Chapter

Abrasive Water Jet Cutting: A Risk-Free Technology for Machining Mg-Based Materials

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Abstract

Mg-based materials are considered to be the most machinable of all materials due to their good machinability. Though conventional machining of Mg-based materials is a topic that has been widely discussed, they are associated with ignition issues. Ignition risk in conventional machining of Mg-based materials thus cannot be denied and should be avoided. Literature has witnessed ignition risk when machining temperature reaches above 450°C during turning and milling processes, and some cases are reported with fire hazard. In order to obtain the safest machining atmosphere, abrasive water jet machining, a most desired machining technology for machining Mg-based materials, is discussed in the present chapter. The text covers ignition risk in conventional machining of Mg-based materials, an overview of non-traditional methods for machining Mg-based materials, advantages of abrasive water jet machining over other methods, abrasive water jet linear cutting of Mg alloys and composites, and drilling of Mg alloys. Experimental investigations are carried out to know the effect of abrasive water jet process parameters on machining Mg alloys and Mg nanocomposites. Surface topography of cut surfaces is analyzed. Suitability of abrasive water jet in drilling Mg alloys is justified by comparing results with holes drilled by conventional drilling and jig boring.

Keywords: ignition risk, Mg, machining, AWJ cutting, AWJ drilling, topography

1. Introduction

During the past decades, significant research has been carried out on the development of novel magnesium-based materials as traditional alloys and composites using different techniques such as casting, powder metallurgy, disintegrated melt deposition etc.; several secondary processing techniques have also been used to enhance the physical and mechanical properties of Mg-based materials, namely, heat treatment, equal channel angular pressing (ECAP), forging, rolling, hot extrusion, etc. Mg-based materials have turned out to be a choice for industries to replace structural materials like cast iron, steel, copper, etc. In particular, automobile industries have become potential market for Mg-based materials. Increase in demand for Mg-based materials for lightweight automotive components witnessed significant growth during recent years. Global forecast report has estimated Mg alloys market to reach 1.30 billion in 2018 and is projected to reach USD 2.37 billion by 2023 at a compound annual growth rate (CAGR) of 12.7% during forecast period [1]. Extended applications in 3Cs (consumer electronics, computers, and cell phones) have enhanced the demand and growth of Mg-based materials in global markets. With this increase in demand, researchers and engineers are continuously focusing on machining aspects of Mg-based materials to expand the industrial applications through advanced machining technologies.

2. Ignition risk in conventional machining of Mg-based materials

Even though Mg-based materials are considered to be the easiest materials to machine due to their low cutting forces, well-formed chips, and good surface finish, they are highly inflammable. The risk of ignition rises when process temperature crosses 450°C, which is close to the melting temperature of Mg [2, 3]. In spite of advantages such as 50% lesser cutting forces compared to aluminum in turning operations and cutting tools retaining sharp edges for a long period, Mg possess high affinity to oxygen at higher temperatures (>450°C). Mg is also reactive in nitrogen and carbon dioxide atmosphere even in the absence of oxygen. Ignition temperature of Mg can be controlled by adding alloying elements such as calcium and beryllium and rare earth metals such as cerium, lanthanum, or yttrium but cannot be avoided [4–6]. Ignition of chips occurs during high-speed machining especially during finishing operations, i.e., chips in the form of powder (<500 μm) tend to explode. These powders not only create safety hazard but can also damage the machine tool components [7].

Weinert et al. [2] highlighted the importance of removing the chips from the workspace of the machine tool during machining. It was reported that the hot chips generated during machining contains up to 90% of the heat generated at the cutting zone, which can significantly affect the workpiece and machine components by transferring the heat. Thermal expansion of both machine tool and workpiece thus required to be identified. The risk of fire and potential damages to the workpiece as well as the machine tool can be significantly controlled by fast and reliable removal of the chips. Controlling the temperature during machining is therefore crucial in preventing the ignition. Ning Zhao et al. [8] reported three types of ignition that occurs during face milling of AM50A magnesium alloy which includes sparks, flares, and continuous flares. Among three types of ignitions, it was reported that flares and continuous flares are dangerous for safe production. Therefore in order to reduce the temperature of chips and powder-type dust generated during machining, many researchers have used cutting fluids during machining process [9–13]. The use of cutting fluids also resulted in reaction with magnesium which forms hydrogen, a highly explosive and flammable gas. For this reactivity issue, mineral-based oils are recommended during machining of Mg-based materials by selecting appropriate process variables. However, it is necessary to take proper care at higher cutting speeds to prevent flank buildup (FBU) on tools while using mineral-based oils because formation of flank BUE and burrs creates another problem in machining Mg-based materials due to high thermal expansion coefficient, and this may further lead to decreased accuracy of machined surfaces. The presence of FBU increases cutting forces and affects surface quality [14].

On the other hand, conventional machining of Mg-MMC is also challenging. In addition to ignition risk, the presence of harder ceramic particles in MMC causes serious abrasion of the tool, which shortens the tool life, and increasing volume fraction of ceramic particles leads to increased cutting forces [15, 16]. This in turn, increases the manufacturing cost. Tonshoff et al. [7] investigated tool wear in turning Mg-MMC containing SiC particle reinforcement (MELRAM 072TS) using polycrystalline diamond (PCD) tool and PCD, TiN-coated tools. The tin-coated tool was destroyed immediately due to the impact of SiC particles. Chipping off the layer was observed in PCD tool. Furthermore, molten material was observed on edges of all tool materials. This adhesive effect between work and tool material not only creates a negative influence on machining forces but also leads to creating poor surface quality.

