POWDER MIXED ELECTRICAL DISCHARGE MACHINING AND BIOCOMPATIBILITY: A STATE OF THE ART REVIEW

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ABSTRACT

Electrical Discharge Machining (EDM) is a well-known process for machining of difficult to cut materials. Along with adding the powder in dielectric liquid, change in properties of machining gap results in a variety of sparks forms and lead different mechanisms under specific operational conditions during machining. The discharge models significantly differ from conventional EDM and leave its characteristics surface features. Primary studies of Powder Mixed Electrical Discharge Machining (PMEDM) focused on the understanding of material removal rate, surface quality, and tool wear rate concerning the widespread of the operational conditions evolved in the process. Then, the interactions with the powder material during discharging and the resultant surface properties impel the researcher's interest to achieve functional surfaces. In this respect, PMEDM is a significant concern in recent years as an alternative and simple production technique to obtain functional surfaces for specific needs. Nowadays, among the specific needs, production of biocompatible surfaces with the use of the technique provides a challenging opportunity to the researchers to address osseointegration issues. The study presents an introduction and review of the research work in PMEDM. The studies concerning machining efficiency, surface integrity, and generation of functional surfaces are presented and discussed in the light of current research trends. Attempts made to improve biocompatible surfaces with the use of the process also included to clarify the future trends in PMEDM.

Keywords: Powder Mixed Electrical Discharge Machining, Machining Efficiency, Surface Integrity, Biocompatibility, PMEDM

1. INTRODUCTION

Electrical Discharge Machining (EDM) is a natural adaptation phenomenon recognized as lightning to production industry. Fundamentally, sparks are sudden electrostatic discharges between electrically charged regions. Thus, charged electrodes separated with a gap distance immersed in a dielectric liquid and one of the electrode forwarded across to the other with the aid of a servo system. The decreased inter-electrode gap increase in electric field intensity and finally exceeds the dielectric strength at a specific distance where the dielectric breaks and current start to flow in a formed discharge channel. In the period of discharging, the electrons and polarized ions strike to both electrode surfaces and transfer the particle kinetic energies in the form of heat and pressure that are sufficient to raise the local temperatures beyond the boiling points and under extreme pressures blocking evaporation of the superheated material. Elimination of the channel pressure at the end of the pulse period triggers a severe superheated cavity blast into the dielectric liquid that covers in the volume involved by the discharge channel. Therefore, both electrode surfaces, as well as the, exploded material cools down rapidly in the circulating dielectric liquid that renews the inter-electrode conditions for the next cycle and produces a tiny crater on both of the electrode surfaces (Figure 1).

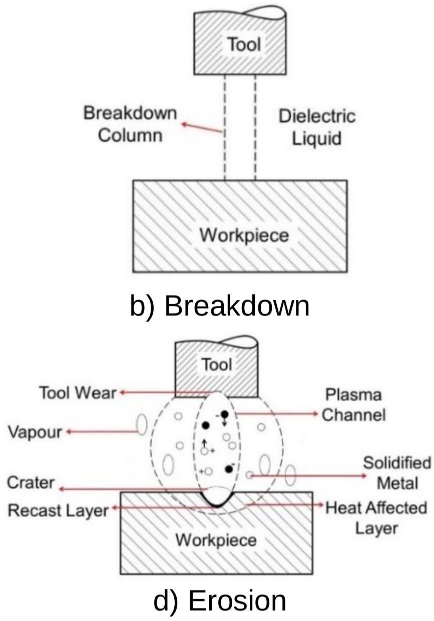


Figure 1 Schematic illustration of EDM Mechanism.

Successive application of electrical pulses (Figure 2) and forward movement of the driving electrode result in the formation of complementary shapes of the electrodes. Therefore, one of the electrodes (tool) is shaped to the form the cavity of the other electrode (work material) in EDM applications. Easiness of adjusting the electrical parameters such as pulse current and duration in a wide range gives the opportunity of controlling the machining performance and surface topography. Moreover, the interactions among the materials evolved during discharging put a challenging opportunity to estimate the resultant surface integrity in EDM.

