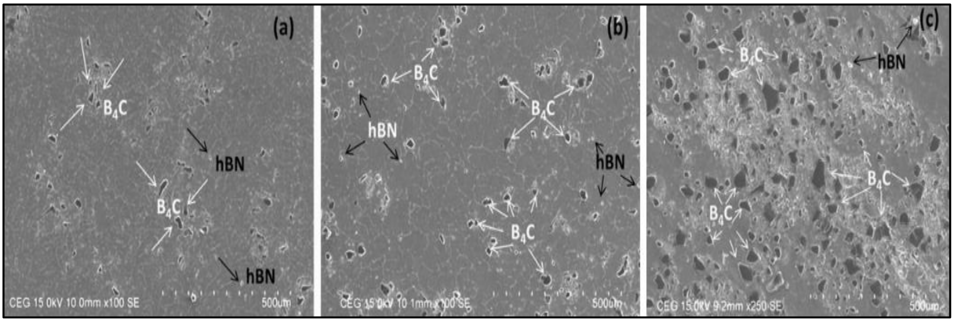

Figure 3.1. SEM images of hybrid AMMCs (a) %5 B_4C, (b) %10 B_4C, (c) %15 B_4C [16]

In another research about laminate hybrids, Putz et al. investigated machinability of hybrid layered composites by using AWJC technology. Carbon fiber reinforced polymer (CFRP) composite and aluminum materials were trimmed with AWJC process separately in order to provide desired 3D shape. For this reason, overlapping area was formed for CFRP and CFRP was jointed to the metal. After 3D forming, hybrid layered composite joint was cut and two different cutting strategies shown in Figure 3.2 were analyzed. It was observed that compared to 2,5D strategy, 3D strategy enabled more homogenous surface quality and did not lead to shearing load on the joint interface. In fact, this original work emphasizes that when cutting layered and curved hybrids, cutting strategy should be taken into account certainly and this input factor could be counted as a kind of traverse direction. Also, joint type, geometry and matrix/reinforcement combination may change for different applications but if cutting strategy is decided truly, high quality surfaces can be acquired without any joint failures [28].

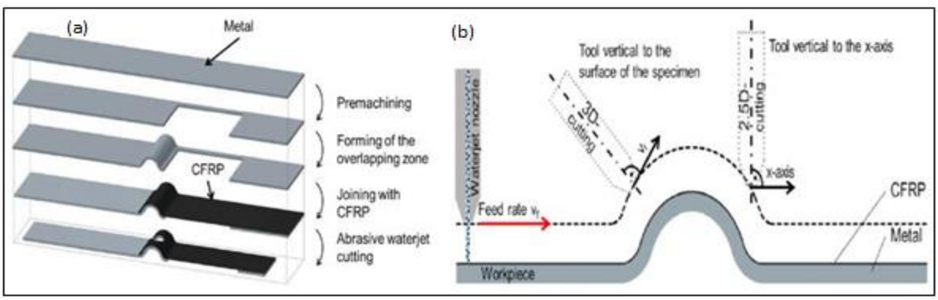

Figure 3.2. Specimen preparation steps (a) and different cutting strategies (b) [28]

Apart from their strength and inherent low density, carbon fiber reinforced polymer composites exhibit good corrosion resistance, long fatigue life and low-price assembly. Therefore, accurate machining and forming of them is a vital situation when considered potential using sectors. Earlier studies about machining of these materials indicate that milling and CO_2 laser trimming can be applied but compared to abrasive waterjets some setbacks such as low tensile stress and heat affected zones may be happened [77]. Wong et al. focused on delamination and kerf taper problems in the AWJC of fiber reinforced polymer (FRP) hybrid composites. In this work, authors stated that even though typical carbon fiber reinforced polymer composites have many application areas like aerospace and automotive, their low ratio of compressive to tensile strength and low elastic modulus to weight ratio of glass fiber composites triggered researchers to prone to hybrid fiber reinforced composites, so Wong et all utilized carbon and E-glass woven fabric reinforced epoxy resin. Cutting design of the specimens and kerf tapers obtaining with different stand-off distances (SOD) are illustrated in Figure 3.3. Response surface experimental design was used to figure out effects of process parameters. Experimental outcomes revealed that stand-off distance and traverse rate were the most influential factors affecting the kerf ratio. As for delamination setbacks and damages, abrasive flow rate, traverse rate and hydraulic pressure could be accepted as noteworthy factors. According to investigators, minimum kerf ratio and delamination could be obtained by raising the kinetic energy of jet flow. Optimum process parameters for quality products after abrasive water jet process were at abrasive flow rate of 600 g/min, hydraulic pressure of 2626 bar, stand-off distance of 2 mm and traverse speed of 2500 mm/min [70].