Xiangyu Teng et al. [17] studied micro machinability of Mg-MMC containing titanium (Ti) and titanium diboride (TiB_2) nanoparticles. AlTiN-coated tungsten carbide micro-end mills were used to machine Mg-MMNC. Machined surface was characterized by surface morphology and surface roughness. Investigations revealed cutting tool was affected by chip adhesion. This chip adhesion found more in machining Mg-MMC containing nano-sized Ti particles compared to Mg-MMC containing TiB_2 nanoparticles. Further it was reported that cutting forces while machining Mg/Ti MMC found nearly two times compared to Mg/ TiB_2 nanocomposites. Increase in cutting forces increased the roughness of surfaces and also induced burrs on slot edges of cutting tool. The surface of cutting tool was also affected by coating peeling off while machining Mg/TiB_2 nanocomposites.

Therefore machining Mg-MMC with conventional methods is also associated with several problems such as increased cutting forces, surface roughness, and chip adhesion to tool material. It is really challenging to achieve a surface quality and accuracy MMC through conventional machining. Apart from these difficulties, conventional machining system for Mg-based material requires provision of storing chips in closed containers or the use of chip removal systems, protecting the machines using protection systems against explosions, adequate availability of class D fire extinguishers in the machine area, storage of dry sand in containers, and safeguarding the operators and installation of alarm systems in order to create the safest workplace [2, 18]. Indirectly these actions result in higher processing costs. Cost-effective processing of Mg-based materials is therefore an essential criterion to expand the application areas.

3. Overview of nontraditional machining of Mg-based materials

Conventional machining demonstrated significant importance in machining Mg-based materials when compared to NTM over the years, despite serious problems such as ignition risk, tool wear, shorter tool life, and surface finish. Researchers are required to pay more attention to NTM processes to overcome difficulties of conventional machining. Literatures have witnessed the successful implementation of NTM processes in cutting a wide range of materials for different applications. Despite few limitations, nowadays NTM processes are having greater potential than conventional machining. However better understanding is required on the suitability of NTM before being applied in practical fields.

During the past decades, numerous research efforts have been placed on NTM machining of different types of materials including MMCs. However, very limited studies are reported on machining of Mg-based materials and Mg-MMC through NTM techniques. Advantages and limitations of few NTM processes such as laser beam machining (LBM), laser-assisted machining (LAM), electric discharge machining (EDM), and AWJM are discussed in the present section.

Nowadays EDM is extending its application areas by cutting a wide range of metals and MMC. EDM uses high thermal energy to remove the material by electric spark erosion. EDM regardless of the hardness of materials has typical advantages in cutting intricate and complex shapes. EDM eliminates mechanical stresses, vibration, and chatter during machining since there is no direct contact between tool and work material. EDM is especially used in the production of die, mold, automotive, surgical, and aerospace components. EDM is most suitable for machining of geometries with high aspect ratio and microstructures. EDM can drill a hole of size 0.1 mm [19]. Ponappa et al. reported with high aspect ratio holes of ϕ 0.5 mm with 12 mm height drilled by EDM in Mg/Al_2O_3 nanocomposites. However, recast layer was observed at some portion of the cut zone due to a series of spark generation and generation of high temperatures between the tool and work [20]. Generation of high temperature during the process can alter the target material properties. The presence of reinforcement particles makes machining of MMC slower by creating difficulties due to the breakage of conductivity caused by non-conductive and high melting points of reinforcement particles. Breaking of wires in WEDM during the process is one of the major problems. Due to high temperature caused between tool and work interface, wire electrode breaks usually in the top edge of the machined surface. Another major limitation of EDM falls in its incapability in cutting non-conductive materials.

LBM uses thermal energy to remove the material using a laser beam by melting and vaporizing. Unlike EDM, LBM is not only limited to conductive materials; it can be applied for a wide range of materials [21]. The major advantage of LBM lies in its capability to produce geometrically complex shapes and miniature holes. LBM have the capability to make slot as low as 0.25 mm width. Generally, machining operations in LBM includes drilling and grooving. Mechanically induced material damage, cutting forces machine vibration, and tool wear are absent in LBM [22]. Machining speed and material removal rate can be increased in LAM. However, an increase in machining speed resulting in a rough surface that splits out into striations is caused by the unsteady motion of molten layer or repeated blockage of plasma. LAM is having its own limitations when machining Mg-based materials, the reflectivity of Mg can result in inadequate heating which limits the cutting capability, and also small chips produced during machining tend to ignite when in contact with the laser beam. Therefore, LBM of thermally sensitive Mg-based materials is risky. Melting of reinforcement material and chemical reactions were reported in LBM of MMC which also affects the microstructure.

AWJM technology is one of the leading and fastest growing NTM technologies for cutting a wide range of materials such as metals, stone, tiles, plastics, FRP, composites, food, ceramics, rubber, etc. In AWJ cutting the impact of solid particles at high velocity along with water at high pressure removes the target material by means of erosion [23]. AWJ uses cold water during the process that eliminates slag deformation and dross waste that is generally found in plasma and laser cutting processes. Additionally, both garnet (abrasive) and water used in the cutting process can be recycled [24]. The AWJM process is therefore environmentally friendly when compared to other cutting processes. The process is also clean and does not involve chips, chemical reactivity, and air pollution. Water jet eliminates dust by carrying away the eroded material and does not generate fumes which are generally present in other NTM processes [25]. In recent years AWJM has received tremendous attention especially in machining difficult to machine and thermally sensitive materials [26, 27]. Due to its versatility, ease of operations and extended capabilities, AWJM has become the hot choice among different machine tools for manufacturing industries. Application areas include automotive, aerospace, construction, medical industries, etc.

