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Abrasive Machining Techniques for Biomedical Device Applications

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Abstract

Abrasive machining and finishing processes are techniques of material removal that are introduced in order to cut workpiece materials with the nominal mechanical and thermal residual stresses. These processes utilize continuous material removal by abrasive medium that can be in forms of water, abrasive particles or a mixture of these two. The benefit of eliminating excessive mechanical cutting force results in enhanced cutting of brittle or soft materials. On the other hand, removal of thermal cutting source provides a capability of cutting plastics and diminished the chances of thermal cracking in workpiece. Abrasive finishing processes have been introduced as complementary to abrasive cutting techniques in order to increase the precision and surface quality of manufactured parts. The most common of these techniques are water jet machining (WJM), abrasive jet machining (AJM), abrasive water jet machining (AWJM) and magnetic abrasive machining processes such as magnetic abrasive finishing (MAF), magneto-rheological abrasive finishing (MRF) and magneto-rheological abrasive flow finishing (MRAFF).

Keywords: Abrasive Machining; Water Jet Machining; Abrasive Finishing; Biomedical Devices

Abbreviations: WJM: Water Jet Machining; AM: Additive Manufacturing; AJM: Abrasive Jet Machining; AWJM: abrasive water jet machining; MRF: Magneto-Rheological Abrasive Finishing; MAF: Magnetic Abrasive Finishing; MRAFF: Magneto-Rheological Abrasive Flow Finishing; CBN: Cubic Boron Nitride; WC: tungsten carbide; HAZ: Heat Affected Zone; CNC: Computer Numerical Controlled Machines; CN: Numerical Controlled

Introduction

Manufacturing processes are the key to advance in technology. In every field of science, there is a need to fabricate parts and produce devices from those parts. There are many different processes such as casting, forming, machining and welding that are in charge of manufacturing parts and machines from years and decades ago. These processes have developed over time and increased the accuracy of the parts fabricated. However, there is no limit in accuracy and it can always be enhanced [1]. As years ago, the researchers were working on millimeter scales and nowadays they are more focused on micro/nano meter scales. Among all of these processes, machining is the key process that changes the produced bulk materials into parts in different sizes and shapes [2]. In addition, with a higher accuracy in machining processes, there is a higher accuracy in fabricated parts that result in more precise machines and devices that give us a higher quality of results [3]. In recent decades, numerical controlled and computer numerical controlled machines (NC and CNC, respectively) have been developed that significantly improved machining speed and accuracy [4].

In recent years, many different manufacturing processes have been introduced that enhance the quality of production with an increased rate of production. Among these, high speed machining [5], additive manufacturing (AM) [6], laser welding [7], and abrasive processes are the most reliable ones [8]. All the mentioned processes utilize computer-controlled systems and provide a high degree of freedom in manufacturing while they offer a high accuracy in submicron scales. However, there are deficiencies with additive manufacturing processes as they mostly implement extreme thermal, chemical or thermochemical conditions in order to fabricate a part. On the other hand, the same happens during different types of welding. High speed machining, especially when it comes to high speed machining of metal matrix composites, leaves a considerable thermal and mechanical residual stress in the matrix or workpiece. However, all of them are reliable techniques of manufacturing.

With a deeper investigation of these processes reveals that abrasive machining processes offer the lowest adverse effects on workpiece materials. Different types of abrasive machining are introduced that water jet machining (WJM), abrasive jet machining (AJM) and abrasive water jet machining (AWJM) are the most common ones [9-11]. These techniques utilize the abrasion power of the cutting media (i.e. water, abrasive particles, slurry of water and abrasive particles, and a mix of abrasive slurry and air). The impact of these materials to the surface of workpiece removes the material and in a progressive process, the workpiece is cut into the desired shape and depth. However, these processes are working on high-speed and high-pressure basis and require precautions and materials selection prior to implementation. In order to optimize these processes or model their behavior, numerical and continuum mechanics approaches may be applied [12-15].