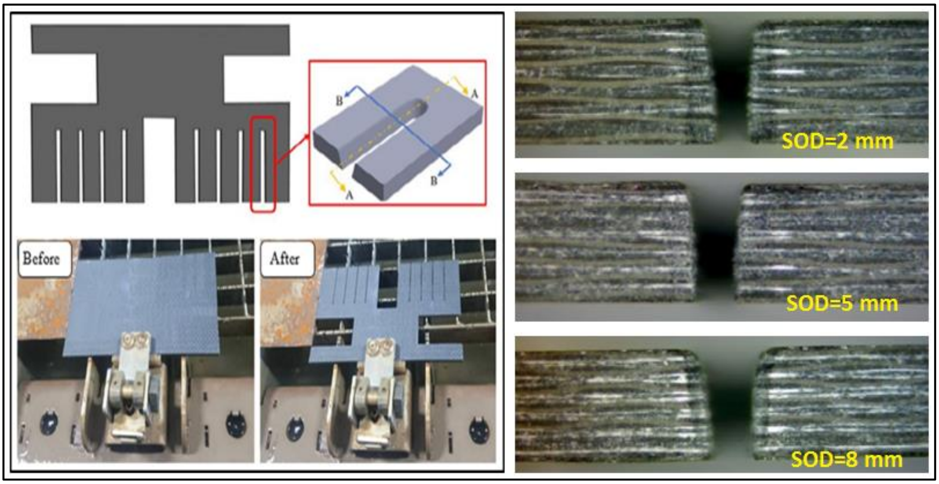

Figure 3.3. Cutting design for FRP hybrid specimens and alteration of kerf tapers based on stand-off distance [70]

Nag et al. checked up on the effects of different abrasive particles on AWJT ability of aluminum matrix hybrid composite materials. Abrasive particles were garnet and olivine. As hybrid samples, %2 B_4C and %2 Al_2O_3 particle reinforced A359 Al alloys were used in the study. Abrasive flow rate was selected in the range between 100 and 400 g/min while standoff distance and water stream pressure were 8 mm and 300 MPa respectively. As a result of the survey, minimum surface roughness value of 6.4 μm was attained by adding olivine abrasives into the jet stream. In the light of this study, it can be concluded that although garnet is very common abrasive material in AWJC process, in some circumstances other abrasives might be better alternative [78]. Lately, efforts for process development are stepping up by trying to use new abrasive alternatives (i.e crushed glass, corundum) in order to get better results for desired improvement features [65], [79]. Nag et al. searched also influence of AWJT process parameters on variation of diameter of hybrid metal matrix composites in another study. Hybrid composites (A359 aluminum matrix/B4C and Al2O3 particles) were manufactured by electromagnetic stir casting method. In order to assess effective parameters of abrasive type and mass flow rate, one variable-at a time (OVAT) methodology was embarked on. It was apparently observed that abrasive particle type was more effective than mass flow rate on the deviation of diameter from the target diameter value [80].

Ming et al. performed an experimental study and investigated abrasive waterjet machining ability of hybrid carbon/glass fiber reinforced plastic composite for good surface quality. A 3,5 mm thick polymer matrix material with 12 layers of simple-woven glass and 7 layers of simple-woven carbon fibers was cut and machined with AWJ technology [81]. During the all cutting operations, while some parameters such as orifice, nozzle and mixing tube diameters (0.28, 0.76 and 0.08) and jet impinge angle (90°) were constant, others listed in Table 1 were altered to determine their effects on the surface quality. 30 experiments were carried out and tried different combinations of the factors. For minimum surface roughness of 5 μm, they found that abrasive flow rate, hydraulic pressure, stand-off distance and traverse rate should be chosen 600 g/min, 320 MPa, 2 mm and 1000 mm/min respectively. The most outstanding factor was abrasive flow rate and it was followed by stand-off distance. Figure 3.4 illustrates cross section topographies of samples having minimum and maximum roughness values.

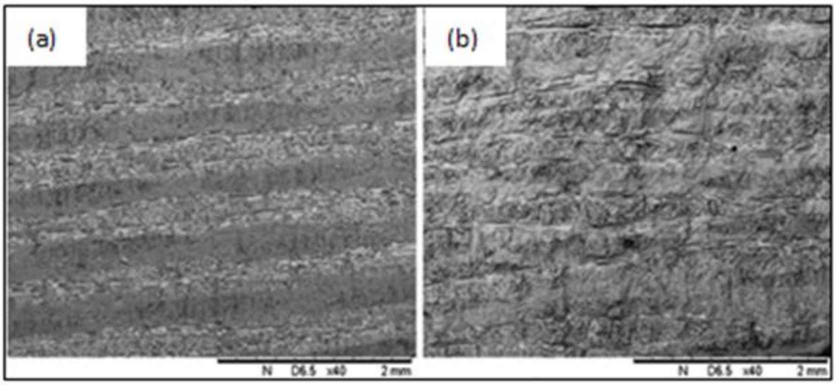

Figure 3.4. Cross sectional surface topologies: the lowest (a) and the highest (b) quality [81]

Rajesh et al. tried to optimize some important parameters of machining in the abrasive jet system. In their survey, researches deliberately used an experimental design method of Taguchi so as to dig out machinability of aramid (kevlar fiber) and natural fiber (kenaf and neem) reinforced hybrid composite [82]. After the process, surface roughness and material removal rate (MRR) values were observed as output factors. Input parameters utilized in the experiments were abrasive flow rate, feed rate of nozzle and stand-off distance. Taking advantage of Taguchi method and analyze of variance (ANOVA) results, researchers pointed out that abrasive flow rate plays a serious role for achieving better surface quality as well as high MRR and this situation could be attributed increasing kinetic energy of the abrasive particles.