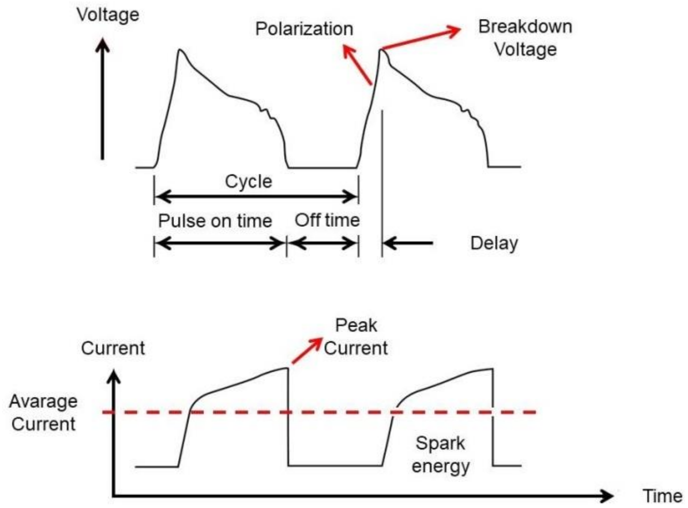


Figure 2 Pulse waveforms during EDM.

The contactless thermal nature of the material removal process enables machining of complex geometries on electrical conductive high strength, high hardness materials that are difficult to cut with known traditional machining processes. Parallel to technological developments, there is an increasing interest in EDM as a non-traditional production method, especially in the molding industry. Powders addition in the dielectric liquid is known as a new advancement and innovative technique in the direction of process capabilities and called as Powder Mixed EDM (PMEDM). Suspended powders altered the inter-electrode gap conditions and result in various surface properties and performance outputs that are different from conventional EDM. Therefore, the machining mechanism of PMEDM is distinctive and changes with the type, size, geometry, and concentrations of the added powders.

An adequate amount of powder added to the dielectric liquid leads improved machining performance and promises exceptional surface accuracy and quality [Kumar, 2015]. The altered inter-electrode gap conditions result in numerous breakdown zones and inhomogeneous forms throughout the pathways of discharges. The replacement of single-channel discharges with the modified ones in various forms points its distinctive consequences on the machined surfaces. Thus, categorization of surface structures, subsurface demolition and varieties of secondary discharge become a vital subject in PMEDM. Moreover, suspended particle migration onto the work material surface is probable when using specific machining conditions [Ekmekci et al., 2016a]. Specific operating conditions is critical in this respect and reflects the complicated non-linear nature of the process and revealing the different types of material transfer mechanisms encountered.

The actual sequence of processes involving sparking, heating, melting, vaporization is complex and not yet fully understood at the microscopic level due to difficulty in its scientific observation. The main attractive point of the process is the ability to provide extreme heat and pressure cycles in microscale that could not be achieved by other known techniques. Therefore, the idea of adding the powder in a dielectric liquid and modifying the machined surfaces for specific needs promising an innovative and practical alternative technique. Discovering the controllable parameters of the process (Figure 3) for the desired surface properties become a crucial concern for the current studies. Nowadays, among the specific needs, the possibility of generation of biocompatible surfaces with the use of the process became an attractive alternative to the known surface modification techniques such as plasma spray, shot peening, abrasive blasting, aqueous spray, and pulsed laser deposition.