Abrasive machining processes are reliable methods of material cutting. However, in ultra-precision applications there might be a need of higher precision or a higher surface finish. Another type of abrasive processes are introduced that implement magnetic abrasive particles and control the material removal during the machining process [16]. Magnetic abrasive approaches are mostly in the scale of finishing, although in some cases they have been used for machining purposes. There are several types of magnetic abrasive finishing that magnetic abrasive finishing (MAF), magneto-rheological abrasive finishing (MRF) and magneto-rheological abrasive flow finishing (MRAFF) are the most common ones [8,17]. The finishing process becomes crucial when there is a risk of fatigue failure or corrosion initiation in the rough surface of a material. Although other post-processes such as coatings can be implemented to reduce corrosion susceptibility of materials, the fatigue life is in need of a high surface quality [18,19]. The following discussion explains these processes, parameters, advantages and disadvantages. A brief discussion on applications is provided that might be a clue for further investigations.

Water Jet Machining (WJM)

WJM is a type of abrasive machining processes that erodes substrate materials by friction between a focused stream of water that travels in high speeds up to 900m/s (Mach 3). The water stream in this high speed acts as a solid material and removes material from the target upon impact [20]. However, there have to be careful considerations regarding equipment design and reliability as the process consists of parts working under high-pressure/speed. A WJM setup consists of hydraulic pumps, accumulators, tubing and nozzle, in general [21]. However, there are more parts if a detailed view is needed. Figure 1 represents a schematic view of WJM and the components of this system. sThe hydraulic pump is one of the most important components of WJM systems. This unit is in charge of preparing the required pressure for the working medium, i.e. water, in order to reach to high velocities mentioned above. The hydraulic pump can feed multiple waterjet nozzles at the same time, based on the application and required pressure. It has been mentioned that the pressure of hydraulic pumps working in WJM can reach to more than 100bar. In the next step, the pressure produced by hydraulic pump is used to actuate an intensifier system that increases the pressure of the water stream to high pressures up to 4000bar. A reciprocating mechanism increases the pressure of inlet water with assistance of an accumulator that keeps the high-pressure water in a stable state with no fluctuation in pressure. After this section, the high pressure water is transported to nozzle head with specially designed tubing system. The nozzles are in charge of controlling cutting conditions for soft or hard materials and how deep is the cut [1,22,23]. Mostly, the nozzle tips are made of synthetic diamond, cubic boron nitride (CBN) and tungsten carbide (WC) as these materials offer high wear resistance [24,25]. On the other side of cutting surface, there is another part known as catcher that collects the working water and reduces cutting noise, simultaneously.

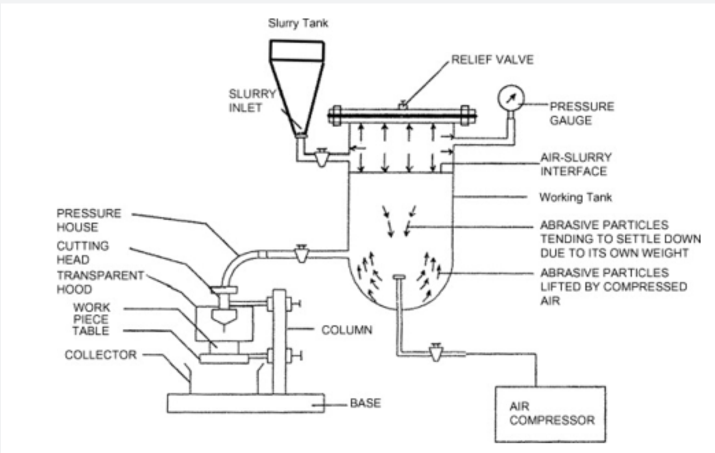

Figure 1: A schematic WJM setup with different parts [21].

The affecting parameters of WJM are mostly nozzle conditions, working medium properties and substrate material characteristics. Each of these parameters affect the quality of cut to a significant extent. The distance between nozzle head and workpiece surface is another crucial variable of WJM [26]. It has been mentioned in literature that the optimum distance has

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to be in the range of 2-5mm. depending on workpiece material toughness and the pressure on nozzle head, this distance can be modified [27]. As an instance, in lower nozzle diameters and lower gap distance, the diameter of the material removal rate increases as the extremely high-pressure water tends to diverge after exiting the nozzle. As a result, by increasing the gap distance while a smaller nozzle diameter is used, a more focused stream of water jet will be obtained [28]. As reported in literature, the cutting medium undergoes high pressures in the range of 150-1000MPa with a velocity range of 500-1450m/s. the mentioned ranges provide high flexibility in adjusting cutting quality and depth with a controlled material removal rate (MMR). However, the cutting medium must provide reliable incompressibility properties and low viscosity in order to minimize loss of energy during the cutting process. The most common medium in use for industrial applications is water while alcohol and vegetable oils are being used in some specific conditions [29]. WJM process is mostly used for ductile materials as the high speed of impact will fracture brittle materials [30]. Table 1 represents a summary of various parameters affecting final MMR in WJM.