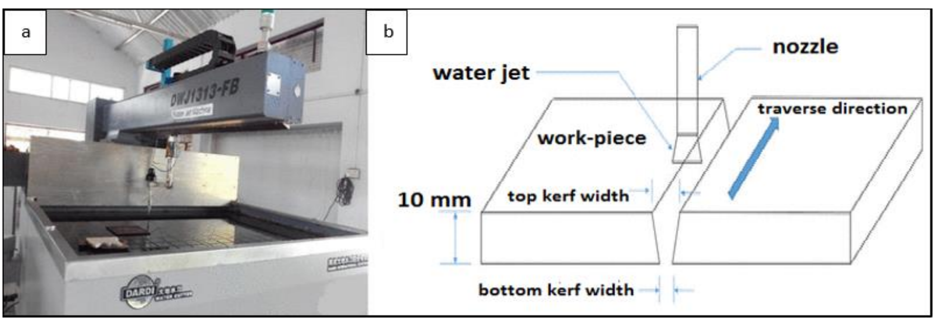

Figure 3.5. AWJC setup (a) and kerf geometry (b) [83]

Sasikumar et al. investigated kerf characteristics of hybrid %5, %10 and %15 TiC and B4C particle (equal amount of each) reinforced 7075 aluminum composite material. In the AWJC of composites, kerf taper shown in Figure 3.5 is a typical affair for researchers and engineers working in research and development departments.

Since authors desired to deal with this problem, they studied mainly on process parameters (jet pressure, traverse speed, stand-off distance) in order to find reason behind and optimize the kerf characteristic. In comparison with others, traverse speed contributed more on top kerf width whereas jet pressure was influential more on kerf angle and surface finish quality. Furthermore, they suggested that if stand-off distance goes down, small top kerf width and surface quality can be obtained. With the intention of analyzing microstructure of the cut surfaces, scanning electron microscope (SEM) and x-ray diffraction (XRD) analysis were conducted and they were interpreted that no entrapment of garnet particles occurred on surface by the reason of high momentum of abrasives and specimen thickness [83].

Pahuja et al. used abrasive waterjet process for fiber metal laminates (FML). They claimed that the combination of metallic sheet blocks dispersed in composite laminates forms a hybrid material and it has corrosion and impact resistance [84]. In spite of its high corrosion and impact resistance, this hybrid material shows different machining behaviors through cutting surface and it makes the cutting operation very difficult via conventional methods. Researchers started off from that point and looked through the AWJC ability of the 10.5 mm thick hybrid composite comprising of graphite reinforced thermoplastic layers and titanium alloy foils. They mainly focused on kerf characteristics demonstrated in Figure 3.6 and surface quality in the survey.

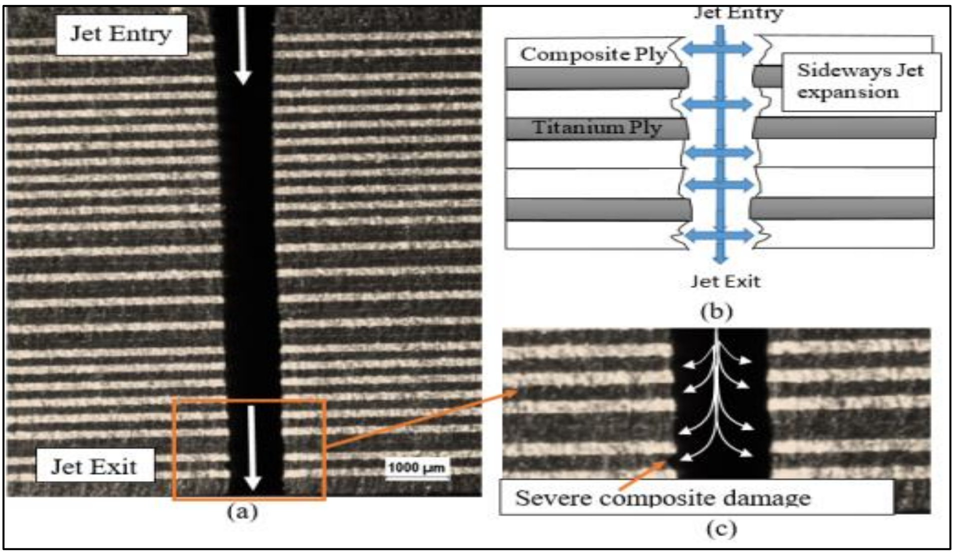

Figure 3.6. Kerf characteristics of 10.5 mm thick specimen, (a) jet direction on the kerf wall, (b) schematic view of the kerf, (c) exit kerf [84]

According to results of this survey, it is right to conclude that kerf taper can be improved substantially by implementing high pressure (600 MPa), minimum traverse speed (50,8 mm/min), high load ratio and high mixing tube/orifice bore ratio (0,23-0,33). Moreover, surface quality of transverse kerf (Rz=9,4µm) can be increased by utilizing low pressure (380 MPa), low traverse speed (50,8 mm/min), high load ratio and high mixing tube/orifice bore ratio (0,5). Compared to other conventional dry machining methods, AWJC technology was more outstanding process due to its properties of low tool wearing, minimum titanium chips and minimum ply deterioration. Alongside, topological characteristics of machined surfaces as well as material removal mechanism were viewed by way of SEM, optic microscope (OM) and surface profilometry. An observation that can be drawn from these is that titanium was sent away by shearing, scratching and ploughing and the composite material matrix was sent away by shearing, but graphite fibers were taken out by micro scale burring, brittle rupture, and bending damage.