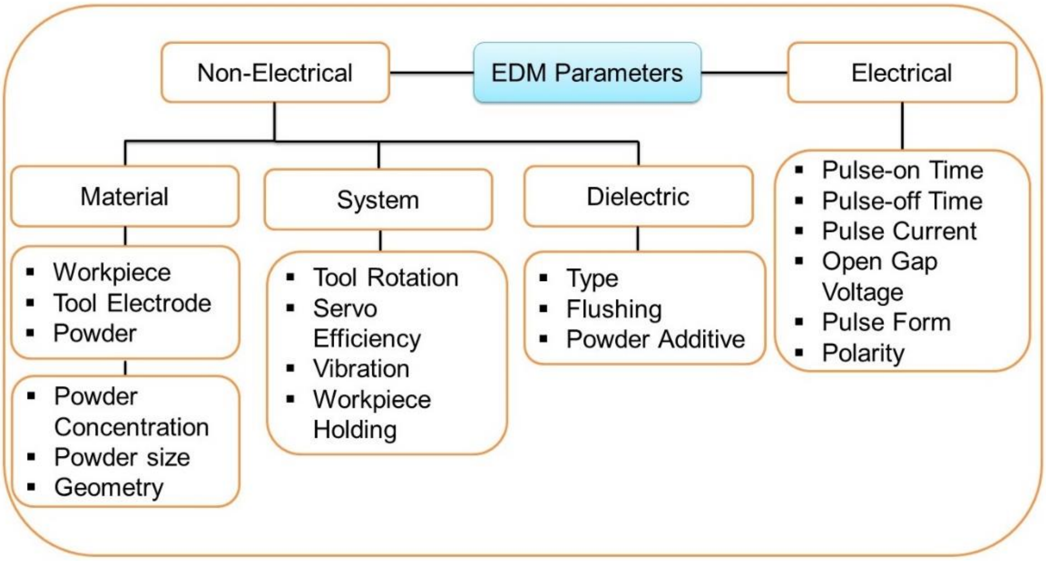


Figure 3 EDM Parameters.

The literature available on the process reveals a need to prepare a review of the research accomplishments in PMEDM. Therefore, the various research activities carried out in the past decade are examined to present a brief discussion on PMEDM and biocompatibility. The studies concerning machining performance, surface integrity, and generation of functional surfaces including studies to improve biocompatible surfaces are summarized and discussed in the light of current research trends.

2. MACHINING PERFORMANCE

The machining performance is usually related to Material Removal Rate (MRR) and Tool Wear Rate (TWR) in the literature of PMEDM. Pulse-on and pulse-off durations, pulse current, polarity and open gap voltage are the evaluated electrical parameters during PMEDM. Researchers examined the response of the machining process performance with the use of different types of work material, powder additives, and dielectric liquids. Erden and Bilgin, 1980 presented the pioneering study in the field. They examined the influence of powder additives and improvement in MRR using carbon, iron, aluminum, and copper, powder addition in commercial kerosene. Increase in added powder to a critical density resulted in an increase in MRR. Then, short circuits observed beyond the limit that lead a decrease in MRR. Jeswani, 1981 indicated a substantial increase in the MRR by %60 when adding 4 g/l of graphite powder in kerosene dielectric liquid. The observed increase in MRR compelled the researcher's attention to uncovering the physical foundation beyond. The decrease breakdown resistance due to the addition of conductive powders provided suitable conditions during EDM and led a significant increase in MRR. Decreased breakdown resistance resulted in an increased inter-electrode gap and hence improved the dielectric circulation. The prospective studies then focused on the optimization of the EDM parameters for improved MRR, and TWR. Since particle size, density, thermal conductivity and electrical resistivity of the added powders have unique roles as well as the electrical parameters. For example, addition of 70–80 nm powders in dielectric liquid cause the slightest increase in the machining gap, but the maximum MRR and minimum TWR. Additionally, Cr powders generated the highest MRR, followed by Al, then SiC [Tzeng and Lee, 2001]. The improvement in MRR also observed when using rough EDM regimes (25 µs<pulse duration<150 µs and pulse current>15A) [Zhao et al., 2002]. Kansal et al., 2005a also reported a noticeable improvement in MRR, TWR and surface roughness with the addition of graphite powder in kerosene when using rough PMEDM conditions.

Kozak et al., 2003 presented the earliest example of using additives in water. Using water as a dielectric liquid cause decrease in MRR and increase in TWR when compared to the use of kerosene as a dielectric. However, adding powders to water dielectric liquid comprehensively decreased the TWR that eliminated the disadvantages of water concerning machining performance. Kansal et al., 2005b studied the influence of the pulse-on time, pulse current, duty cycle, and added Si powder intensity and identified the most critical parameters to maximize MRR and minimize Surface Roughness (SR). Similarly, a maximum peak current of 10A, Si powder density of 4g/l, minimum pulse off time of 15 µs and pulse on time of 100 µs gives the highest MRR in machining of AISI D2 die steel material [Kansal et al., 2007]. Finally, Kansal et al., 2008 developed a numerical model to predict material removal mechanism in PMEDM and obtained an acceptable agreement between the theoretical and the experimental MRR. The difference between Al and Si powders in the dielectric are tried to explain the diversity of discharge energy distribution using a 3D electric field model [Wang and Zhao, 2008].