Unlike other NTM processes (EDM, LBM/LAM) AWJM does not include higher processing temperatures, and most importantly there is no HAZ [28]. Therefore machined surfaces are neither affected by remelting nor by recrystallization. Thus AWJ cutting technology offers risk-free machining of Mg-based materials by eliminating HAZ. The only drawback of AWJM is lesser efficiency in creating high-quality surfaces which can be expected from the other two methods. Bimla Mardi et al. [29] investigated the surface integrity of Mg-based nanocomposites generated by AWJ. Feasibility of AWJ in machining Mg-based nanocomposites was reported. Experimental results were analyzed and compared under varied traverse speeds. It was concluded that lower traverse speeds give better surface finish and higher traverse speed results in the poor surface finish. Furthermore, it was concluded that for machining Mg-based MMC, AWJ machining is the most promising method with good surface finish and minimum subsurface damage.

Due to omnidirectional cutting capabilities of AWJM at higher feed rates, it is considered to be the fastest machining option for MMCs [30]. Based on available literature, it can be concluded that even though LAM/LBM and EDM can be efficiently used to machine Mg-based materials, the risk of ignition cannot be avoided. Therefore AWJM is the most suitable and risk-free machining technology for Mg-based materials. Below are some of the distinct advantages of AWJ machining over other methods:

- No heat affected zone.
- Lower setup time.
- No microstructural and microhardness changes occur in the machined surfaces [31].
- No thermal distortion, high machining versatility, and high flexibility [32].
- Simple programming methods.
- High productivity.
- Higher feed rates can be achieved especially in MMC.
- Elimination of dust.

4. AWJ machining operations and process parameters

AWJ technology is being utilized by many modern industries such as automotive, aerospace, chemical processing, environmental engineering, construction engineering, medical, etc., for performing different operations such as industrial cleaning, surface preparation, paint, enamel and coating stripping, manufacturing operations, etc. Since this chapter is mainly focused on machining aspects, only linear cutting, drilling, turning, and milling machining operations are discussed. AWJM involves a number of process parameters to achieve qualitative and quantitative results. Geometry and quality of the machined surfaces depend mainly on the appropriate selection process parameters. **Table 1** shows detailed AWJ process parameters for different machining operations.

In the present chapter, in order to identify the machining capability of Mg-based materials, experimental investigations on AWJ linear cutting and AWJ drilling operations were carried out. The effect of input parameters on the depth of penetration and surface integrity of AZ91 alloy and nanocomposites was analyzed. AWJ drilling of AZ91 Mg alloy was carried out and compared with conventional and jig boring processes. Overview of AWJ is turning, and AWJ milling operations were discussed. Further research possibilities in AWJ machining Mg-based materials are also highlighted.

AWJ parameters	Machining parameters			
	Linear cutting	**Drilling**	**Milling**	**Turning**
Water pressure Jet diameter Abrasive particle size Abrasive material Abrasive flow rate Abrasive condition Mixing tube length Mixing tube diameter	SOD AOI TS Material thickness Number of passes	Angle SOD Dwell time Material thickness	TR Lateral increment Number of passes Number of sweeps	Rotational speed Direction of rotation Angle Traverse rate Initial diameter Final diameter DOC
Output variables (dependent)				
	DOP Width of cut Surface finish	Diameter Drilling time Hole shape	VMR Depth control	Turned diameter Surface finish Machining time

Table 1.
AWJM process parameters for different operations [33].

4.1 AWJ linear cutting

Being most important in industrial applications, depth of penetration and surface quality decides the efficiency, process capability, and performance of AWJ. During past decades theoretical and experimental investigations were made to determine the cutting performance of ductile materials such as aluminum and its alloys, mild steel, stainless steel, copper, brass, etc., with AWJ machining technology [34–36]. However, limited studies are available on AWJ machining of Mg-based materials. Therefore in the present section, experimental investigations were carried out to know the penetration capability and surface quality of AZ91 Mg alloy and nanocomposites by AWJ linear cutting. OMAX 1515 state-of-the-art AWJ machine equipped with 30 Hp direct drive pump to create water pressure ranging 100 MPa to 345 MPa shown in **Figure 1** was used to carry out experiments. The machine also supported with gravity feed-type abrasive hopper and pneumatically controlled three axis movements with traverse speed capacity of 1 mm/min to 8000 mm/min.

AZ91 Mg alloy and nanocomposites with volume percentage of 1, 1.5, and 2% Al_2O_3 nanoparticles (<50 nm) produced by stir casting were used to conduct experiments. Elemental composition of AZ91 is shown in **Table 2** (obtained by EDS) analysis. **Figure 2** shows EDS spectrum of AZ91-nanocomposites containing 1% Al2O3.

Figure 1.
State-of-the-art AWJM technology.

Al	Zn	Mn	Si	Cu	Fe	Be	Magnesium
9.41	1.42	0.25	0.03	0.003	0.015	0.001	Rest

Table 2.
Elemental composition of AZ91 Mg alloy.

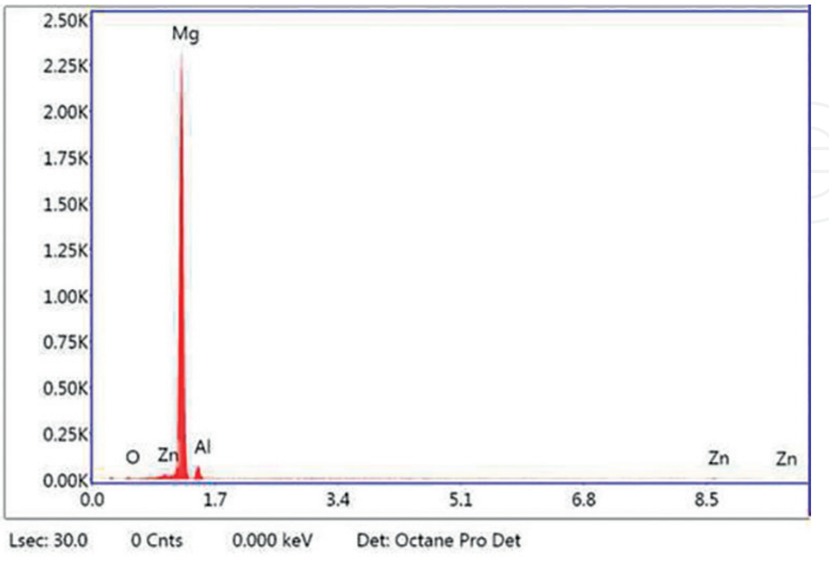

Figure 2.
EDS spectrum of AZ91/1% Al2O3 nanocomposites.