Selvam et al. studied on performance of the AWJC for glass/carbon fiber reinforced epoxy matrix hybrid composite material. The work-piece size was 800×200×25 mm and manufactured by hand lay-up technique. In this paper, authors searched various cutting factors with regards to surface roughness and kerf taper by taking advantage of response surface experimental design method. As a consequence of response surface methodology, it was beheld that the lower stand-off distance the lower kerf taper and the higher kinetic energy of jet system the lower surface roughness. For the best values of kerf taper (0.408) and surface roughness (3.38μm), optimal values of process parameters were identified as following: traverse speed of 137 mm/min, abrasive mass flow rate of 454 g/min, water pressure of 300 MPa and stand-off distance of 2 mm [85].

Gnanavelbabu et al. scoped abrasive waterjet machining of hybrid AA6061-B4C-carbon nanotube (CNT) and analyzed effects of some input parameters (mesh size, water pressure, traverse speed) on surface roughness, kerf characteristic and MMR. In the research, two different compositions of B4C (5, 15 vol. %) and CNT (5, 15 vol. %) were used and the hybrid material was fabricated using stir casting. The results observed by researchers indicate that as long as the volume percentage of reinforcements goes up, kerf taper angle (θmin=0.065°) shown in Figure 3.7 improves and MMR (16.26 mm3/min) scales up. Moreover, provided that volume percentage of reinforcements diminishes, lower surface roughness values (Ra=3,012 µm) can be attained. By the reason of healthy assessment of parameter effects the authors capitalized from Taguchi experimental design method. This design allowed them to find that low mesh size (80#), high water pressure (275 MPa) and high traverse speed (120 mm/min) have to be chosen for maximum material removal and minimum surface roughness [86].

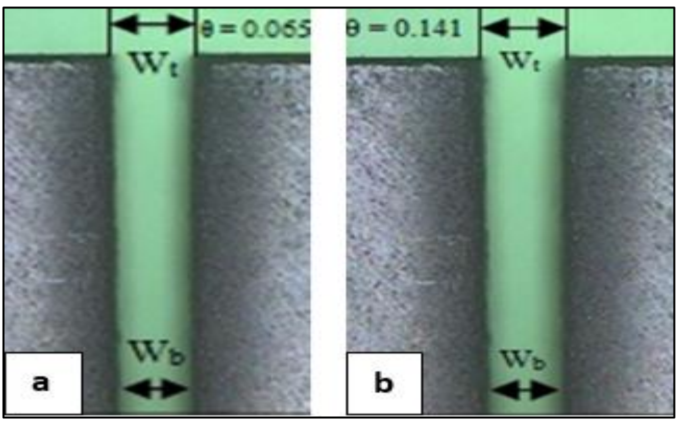

Figure 3.7. Kerf taper angles of the different vol. reinforced samples; high (a), low (b) [86]

Jani et al. surveyed the machinability of hybrid natural fiber composite with and without filler as reinforcement [87]. AWJC technology was exploited in the study and the effects of cutting parameters are evaluated in depth in terms of kerf structure and surface quality. Kevlar-hemp-epoxy (6+24+70 wt.%) and Kevlar-hemp-filler-epoxy (5.5+21+5.5+68 wt.%) composite specimens were subjected to jet cutting in the conditions pointed in Figure 3.8. At the end of the study, investigators particularly underlined that traverse speed was the most powerful factor for kerf wall inclination and material removal rate (MMR). In addition to this, filler (palm shell and coconut shell) addition provided better surface quality and MMR in comparison with kevlar-hemp-epoxy samples.

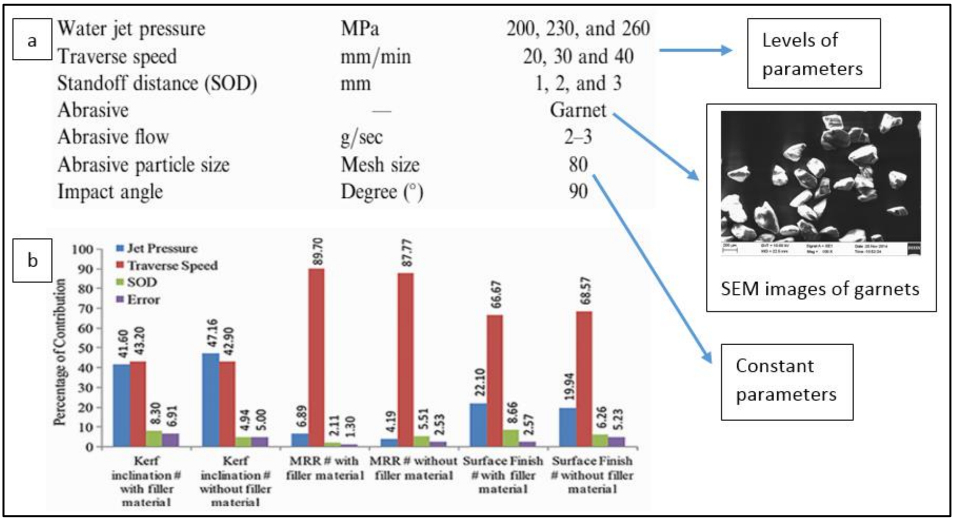

Figure 3.8. Cutting parameters (a) and percentage contribution of parameters to the results with regards to kerf structure, MMR and surface finish (b) [87]