Machining performance studies of non-ferrous work materials also pointed out similar results. For example, Chow et al., 2008 related the use of pure water alone with SiC powder additive for titanium alloy in EDM. They emphasized that the dispersing effect (Figure 4) of discharging energy could be the main reason for the improvement in MRR and surface roughness due to SiC powder addition in the dielectric. [Kung et al., 2009] revealed an increase in MRR with the addition of Al powder in mineral oil when machining WC. However, this trend was founded to be valid up to a maximum powder concentration that leads a decrease in MRR beyond the limit. Moreover, both MRR and TWR increase with an increase in suspended particle size. [Jahan et al., 2010] examined the influences of conductive, semi-conductive and nonconductive nanopowders on powder mixed micro EDM. Using conductive or semi-conductive powder can powerfully alter the machining outputs, e.g., higher MRR, lower TWR and better surface finish on WC work material. However, the use of nonconductive nanopowders revealed the negligible effect on discharge breakdown strength and uniformity. [Kumar et al., 2011] have shown the effects of particle concentration and size of added powders in machining efficiency on Inconel 718 superalloy when using negative polarity Cu tool electrode. They have claimed that 325 mesh size Al additive powder reduces TWR by 80%.

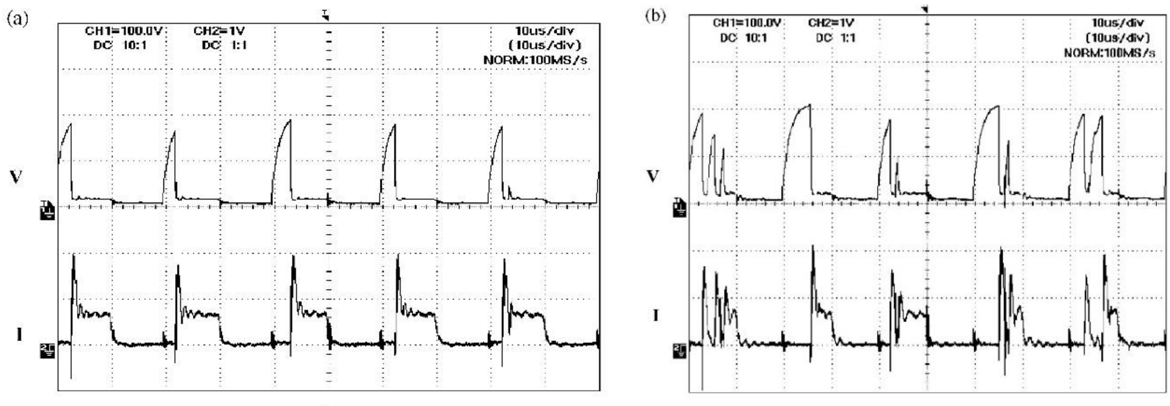


Figure 4 Typical waveform of voltage and current using (a) pure water alone and (b) pure water added SiC powder with Pulse Current: 0.5 A and Pulse on time: 10 μs in EDM, [Chow et al., 2008].

[Kumar et al., 2010] study of Si abrasive mixed EDM on EN-24 tool steel. [Bhattacharya et al., 2011] indicated that current and pulse on time were a most effective factor for MRR and TWR. They have pointed out the meet of different powder additives for the achievement of optimal machining performance, for example, Cu powder was found to be the best additive for high carbon high chromium and hot die steels. However, Tungsten powder gives better results during machining of high carbon steel.