4.1.1 Experimental conditions

In the present study, influence of only major dynamic parameters such as water pressure, traverse speed, and abrasive mass flow rate on the depth of penetration and surface integrity is considered. Topography and microstructural features of cut surfaces were examined using SEM technique. All the linear cutting experiments were carried out using standard 80 mesh garnet particles. L18 orthogonal array was used to conduct cutting experiments. Specimen was prepared into trapezoidal shape to make through cuts. This method of making trapezoidal shape is popular among different methods to determine the DOP. Profile projector was used to obtain exact depth of cuts since this method gives accurate values compared to other methods [37]. **Table 3** shows detailed experimental conditions.

4.1.2 Results and discussion

4.1.2.1 Effect of input parameters on the depth of penetration

The effect of control factors such as water pressure, traverse speed, and mass flow rate on the depth of penetration was analyzed by considering mean values of depth of penetration. **Figure 3** shows the effect of input parameters on the depth of penetration in AZ91 magnesium alloy and nanocomposites. It can be observed that depth of penetration increases with an increase in water pressure, due to the increase in kinetic energy of water and abrasive particles with an increase in water pressure. In contrast, more energy of the particles as well as water was able to remove more material. It is also observed that, when compared to Az91 Mg alloy, penetration ability of Mg nanocomposites decreases with increase in vol. % of Al_2O_3, since MMCs offer resistance to the jet penetration due to the presence of harder nanoceramic particles.

Dynamic parameters				
Water pressure (P_w)	Unit	Level 1	Level 2	Level 3
	MPa	100	200	300
Traverse speed (t_s)	mm/min	150	300	400
Mass flow rate (m_f)	g/min	309	425	611
Constant parameters				
Abrasive mesh size		80		
Orifice (jewel) diameter	mm	0.35 and material is sapphire		
Focusing nozzle diameter	mm	0.76 and material is tungsten carbide		
Angle of target		90°		
Standoff distance	mm	1.5		

Table 3.
Detailed machining conditions selected for cutting experiments.

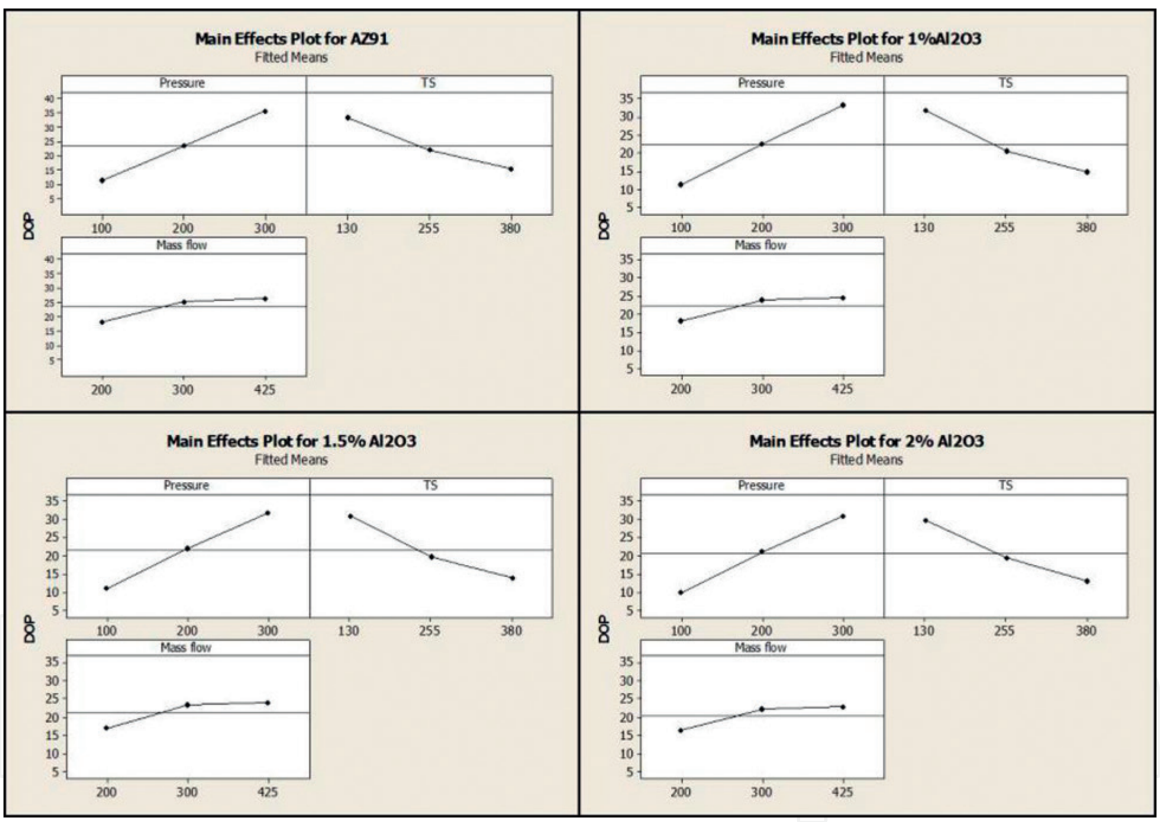

Figure 3.
Effect of input parameters on depth of penetration.