Srivastava et al. made a survey of abrasive waterjet tangential turning of hybrid A359/B4C/Al2O3 composite material [88]. Australian garnet was used as an abrasive and number of revolutions were 400 rpm. Water pressure of 400 MPa, abrasive mass flow rate of 400 g/min and stand-off distance of 9 mm were constant. Hybrid metal matrix composites were manufactured by utilizing electromagnetic stir casting and fabrication process was justified with SEM and X-ray diffraction analysis. From the result values, investigators clearly stated that traverse speed was one of the important factors in the AWJT of the hybrid composite and influenced considerably surface quality as well as MMR. Additionally, increasing traverse speed caused to high surface roughness values because of cutting traces and increasing trend of the traverse speed also brought about low material removal rate. Figure 3.9 demonstrates the relationship between traverse speed and MRR/surface roughness. By looking at the SEM micro images given in Figure 3.10 researchers claimed that surfaces of the turned samples deformed plastically and carried signs of ploughing. Besides, some craters which could be omitted in comparison with high MMR and micro cracks were beheld on surface, because high speed waterjet dislocated the reinforcements.

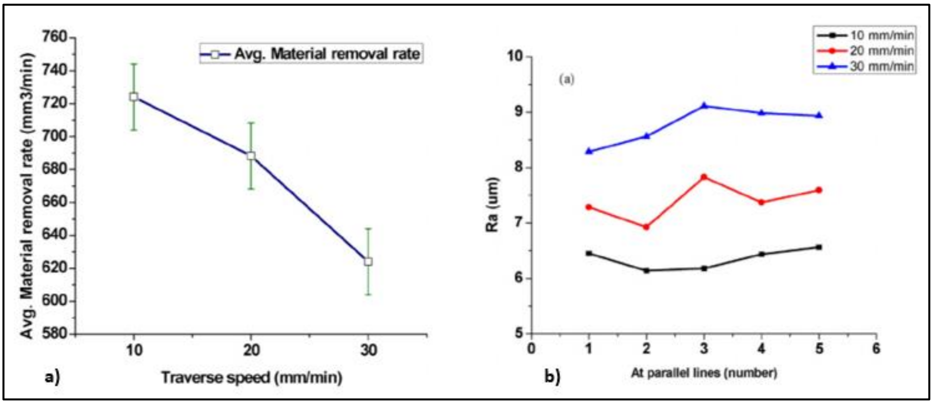

Figure 3.9. Relation between traverse speed and MRR (left) and roughness (right) [88]

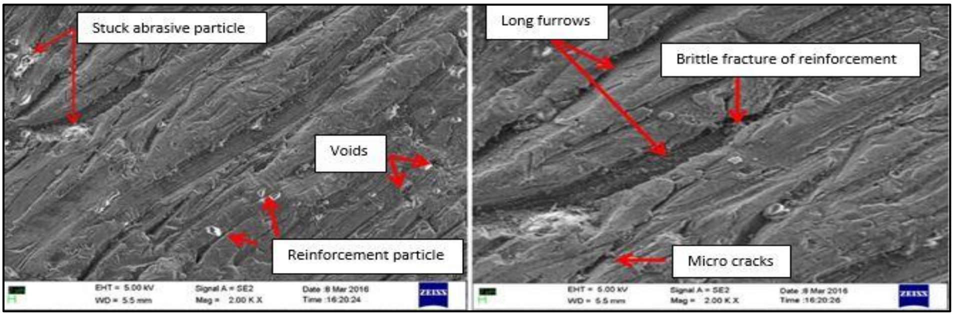

Figure 3.10. SEM images of turned sample surface and some microstructural detections [88]

Irina et al. carried out some experiments on abrasive waterjet trimming capacity of fiber reinforced polymer composites (FRP) [89]. Carbon and E-glass fiber reinforced hybrid epoxy polymer composite materials having 1,66 g/cm3 density and 453,4 MPa ultimate tensile strength were subjected to trimming operation in the study. They mainly focused on delamination and surface roughness after the trimming operation. In order to interpret input parameters comfortably, researchers preferred to use 2^k factorial experimental design because of its ability of indicating the joint effects of input factors and ANOVA tables. Four trimming factors were namely abrasive flow rate, hydraulic pressure, traverse rate and stand-off distance scrutinized. After the results taken from design of experiment, it was utterly observed that stand-off distance, abrasive flow rate and traverse rate had greater effect on the surface roughness than water pressure and abrasive flow rate was the most important parameter for surface roughness. When the delamination problem took into account, it was also similar findings with that of the surface roughness. Minimum roughness and least delamination were noticed at lower traverse speed by raising the kinetic energy or momentum of abrasive waterjet stream.

Srivastava et al. compared AWJT method with wire electrical discharge (WED) turning to construe with correctly hardness properties of hybrid A359/Al_2O_3/B_4C composite substrates [90]. According to results, they found out that surfaces turned with WED exhibited dull appearance while glossy surfaces were beheld after the AWJT demonstrated in Figure 3.11.