Based on the properties of WJM, researchers have utilized this process for various applications such as cutting, drilling, deburring and surface treatment/cleaning. Also, it has been implemented in different industries that produce food products and it has been proven to be a safe technique [31]. In addition, as this process only works based on friction between waterjet and workpiece material, there are no residual chemicals, no emitted toxic fumes and as WJM does not utilize thermal features during material processing, there is no heat affected zone (HAZ) that causes material microstructure change and consequent residual thermal stresses [32]. Also, WJM-treated surfaces exhibit reliable surface roughness and geometrical accuracy. As a result, this process can be an alternative to the current processes of fabricating biomedical devices (e.g. implants, artery stents, bone fixations, surgery tools, etc.) [33].

Table 1: A summary of process parameters of WJM.

Parameters	Variables				
Working medium	Chemical/physical properties	pressure	Flow rate	Velocity	Viscosity
Nozzle head	Geometry	Diameter	Gap distance	Material	Moving speed
Substrate	Thickness	Material	Feed rate	-	-

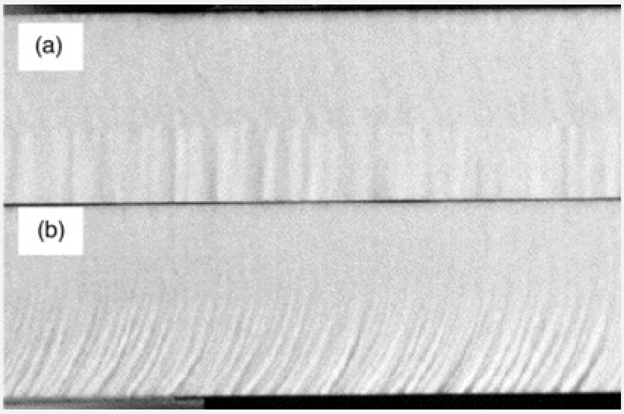

Figure 2: Cut surface of ceramic after applying WJM process [37].

Most of these parts are made from stiff materials that are difficult to fabricate via different types of manufacturing processes. Some of these materials are stainless steel 304/316L, NiTi alloys and reinforced metal/polymer matrix composites [34]. From other benefits of WJM, the following ones can be named: low part deflection, less burr production compared to conventional machining specially in reinforced composite materials, no need for tool design by eliminating tool/material contact, no dust of dry machining, ability to cut soft materials such as foams and sponges, and ability to cut aluminum and copper that their high reflectivity makes difficulties in laser beam machining. However, WJM cannot be used as a high production rate process as it needs costly maintenance [35-37]. Figure 2 depicts effect of WJM process on cutting interface.

Abrasive Jet Machining (AJM)

AJM is another type of abrasive machining processes that is similar to WJM but the active cutting medium is a mixture of pressure and high-speed air and abrasive particles. AJM utilizes a nozzle head that concentrates the flowing stream of air-particle mixture toward the target material and by numerous impact of abrasive particles on substrate, material removal takes place [38]. Mechanism of AJM is similar to WJM regarding pressurizing the gaseous medium. A high-power compressor increases gas pressure to 0.2-0.7MPa and transfers it to a high-pressure membrane full of abrasive particles. In the next step, the high-pressure gas is mixed with particles and transferred to the nozzle tip that is controlled by a computer unit [39]. At the moment that abrasive jet exits nozzle head it can reach to speeds

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in range of 150-300m/s. with consecutive impacts of abrasive particles, material is removed from surface of workpiece and cutting process takes place [40,41]. Figure 3 shows a schematic micro-AJM setup.