Relationship between traverse speed and depth of penetration indicates that increasing the traverse speed lowers the impact of numbers of abrasive particles and results in decreasing the depth of penetration. The influence of traverse speed on the depth of penetration, therefore, lies on the exposure time of abrasive water jet. The lesser the exposure time, the more the depth of penetration. The effect of mass flow rate on the depth of penetration indicating an increase in abrasive mass flow increases the depth of penetration due to the participation of large number of abrasive particles in cutting. This trend remains stable till the value of mass flow rate reaches to a critical level. After that depth of penetration decreases since the higher abrasive flow rates sometimes block the nozzle and at higher abrasive mass flow rates. Due to some damping mechanisms such as generation of water-solid films and abrasive particles, collision in mixing chamber significantly reduces the specific energy of abrasive particles [38]. It is evident from the previous studies that the velocity of abrasive particles decreases with an increase in abrasive mass flow rate [39–41]. This reduces the depth of penetration.

4.1.3 Topography of cut surfaces

Literatures have witnessed solid particle impact in the material removal process by abrasive water jets by erosion [42]. In ductile materials, material removal process is divided into two zones such as micro cutting zone observed at the top surface and deformation zone, which occurs at the bottom surface [43]. Similar observations were noted down in surfaces of MMC [44]. In the micro cutting region, material removal takes place by sharp-edged and angular abrasive particles at low cutting depths. Impact of the abrasive particles at shallow angles promotes micro cutting, termed as "cutting wear." At larger cutting depths, the impact angle of abrasive particles becomes more obtuse and causes "deformation wear." Plowing is responsible for material removal in the bottom region due to spherical abrasive particles [45]. Deformation wear zone is affected by surface waviness caused due to instabilities of the water jet. Loss of jet energy reduces the capacity of material removal creating waviness and thus dividing cutting and deformation wear zones as shown in **Figure 4**.

4.1.4 Integrity of the cut surfaces

A surface characteristic of cut surfaces is evaluated in two regions, i.e., smooth cutting zone (SCZ) and rough cutting zone (RCZ) as shown in **Figure 5** [46, 47]. Surface integrity of cut surfaces can be obtained by measuring surface roughness in both regions using either a contact-type or noncontact-type measuring device. Most of the researchers have used optical profiler for measuring surface roughness which is the noncontact type. Several researchers have used contact-type roughness measuring devices, which use a stylus tip to measure waviness of the surface.

In the SCZ, initially the surfaces are clear and smooth but affected by the formation of uniform wear tracks in the direction of the jet traverse at the bottom portion of the SCZ. Since this zone is shared by both micro cutting and deformation modes, surface roughness increases further down the surfaces. In RCZ the surface roughness is affected by striations caused by deflected water jet. **Figure 5** shows the presence of deviated wear tracks with waviness produced by a stream of the

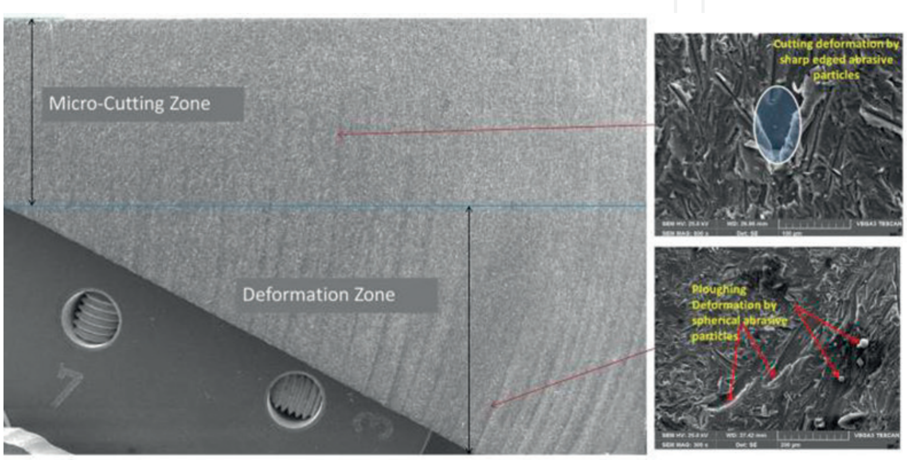

Figure 4.
Material removal mechanism.

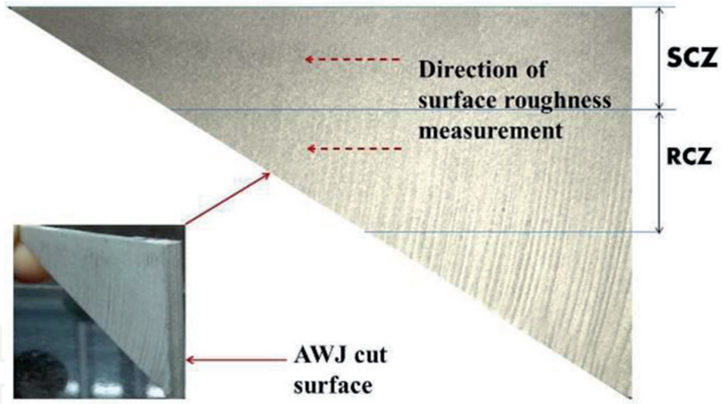

Figure 5.
Regions of cut surfaces.