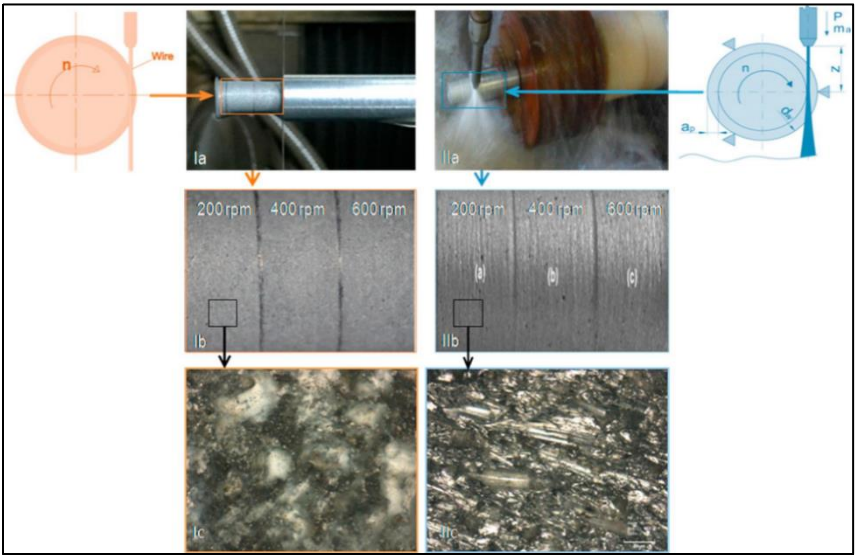

Figure 3.11. WED and AWJ turning processes and comparison of machined surfaces in the same rotational speed [90]

In microscopic inspections, researchers mentioned that re-solidification problem occurred immediately after WED turning by the reason of vaporizing and melting behavior of the substrate and decomposition of zinc/brass wire, but nevertheless, even though AWJT caused some pits, craters and micro cracks all of them could be omitted when it material removal rate capability was taken into consideration. Besides, it was observed that hardness variation was considerably low in AWJT in comparison with WED turned sample surfaces due to recast layers and AWJT process didn't lead to any microstructural changes near the turning area. Rotational speed had affirmative influence on surface roughness for both methods. However, quality of WED turned surfaces were better than that of AWJT while process time in AWJT was shorter than that of WED turning due to the fact that the process generally works in slow traverse speed values (0.1-0.3 mm/min).

Raj and Kanagasabapathy searched AWJ machinability of hybrid AA7075-$ZrSiO_4$-hBN and the effects of input parameters on performance characteristics. Three unlike composition were set by changing only $ZrSiO_4$ percentage (%5, 10 and 15). Cubic boron nitride amount was kept constant at %5. Water pressure, traverse speed, abrasive flow rate and mesh size were inputs while surface roughness and kerf taper were outputs. After the tests and measurements, investigators explained that lower traverse speed (90 mm/min) resulted in at least kerf taper and maximum abrasive flow rate (440 g/min) gave rise to minimum surface roughness because of the sufficient interaction between abrasive particles and reinforcements. At higher traverse speed of 150 mm/min, disassembly of hBN particles triggered formation of voids which were responsible for badly surfaces. They also expressed that water pressure (250 MPa) should have been at the maximum value to obtain quality surfaces and lowest kerf taper and what's more; when the percentages of $ZrSiO_4$ in the hybrid went up, possibility of wide kerf angle and poor surfaces also ascended. In a similar vein, increasing of $ZrSiO_4$ ratio altered the effect of abrasive flow rate and it brought about negative results due to erosion of garnet particles on the aluminum matrix [91].

3.2. Discussion and Future Opportunities/New Horizons

The subject of abrasive water jet machining of the hybrid composites is thought as relatively new for many researchers and engineers and especially nowadays, technical studies about that escalate in a noteworthy manner. If we analyze these investigations, it can be noticed that water pressure, abrasive properties, stand-off distance and traverse speed are the most favorite input parameters. Concordantly, surface roughness and MMR are seriously dominant as output factors but to reduce the process to this limited frame may give rise to a mistake. In addition to these input and output factors, some technological/water system parameters (i.e: impact angle, orifice diameter, nozzle type) and output properties (depth of cut, waviness, etc.) also can be checked up on in the next surveys for hybrids since finding out optimum machining parameters not only develops output properties and blocks unnecessary energy consumption but also facilitates low cost sample production. Today's modern industry gives more importance to production of low cost and high-performance components. On the other hand, environmental sensitiveness, recycling in the production and green manufacturing subjects are very momentous for manufacturers in terms of both mechanical/physical features of products and cost effectiveness. Currently, in production of hybrid composite materials, material science researchers try to integrate industrial wastes and natural based fillers (fly ash, expanded perlite, coconut shells, rice husks, etc.) into metal or polymer matrix as a reinforcement element because of their high potential answering desired performance conditions and recycling ability. With these efforts, manufacturing of low cost, low density and high-performance hybrids is aimed for several sectors from automotive to construction. At the same time, machining issue of this kinds of hybrids emerges necessarily as they must be cut or machined to fulfill basic functions in real service or test conditions. Abrasive waterjet technology can be considered as a great option for that purpose, because neither it emits any hazardous gas and leads to dirt nor damages filler and matrix structure during cutting or turning. The idea of manufacturing of green hybrid materials by means of environmentally friendly AWJ technology is hugely promising for the future studies.