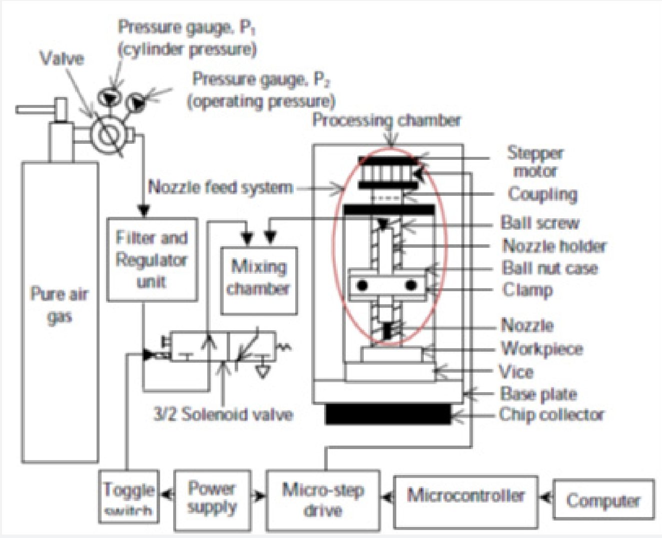

Figure 3: Schematic setup of micro-AJM process [41].

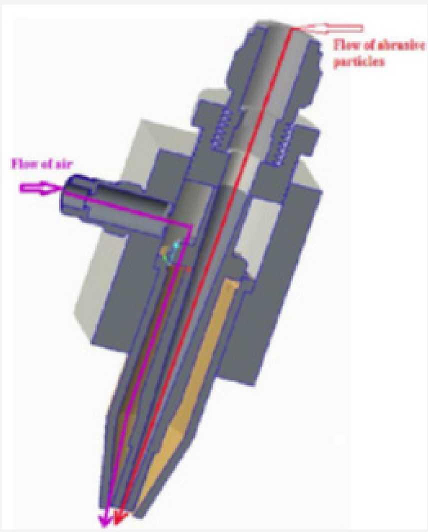

Figure 4: A CAD model of AJM nozzle head [46].

The carriage gases used in AJM are mostly air, CO_2 and nitrogen. It has to be concerned that the oxygen level of air maintains a standard level in order to prevent any ignition [42]. The ignition happens since the process is on a dry nature and produces tiny particles of workpiece material and at the same time small abrasive particles are available. On the other hand, the high speed of air causes a ready-to-ignite condition and there might be a risk of explosion. The most common abrasive materials utilized in AJM are Al_2O_3 and SiC particles are they are highly resistant to wear and enhance MRR of abrasive processes [43]. However, other abrasive materials can be used in finishing processes with less MMR. From these materials, sodium carbonate and magnesium carbonate are the most common ones. Since wear and erosion is significantly high at the nozzle head, specific materials are needed that tungsten carbide (WC) is the most common one [44]. Applications of AJM are mostly cutting, drilling, etching and deburring of extremely hard and tough materials such as ceramics, metal oxides, glass and hard superalloys [45]. Such as WJM, there are different parameters that affect cutting quality. Gap distance, particle size, jet pressure and velocity are the most critical parameters. AJM is a dry process and there is a risk of hazardous dust generation that needs special catcher facilities in order to eliminate the risk. AJM is a solid alternative for machining processes on brittle materials such as glasses, bio-glasses and bio-ceramics. From this point of view, there is a need for more and deep investigation of bio-applications of this process. Figure 4 depicts an AJM nozzle head [46].

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There are numerous parameters affecting AJM quality and each of these parameters has a continuous range of variation. Utilizing the wide range of combinations of these parameters, many different applications can be achieved rather than machining. The main sub-applications of abrasive jet process can be micro-etching and cleaning of corroded metallic structures. Also, this flexibility ensures capability of AJM in rough machining and finishing steps [47]. AJM is similar to WJM in cutting mechanism and prevent any HAZ regions and consequent thermal cracking. In addition, there is no need to design specific tools for different materials and the abrasive particles are ceramic compounds that do not react with metallic, polymeric, ceramic and glass workpiece materials [48]. However, this process suffers from divergence of abrasive jet as it is difficult to control the path of a solid stream. In addition, the process speed is low and there is always a chance of surface inclusion by abrasive particle penetration into substrates. Also, the process utilizes solid particles that transfer their energy at the moment of impact and as a result, AJM is unable to cut soft materials such as foams and sponges. Table 2 presents process parameters of AJM process in a brief.

Table 2: Process parameters of AJM in brief.