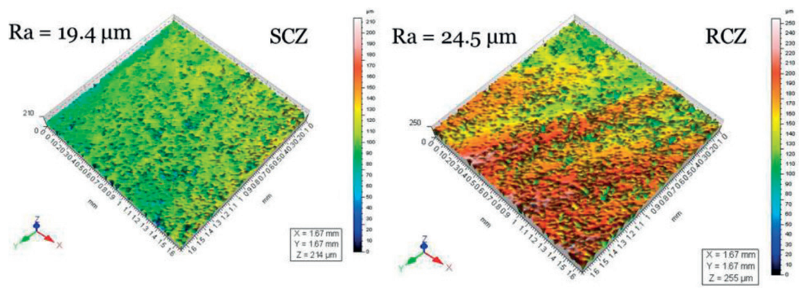

Figure 6.
3-D images of SCZ and RCZ.

deflected water jet. In cutting AZ91 magnesium alloy, the embedment of spherical abrasive particles and pocket-like structures is observed at the shallow impact angles as shown in **Figure 4**. The surface roughness at RCZ zone is higher than SCZ zones. **Figure 6** shows the 3-D images of SCZ and RCZ generated in optical profiler.

The surface roughness of the AZ91 and nanocomposites in the SCZ zones is found between 5–20 μm and 20–40 μm in RCZ at lower traverse speeds. This is due to the increase in the impact of a number of abrasive particles and exposure time. Surface roughness is a function of water pressure because the kinetic energy of water jet increases the velocity of particles which in turn increases the surface quality, and also the influence of abrasive mass flow rate on surface roughness depends mainly on water pressure. However, at higher traverse speeds, an increase in water pressure increases the surface roughness. Hence traverse rate is the most significant parameter in deciding the quality of cut at two zones.

4.2 AWJ drilling

Earlier studies have proven that AWJ technology is a viable tool for drilling different materials such as pure commercial aluminum, Al6061, brass, S1030 low-carbon steel, D-3 cold working tool steel, etc. AWJ drilling does not affect microhardness and mechanical properties of the material [48]. Burr-free surfaces can be obtained in AWJ drilling. Drilling at different angles is also quite convenient with AWJ. In AWJ technology drilling can be performed by tilting the cutting head up to 590. Though many types of research are carried out in drilling different materials, no work has been notably reported on drilling of Mg-based materials through AWJ technology. In the present section, experimental investigations are carried out to know the features of holes drilled by AWJ in Mg alloy. Surface roughness and taper of drilled holes are measured and compared with holes drilled by conventional drilling and jig boring.

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↓**Method**	→**Hole dia** / ↓**Drilling conditions**	**ϕ3 mm**	**ϕ5 mm**	**ϕ10 mm**	**ϕ15 mm**	**ϕ20 mm**
AWJM	P	300 MPa constant for all holes				
	M_f	425 g/min constant for all holes				
	SOD	1.5 mm constant for all holes				
	Time in min	2.5	3.5	5.4	6	7.9
Conventional drilling	Speed	1200 rpm	1100 rpm	1000 rpm	900 rpm	800 rpm
	Feed	0.1 mm/rev: constant for all holes				
	Time in min	3	2.5	1.5	1.5	1.5
Jig boring	Speed	1200 rpm	1100 rpm	1000 rpm	900 rpm	800 rpm
	Feed	0.1 mm/rev: constant for all holes				
	Time in min	2.9	2.3	1	1	1

Table 4.
Conditions for drilling holes.

Five holes with diameter 3, 5, 10, 15, and 20 mm were drilled in 40 mm thick AZ91 Mg alloy block. Roundness and taper of drilled holes were obtained using profile projector. Drilling time of each hole was also determined and compared. The conditions at which the holes were drilled are given in **Table 4**.

Table 5 gives actual dimensions of five holes drilled by different methods measured using a profile projector with taper percentage. Diameters of drilled holes were measured in both sides (top and bottom) to know the variations in drilled holes. It can be observed that compared to holes drilled by conventional methods, AWJ-drilled holes were affected by the taper. The taper was comparatively higher in drilling less than 5 mm hole. This is due to hit back of jet from the channel during the drilling process, and this trend will last until full penetration is achieved. Meanwhile, the base hole will be abraded by the perimeter of the jet and thus affects the shape (roundness) and diameter of the hole as shown in **Figure 7**. When compared to other methods, AWJ-created holes are slightly larger than the required size and require comparatively more time to drill holes.

Figure 8 shows a cross section of holes drilled in AZ91 Mg block using three different methods. The surface roughness of drilled surfaces with diameter 10, 15, 20 mm were measured using contact-type Taylor and Hobson surface roughness measuring instrument by considering 5 mm cutoff length. Measurement was taken in three regions of the depth (top-middle-bottom) of drilled surfaces. The average of three readings in each zone is noted down. **Table 6** gives surface roughness (Ra) of drilled surfaces.

Desired Φ	Conventional		Taper %	Jig boring		Taper %	AWJ		Taper %
	Φ at top	Φ at bottom		Φ at top	Φ at bottom		Φ at top	Φ at bottom	
2.5	2.384	2.451	0.17	2.375	2.435	0.15	3.526	2.321	3.012
5	5.129	4.955	0.44	4.930	5.071	0.35	5.841	5.263	1.445
10	9.960	9.981	0.05	10.013	10.069	0.13	10.555	10.161	0.985
15	14.796	15.133	0.84	14.790	15.196	1.09	15.375	15.021	0.885
20	19.549	20.211	1.66	19.867	20.207	0.85	20.355	20.100	0.637

Table 5.
Dimensions and taper percentage of drilled holes.

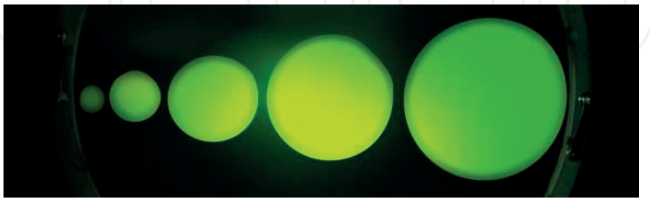

Figure 7.
Roundness of holes produced by AWJ.