The advantageous properties of hybrid nanocomposites have brought about researchers and companies to think benefiting from this material in a lot of different fields. From the lightweight sensors to batteries with greater power output, they have wide using areas. If we look from the viewpoint of mechanical applications, stronger, lighter and stiffer hybrids can be fabricated thanks to nano particles. Since high strength to weight ratios are very important especially for automotive (hoods, doors and fenders), aviation (spars, brake disks and fuselage parts) and aerospace (jet engine components) industries in which fuel savings is critical for economic and environmental aspects, attention to the nano reinforced hybrids increases continuously. Although traditional turning and cutting set-ups are able to machine this kinds of hybrids, values of surface roughness and the risks of tool wear are relatively high. Recently, some investigators begin to tend towards AWJ technology in order to produce better quality nano hybrids but unfortunately studies are very limited yet. Apart from process parameters, surface morphology and deformation mechanism are still unclear and they should be taken into account in the next efforts. In order to form better surfaces and higher removal rates, deformation behavior of nano particles and correct levels of input parameters should be evaluated together.

Syntactic metal foam is a composite material that is also called as a foam due to its hollow interior structure. Generally, its physical structure composes of a metal matrix and hollow or porous reinforcement material varying from ceramics till metals. However, newly, for improving compressive strength and energy absorption capacity, production of hybrid syntactics (some example microstructures are shown in Figure 3.12) also has become more of an issue.

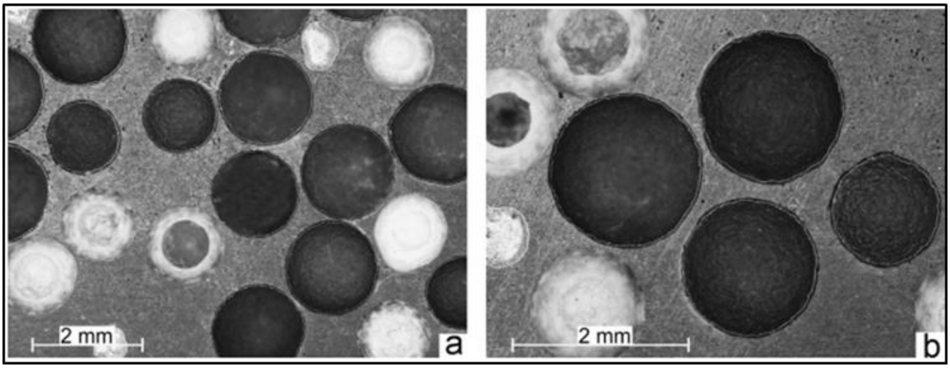

Figure 3.12. Microstructure of aluminum/unlike ceramic hollow spheres syntactic foam [15]

Aviation and automotive are frontier sectors because light and impact absorbable syntactic components either decrease fuel consumption or increase security level in case of probable incident. These foams also are benefited for construction industry as a sound isolator with thin sheets. Hollow or porous particles are generally oxides, carbides, glass bubbles and fly ash cenospheres while aluminum is the most common metal matrix followed by others. Casting methods such as stirring, pressure infiltration, pressureless infiltration, counter gravity infiltration and gas/vacuum pressure infiltration are the major techniques for fabrication of standard syntactic foams, but all these methods have no enough capability to form intricate geometries after the operation. In addition to this, in certain circumstances, syntactic foams are need to be cut immediately after casting because small slices of them can be used both for sound isolation and intermediate layer of sandwich hybrid vehicle parts. In this point, we argue that AWJC process can be introduced as a seconder process and thanks to its ability of cutting rocklike and glassy materials it is a proper method for hybrid syntactic metal foams. During the cutting, possibility of any setbacks, namely kerf taper, surface roughness, waviness, can be diminished by optimizing input and technological parameters just as it could be successfully done for standard hybrid composites. Thus, we consider that it is worth to try the AWJC process for cost effective/high quality hybrid syntactic components.

Hybrid word is a versatile term that is also utilized for process itself and this is called hybrid machining. Main target of the process hybridization is to rise efficiency and to drop total manufacturing costs. Even though hybrid machining processes consisting of AWJM and other techniques such as ultrasonic machining, EDM and WEDM have been tried for different engineering materials by researchers, hybrid composites have not been taken into account yet. We think that hybridization efforts certainly should not be ruled out for machining of hybrid composites since they have a great potential for dimensional accuracy and very high-quality surfaces. In the next efforts, hybrid machining processes can be focused for hybrid composites in detail to gain time and to improve product quality as much as it can be. For instance, with the support of ultrasonic sound waves, total cutting performance and dimensional accuracy of AWJM may change in a noteworthy manner or after the AWJM operation, if there is not a limitation of conductivity stemming from hybrid substrate, WEDM or EDM processes can be applied in order to perform sensitive finish work. AWJ technology is faster and suitable for rough machining, whereas EDM and WEDM are relatively slow but useful for finishing cut, so process hybridization can provide high quality products in a considerably short time by making use of the specific virtues of two unlike methods to a great extent.