Parameters	Variables				
Working medium	Composition	Ratio	Viscosity	Pressure	Velocity
Abrasive particles	Composition	Concentration	Particle size	Velocity	Particle geometry
Substrate	Thickness	Material	Feed rate	-	-

Abrasive Water Jet Machining (AWJM)

AWJM is a modified version of WJM and AJM. In fact, the advantages of these two processes are combined to form a composite process of AWJM [49]. As it has been mentioned, WJM is mostly implemented in cutting of materials that are not as hard as AJM material targets. However, AJM produces more dust and noise during machining process while it is unable to cut soft materials. In order to have a multifunctional process of abrasive machining, AWJM is introduced to benefit from helpful properties of the former processes [50]. The mechanism of the process is similar to WJM and AJM in a many aspects but the cutting medium is a mixture of water and abrasive particles. This mixture significantly enhances MMR of cutting process with a higher power of material removal in hard substrates [51]. The most common ratio of water-abrasive medium is 7:3 while in many research reports, air flow has been added to the mixture [52]. The water portion of the abrasive slurry is usually used as an accelerator. It means that the water part gets accelerated and prior to exiting from nozzle head, abrasive portion is introduced to the stream and water carries the abrasive particles toward the target surface [53]. Existence of water cools down the process and prevents any tiny heat generation and at the same time damps the impact force of particles and provide AWJM with the ability to cut sharp edges [54]. Figure 5 shows a schematic design of AWJM and Figure 6 shows an AWJM nozzle head.

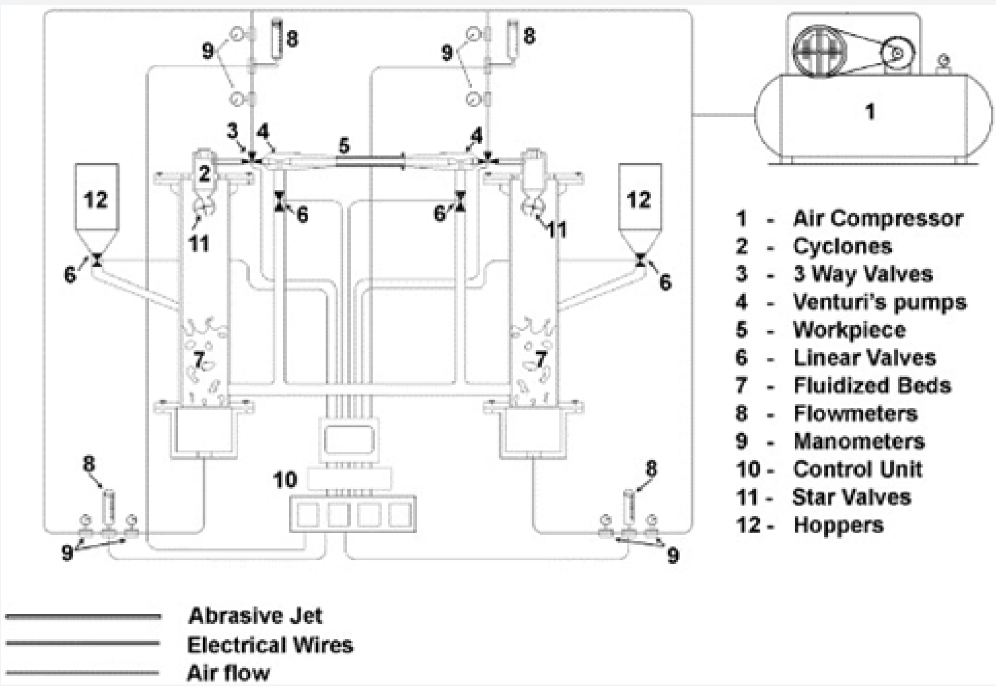

Figure 5: Schematic view of AWJM process design [55].

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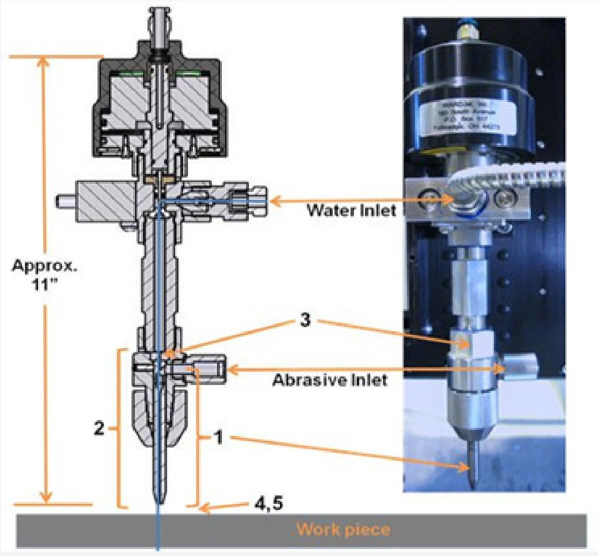

Figure 6: AWJM nozzle head in engineering design and reality [56].