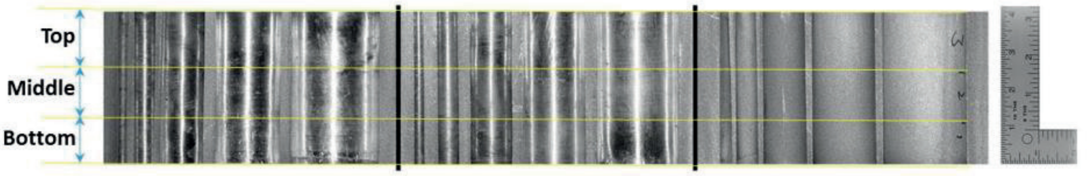

Figure 8.
Cross section of drilled holes.

Measurement zone	Conventional	Jig boring	AWJ
Top (0–13 mm)	2.65 μm	0.93 μm	3.96 μm
Middle (14–26 mm)	3.99 μm	1.48 μm	4.47 μm
Bottom (26–40 mm)	4.30 μm	1.57 μm	5.09 μm

Table 6.
Ra of drilled surfaces measured in different depths.

Figure 9.
Adhesion of material to the drill bit.

From **Table 6**, it can be observed that the surface roughness of AWJ-drilled holes is more than the other two methods in all the regions. Surface roughness increases with increase in depth. This is due to loss of jet energy and a decrease in cutability of the abrasive particles at higher depths and thus deteriorates the surface quality. However comparable results can be achieved by AWJ technology when compared to conventional drilling. Despite few drawbacks, AWJ drilling offers several advantages over other methods. No burrs are observed in the AWJ-drilled surfaces, unlike conventional methods. Adhesion of the material to the drill bit, especially in drilling less than 5 mm diameter holes, is observed in both conventional methods as shown in **Figure 9**. Formation of FBU increases heat generation during drilling. This tendency of the Mg-based materials to adhere to the drill bits is a serious problem. Formation of FBU is completely absent in AWJ drilling since there is no direct contact between tool and work. Therefore risk-free drilling is possible through AWJ technology.

5. Other alternative operations with AWJ

The versatility of AWJ technology makes it suitable for cutting almost all engineering materials. Besides cutting and drilling of materials as discussed in the previous section, AWJ technology has been successfully implemented to perform some of the essential machining operations such as turning, milling, finishing, and piercing. Several investigations are carried out on these machining operations with promising results. Thus AWJ technology has become a potential machine tool for modern machining industries. This section highlights the suitability of AWJ in turning and milling operations based on past studies. Research possibilities in AWJ technology are also discussed.

5.1 AWJ turning

In AWJ turning, workpiece is rotated while the jet is traversed parallel to the axis of workpiece to produce the required shape. Research efforts on AWJT were started by Hashish during 1987; since then several experimental investigations on different machining operations were made to produce near net shape parts with faster material

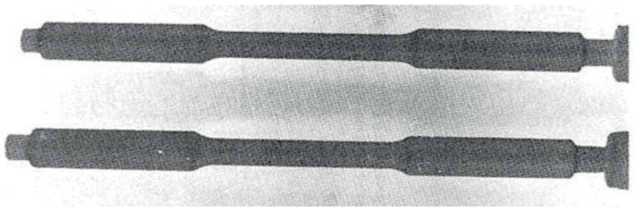

Figure 10.
Tensile specimens produced by AWJ in Mg-B_4C MMC [49].

removal rate [49]. Investigations on samples of Mg-boron carbide MMC, glass, and aluminum concluded suitability of AWJ for performing alternative machining operations.

Preliminary investigations on AWJT has revealed that AWJ turning is less sensitive to the type of material being machined unlike conventional machining, no microstructural changes were observed on AWJ machined surfaces, tensile properties of cylindrical specimens turned by AWJ remains unaffected, and relative insensitivity of AWJ to length-to-diameter ratio of work piece enables the process to turn long and small diameter components. **Figure 10** shows the tensile test Mg-B_4C MMC specimens produced by AWJT. No appreciable microhardness changes were observed during turning of Mg-B4C MMC and aluminum. No ignition issues were observed during machining.

Investigations conducted by the University of Rhode Island [50, 51] have witnessed machining of screw threads on composite materials. Furthermore, it was revealed that a thread produced by AWJ has an excellent potential to provide sufficient joint strength when compared to adhesive bonded joints. Minimal structural damage on machined surfaces was observed during microstructural examinations. Still there are plenty of research opportunities which are open in AWJT field to expand the applications of AWJ in different areas. Detailed studies on AWJT economics, a wide range of machining parameters, and multi-objective optimization still need to be considered in order to make AWJT the most economical and alternative tool for machining.

5.2 AWJ milling

Milling is one of the important alternative machining operations that can be performed by AWJ. AWJ milling has been systematically utilized where conventional machining of material is insufficient to apply. The capability of AWJ in cutting complex shapes with controlled depth has witnessed the success of AWJ milling. Recent studies have proven AWJ technology as the best alternative for milling manufacturing standard flat tensile specimens [52]. In earlier days conventional milling was the only method which was accepted internationally for manufacturing of standard sheet-type tensile specimens. Drawbacks of conventional milling in manufacturing flat tensile specimens, such as difficulties in clamping of thin sheets, requirement of milling tool with same diameter as filler radii of the tensile specimen, contouring several times to obtain desired shapes etc., have created circumstances to choose alternative nontraditional methods [53].