4. CONCLUSION

In our work, we reviewed the latest investigations about abrasive waterjet cutting and turning of hybrid composites in depth in order to enlighten the next efforts, comprehend influences of the input and output parameters and gain new bright viewpoints to the interested researchers and engineers. As a result of this efforts, the followings can be listed below;

- Abrasive waterjet technology is a remarkable alternative for conventional cutting and turning methods and it easily machines many kinds of materials from soft polymers to rocklike materials which leads to wear on tool surface and thermal setbacks in traditional techniques.
- Hybrid composites have different types of fibers, layers or particles in a metal or polymer matrix. Owing to high hardness values of reinforcement components, cutting of them is a very problematic state with the classical machining methods but nevertheless, by virtue of AWJC technology benefiting from high pressure water stream and hard abrasives, quality surfaces with high material removal rate can be obtained. In a similar vein, whilst turning of hard fiber or particle reinforced hybrids is hugely difficult and time-consuming job with conventional lathe techniques, AWJT method allows to engineers and manufacturers to solve this problem notably, so risk of the tool wearing is reduced a lot.
- According to latest researches on AWJC/AWJT of hybrid composites, stand-off distance, traverse speed, abrasive flow rate and jet pressure were studied more than other factors as input parameters. Depending on the types of the matrix materials and reinforcement components, prominence levels of the input parameters on the result features may alter.
- Kerf taper is a very important issue after the AWJC process of hybrid composites and it should be minimized as much as it can be. It is really possible that abrasive waterjet technology is able to solve hugely kerf taper and kerf geometry drawbacks by means of proper optimization of input parameters. Precise control of the system which could be done by collaborating works with control and system dynamics engineers. For proper optimization, statistical approaches are also suitable and true understanding of mathematical background of them can contribute future works.
- By comparison with other abrasive types, garnet is more popular and common type in the industrial applications and academic studies. Nevertheless, in some circumstances regarding with hybrids, for instance against olivine, garnet is not always superior from the point of surface quality, so it can be alleged that different kinds of abrasives should be examined in the abrasive waterjet machining of the hybrid composites, thus, better surface quality and kerf characteristics can be achieved.
- The latest experiments and tests on hybrid composites show us that high material removal rates are possible with AWJC and AWJT technologies and this situation can be interpreted as good news for lots of industrial branches. In the next periods, given that average usage rates of hybrids will increase notably, rapid production matter will become very significant with regards to rivalry.
- Design of experiment methods such as Taguchi, response surface and factorial design are able to provide some advantageous to engineers and researchers to probe thoroughly effects of input parameters and their interactions if exist. Right selection of the input parameters and levels of the factors is highly crucial for desired output features. Furthermore, it is true to say that with help of the experimental design methods the best factor combinations for aimed outputs could be found by conducting lesser experiments. This circumstance is also very helpful for hybrid composites as the hybrids have some extra structural parameters (fiber mixture rate, fiber types, fiber lengths, particle types, particle size, particle amount etc.) and these parameters can be simply integrated in the design of experiment methods.
- Conventional turning method can answer customer demands in a limited scale, particularly for dimension sensitive applications. AWJT is deliberated as a real alternative process that can eliminate a lot of drawbacks that lead to chattering, coarse tolerances, chisel wearing and

surface roughness. These handicaps are very common in traditional turning lathe. Since the implementation of the AWJT process on hybrid composites is comparatively new matter, turning parameters like rotation speed and direction, feed rate and number of passes have not been researched at large yet. In the next studies, we think that these parameters and their influences on the result factors will be investigated in detail.

- As it is well known, hybrid composites comprise of different kinds of engineering materials like ceramic, polymer and metal. Compared to other techniques, AWJ technology has no limitations about subject material. It does not matter whether the material is very hard, electrically conductive or chemically stabile, so AWJC process is one step ahead and is more useful than milling, laser cutting and wire electrical discharge cutting. In general, laser cutting is accepted as an alternative for AWJC but it changes temperatures of the cutting edges and in some cases brings about unwanted metallurgical or chemical alterations.
- During and after the operation, both AWJC and AWJT generate no fumes, hazardous gases and dust. With increment of usage of the hybrid composites, need of the cutting and machining will go up automatically. As a result of this, urging composite sectors and academic circles to abrasive waterjet technology will be really beneficial in terms of clean processing.

Nomenclature

AMMC: Aluminum Metal Matrix Composite
AWJ: Abrasive Water Jet
AWJC: Abrasive Water Jet Cutting
AWJM: Abrasive Water Jet Machining
AWJT: Abrasive Water Jet Turning
CFRP: Carbon Fiber Reinforced Polymer
CNC: Computer Numerical Control
CNT: Carbon Nano Tube
EDM: Electrical Discharge Machining
FML: Fiber Metal Laminates
FRP: Fiber Reinforced Polymer
HAZ: Heat Affected Zone
MEMS: Micro-Electro-Mechanical Systems
MMC: Metal Matrix Composites
MRR: Material Removal Rate
OM: Optic Microscope
OVAT: One Variable at Time
SEM: Scanning Electron Microscope
SOD: Stand-Off Distance
WED: Wire Electrical Discharge
WEDM: Wire Electrical Discharge Machining
WJM: Water Jet Machining

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