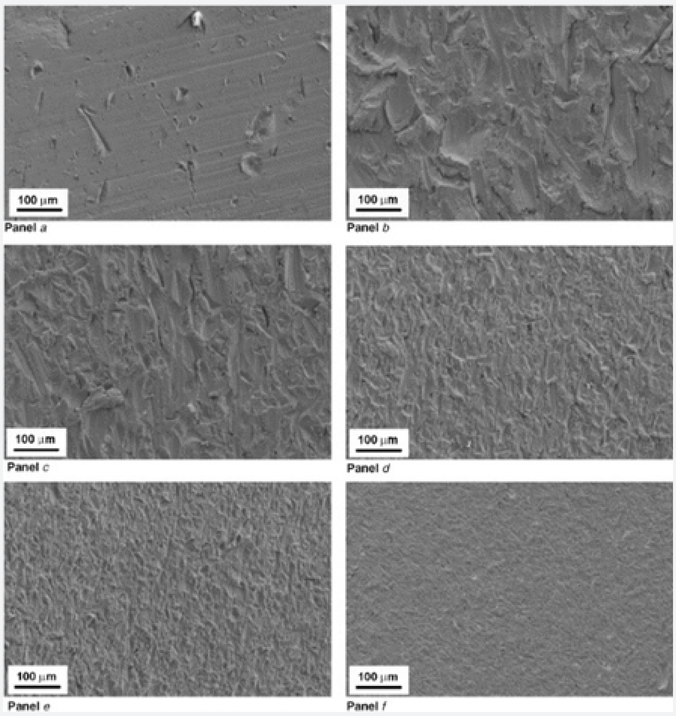

Figure 7: Different surface qualities achieved by different process parameters in AWJM [55].

Table 3: AWJM process parameters in brief.

Parameters	Variables				
Working medium	Composition	Ratio	Viscosity	Pressure	Velocity
Abrasive particles	Composition	Concentration	Particle size	Velocity	Particle geometry
Substrate	Thickness	Material	Feed rate	-	-

AWJM process is known as a solid and reliable machining process with the minimal side effects such as micro-crack formation at the sharp corners, thermal cracks and residual stress and loss of accuracy in high depth of cut. Combining all these features with a CNC nozzle head, the flexibility of the process increases to the extent that almost every engineering material with different complexity in design can be machined [55]. This process provides a high potential of machining bone implants

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and other complicated biomedical devices, with the lowest post-processing concerns. In addition, the process enjoys a higher machining speed compared to WJM and AJM that increases the rate of production. Also, AWJM offers a higher accuracy of cutting and can be used in order to cut parts of complicated structures. The water portion of slurry can be modified or replaced by other low-viscosity liquids in order to enhance corrosion resistance of the cut surface [56]. The additional parameters of AWJM offer a higher combination of possible machining conditions and as a result gives a higher degree of freedom in applicable workpiece and abrasive material. Table 3 represents the effective parameters of AWJM. Figure 7 shows an AWJM-treated surface.

Magnetic Abrasive Machining

Abrasive machining processes are mostly designed to have high MMR and they are used in higher depths of cut and rough cutting. Although with modification of process parameters a high surface quality can be achieved, they need to undergo a fine finishing process for precision applications [57]. In order to overcome this issue, a novel idea has been introduced. Combining abrasive particles with magnetic ones and control the behavior and movement of this mixture using an external magnetic or electromagnetic field can provide a finishing condition, especially in complex geometries. These processes are designed in order to have a lower MMR that results in a higher surface finish [58-60]. There are some common magnetic processes that have been deeply investigated such as magnetic abrasive finishing (MAF), magneto-rheological abrasive finishing (MRF) and magneto-rheological abrasive flow finishing (MRAFF) [61,62]. In a study, be Dehghan Ghadikolaei et al. [63], they have utilized MRAFF process in order to investigate finishing quality on different materials and specially stainless steel 304 as a reliable biomedical material. They have reported a significant surface roughness enhancement. Figures 8 & 9 represents a schematic MRAFF process and equipment.