Advantages such as lesser manufacturing time, reasonable material removal rate, and minimal deformation stress made AWJ milling a viable alternative for conventional milling. Feasibility of AWJ in milling was first proposed by Hashish in 1989 [54]. Investigations on volume removal rates and surface finish of different materials such as titanium, aluminum, and Inconel were made through linear cutting experiments. Cutting parameters such as traverse speed, number of passes, etc. were varied at different levels. Results were compared with other methods, and some of the critical observations noted from the results are listed below:

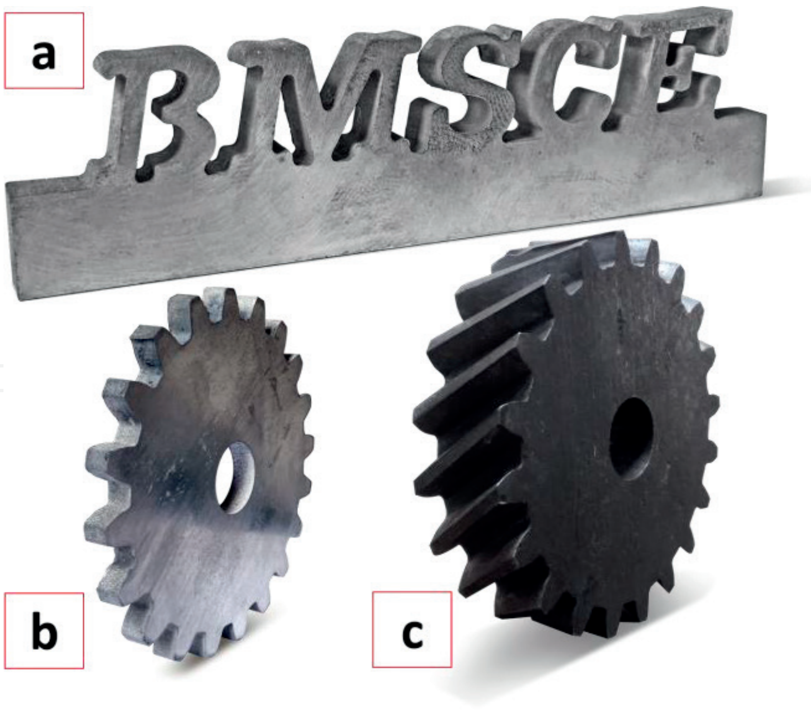

Figure 11.
Profile of helical gear produced by AWJ (a) logo in AM60 Mg alloy, (b) spur gear profile in AM60 Mg alloy, and (c) cast iron helical gear profile.

- Waterjet nozzles that are used for slot cutting are sufficient to do milling operations.
- Reasonable material removal rates can be achieved by AWJ milling with relatively low power levels.
- AWJ machining is environmentally acceptable and safe.
- In terms of energy utilization for material removal, AWJ milling is the most efficient method over other methods.

Figure 11 shows some of the complex shapes (a) and profiles of helical (b) and spur gear (c) produced by AWJ milling.

6. Conclusion

Present study gives comprehensive overview of abrasive water jet cutting technology for machining Mg-based materials and Mg-MMCs. Penetration capability of AZ91 and Mg nanocomposites was investigated through linear cutting experiments. Drilling of holes with different sizes in AZ91 was performed using conventional drilling and jig boring and compared with holes drilled by AWJ. These experimental investigations on machining operations such as linear cutting and drilling have revealed suitability and capability of AWJ. The present study also highlighted the application areas of AWJ in milling and turning of different materials including MMCs. However experimental investigations made in the present study was preliminary and requires detailed process economics, optimization, and comparative studies to extend and explore research possibilities. Performance, capability, and applications of AWJ in machining different grades of Mg and Mg-MMC can be further extended with the use of advanced modeling techniques.

Based on preliminary studies on linear cutting and drilling operations, the following conclusions can be made:

- Pressure remains dominant in deciding depth of cut in both AZ91 Mg alloy and nanocomposites. Traverse speed decides the quality of cut generated by water jets. The lower the traverse speed, the higher the surface quality, and surface quality deteriorates with increase in traverse speed. The abrasive mass flow rate has the least effect on both penetration and surface quality. Similar observations are obtained in machining different ductile materials with AWJ.

- Drilling of AZ91 Mg alloy also revealed acceptable results when compared to conventional drilling and jig boring. No fire ignition issues aroused during both machining operations. The use of profile projector is found to be the accurate and straightforward way of finding the depth of penetration in linear cutting operations and obtaining roundness of AWJ-drilled holes.

- Apart from linear cutting, AWJ can be successfully utilized for other machining operations such as milling and turning of Mg-based materials. Complex shapes and profiles of different types of gears can be easily produced by AWJ with lesser time compared to other NTM and conventional methods.

- AWJ machining of Mg-based materials is the less studied area. Primary results presented in the chapter contribute to the optimization of AWJ process in machining Mg-based materials.

- Overall it can be concluded that AWJM technology could be ideal for flexible and risk-free machining of Mg-based materials and Mg-MMCs.

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Nomenclature

ECAP	equal channel angular pressing
CAGR	compound annual growth rate
FBU	flank buildup
BUE	built-up edge
MMC	metal matrix composite
NTM	nontraditional machining
LBM	laser beam machining
LAM	laser-assisted machining

WEDM	wire electric discharge machining
EDM	electric discharge machining
AWJM	abrasive water jet machining
HAZ	heat-affected zone
SOD	standoff distance
AOI	angle of impact
DOP	depth of penetration
DOC	depth of cut
VMR	volume material removal
EDS	energy-dispersive spectroscopy
SCZ	smooth cutting zone
RCZ	rough cutting zone

Symbols

P_w	water pressure
t_s	traverse speed
m_f	mass flow rate
L	length of cut
h_t/d_p	depth of penetration
θ	wedge angle
ϕ	diameter

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