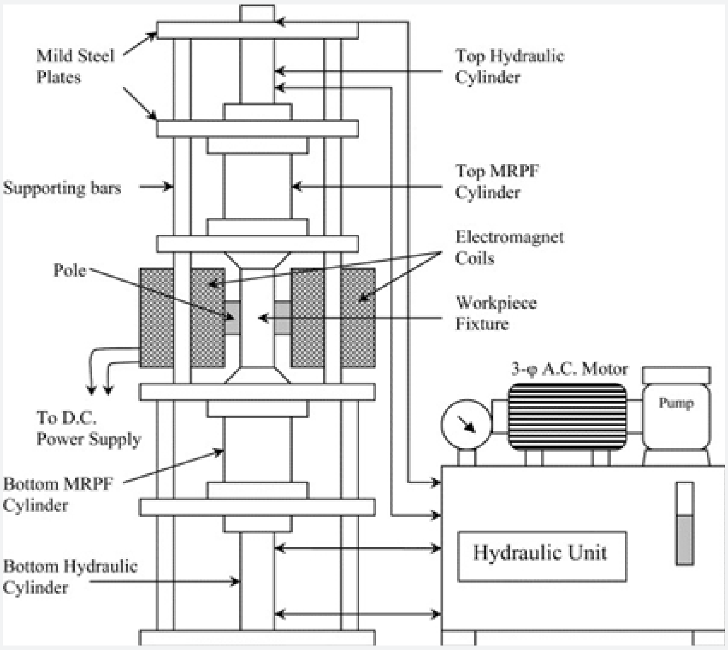

Figure 8: Schematic overview of MRAFF process [61].

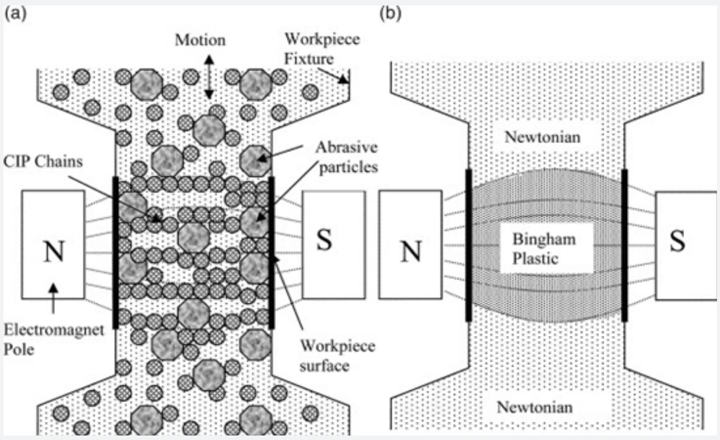

Figure 9: a) Mechanism of MRAFF, b) Change in rheological behavior of MR- fluid [61].

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Magnetic abrasive processes are widely used in bio-applications and bone implants for the surfaces need a high surface quality, such as joints. These areas are usually in irregular geometries and it is difficult to polish them with other abrasive processes [64]. But magnetic abrasive techniques have a high control over material removal in different regions as an external magnetic field controls the process [65]. In general, there are two different types of magnetic processes. One utilizes magnetic abrasive particles and the other one works based on a slurry of magnetic abrasive particles dispersed in a carrying liquid. Both processes benefit from the precise control of magnetic field but the latter one enjoys an excellent precision. Figure 10 represents a view of finishing zone [66]. As it can be seen, the abrasive particles are mixed with magnetic particles.

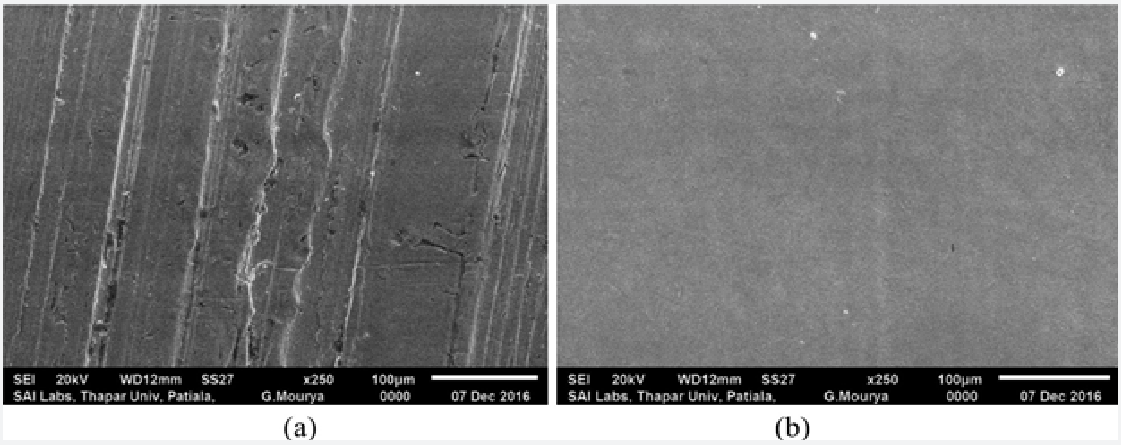

Figure 10: SEM micrograph of copper alloy substrate before and after 7 minutes of magnetorheological nano- finishing [72].

As the external field is applied, the magnetic particles form a clog-shape structure and change the shear properties of the slurry in that specific region. As a result, the abrasive particles are trapped in between of magnetic ones and with applying a hydraulic force, the clog of magnetic abrasive particles move on the surface and remove materials slowly. By continuing this process in cycles, the surface will be finished in a high quality [67]. There are other parameters that can affect the results of finishing process that are temperature of the medium, rotation of the magnetic field and pulse of the magnetic field, that there is a need for a deeper investigation on these variables [63]. Also, this process can be utilized in order to remove micro-cracks on the surface of a workpiece in order to increase the fatigue life and enhance its corrosion properties. The issue of micro-cracks and corrosion gets intense in additively-manufactured parts. Ibrahim et al. [68], have investigated the effect AM on corrosion properties of NiTi alloys. Magnetic abrasive finishing processes can easily resolve the mentioned issues that are crucial in bio-applications.

Table 4: General process parameters of magnetic abrasive finishing processes.

Parameters	Variables				
Working medium	Composition	Wet/dry	Viscosity	Temperature	Durability
Magnetic field	Strength	Distance from workpiece	Pulse	Rotation speed	-
Substrate	Thickness	Material	Ferromagnetism	-	-

There are numerous benefits for magnetic abrasive finishing processes that the following are the most reliable ones: high precision in finishing, high surface quality, extremely precise control over the finishing process and no distortion from mechanical/thermal residual stresses [69]. However, these processes suffer from low MMR and they have to be implemented to the surfaces that are already treated to have a low surface roughness. In addition, magnetic materials such as nickel, cobalt, iron, and their magnetic alloys make difficulties during polishing and many careful considerations are needed [70]. All being said, the first applications of these processes were polishing metallic balls and rollers that need special machine tools and increase cost of finishing process. By introducing MAF and MRAFF, inner surfaces of complicated structures such as helical tubes can easily be finished, and this advantage becomes important when it comes to small diameter of slots and holes in fuel injectors used in special combustion engines [71,72]. Table 4 represents a brief summary of general process parameters in magnetic abrasive finishing processes. Also, depicts the quality of magnetorheological abrasive finishing processes on a copper alloy.

Summary

Abrasive machining and finishing processes are types of non-traditional machining methods that provide excellent characteristics. Among all abrasive processes, WJM, AJM and AWJM are the most common ones with numerous advantages. The most important factor in selecting these processes for

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machining purposes are their ability to offer a clean cur interface without considerable residual stresses and adverse thermal effects. As the abrasive particles remove substrate materials in small volumes, the residual mechanical stresses are negligible. In addition, they have an impact on substrate material at the moment of material removal that can enhance crack initiation due to the peening phenomenon happening on the surface of the workpiece. Also, they implement water, abrasive particles or a mixture of these two and cut the materials without any extreme heat generation.

This property is beneficial when polymers, engineering plastics and heat-sensitive ceramics are being cut. Furthermore, the capabilities of abrasive machining processes provide a precise cut on the top surface of a material without need to a keyhole, which is the common issue in thermal and thermochemical processes. Magnetic abrasive processes, on the other hand, are a set of complementary processes on abrasive machining which enhance surface quality to an ultimate level. With exertion of an external magnetic field, the process is under extremely precise control and can finish irregular shapes easily. However, there are some drawbacks in abrasive processes that is the low MMR compared to other processes such as laser beam machining and ion beam machining. To sum up this discussion, abrasive machining and finishing processes are of high potential to be utilized in different applications that bio-applications are the ones that need more implementation and deeper investigation.

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