[Syed and Palaniyandi, 2012] have pointed out the importance of polarity when using Al powder addition in water dielectric liquid. They have claimed that higher productivity is possible when using positive electrode polarity whereas higher surface quality is obtainable with the use of negative polarity. [Bhattacharya et al., 2012] revealed the independence of the tool electrode material on MRR. However, the addition of suspended powders significantly improves the MRR on machining of three different grades of steels in kerosene dielectric liquid. Effects of nanopowders in dielectric liquid also studied by some researchers. For example, [Mai et al., 2012] revealed an improvement in machining efficiency by 66% and increase in surface roughness by 70% when using carbon nanotubes in kerosene dielectric liquid. Moreover, the addition of carbon nanotubes was found to be more efficient than the addition of Si, Al, and graphite powders. Similarly, the addition of 4 g/l carbon nanotubes into the dielectric provides a mirror-like surface finish on AISI-D2 die steel. The given concentration improved the MRR by 80 % and decreased the SR by 67 % [Kumar, 2015]. [Shabgard and Khosrozadeh, 2017] investigated the effect of carbon nanotubes as additives in dielectric liquid on Ti-6Al-4V work material. Their result also indicates a remarkable improvement of machining stabilities that yields higher MRR, lower tool TWR, and SR.

Boron carbide powder addition into dielectric during EDM of Ti6Al4V provide upgraded discharge density and spark gap. As the powder concentration increases, the TWR also increases, and the optimum concentration for TWR is 1 g/l. Improved MRR and SR are possible at a higher powder concentration that is 15 g/l [Kolli and Kumar, 2014]. Powder addition to dielectric provides enlarged spark gap thereby larger overcut. The ragged surface is formed at cut edges when using elevated pulse-on duration and increased powder intensity. Besides this, the electrodes having different profile shapes with different angles can be used to produce a complex geometric profile. The profile accuracy of the machined surface is better for a tool with a higher included angle [Batish et al., 2015]. [Singh et al., 2014] and [Singh et al., 2015a] studied the graphite conductive powder mixed EDM on Super Co 605 work material and achieved better surface quality and improvement in MRR.

[Kolli and Kumar, 2015a] pointed out MRR increase by the rise in surfactant dilution from 4 to 6 g/l in EDM oil dielectric liquid. However, beyond 6 g/l dilution of surfactants start to decrease MRR. [Reddy et al., 2015] have concluded that the addition of surfactant into dielectric fluid advances the electrical conductivity of the dielectric and thus reduces the delay time of discharges. Surfactant molecules act as a steric barrier and disperse the graphite powders uniformly in the dielectric liquid, therefore, preventing the possible unstable machining conditions and resulting in an increase in MRR.

[Unses and Cogun, 2015] have also revealed an increase in MRR on Ti-6Al-4V material with the use of graphite powder addition in kerosene dielectric. [Marashi et al., 2015] observed that added Ti nanopowder to dielectric improves the MRR and surface topography in all machining conditions except the highest pulse duration of 340 µs. They achieved the highest enhancement at 210 µs pulse-on time, 6 and 12 A pulse current regarding MRR (69%) and surface roughness (35%). [Talla et al., 2016] have examined the effects of different types of powders in kerosene dielectric when using Inconel 625 work material. They obtained significant improvement in MRR, SR, and surface hardening while decreasing the cracks on the surface compared with conventional EDM. They showed that highest MRR was obtained with Al powder whereas Si powder has the potential to enhance surface integrity characteristics. Studies on Aluminum alloy 6061/10%SiC composite material by adding Tungsten powder to kerosene oil dielectric have revealed enhanced the MRR by 48.43% with decreased resolidified layer thickness by 42.85% when compared to conventional EDM [Singh et al., 2015b]. Likewise, tungsten powder in dielectric liquid reduced TWR by 51.12% [Singh et al., 2016].

The literature review on PMEDM machining performance reveals a substantial increase in MRR due to added powders in dielectric liquid up to the critical limit. The improvement is also valid for a variety of work and additive powder materials that points out the change in machining mechanism. Addition of conductive powders in dielectric liquid decrease dielectric breakdown strength and result in the enlarged interelectrode gap. Therefore, increase in MRR could be attributed to the improvement dielectric circulation conditions. However, the explanation does not confirm the performance increase when using non-conductive powders in the dielectric liquid. Thus, the dispersion of discharges into a variety of forms could be considered as a plausible description for material removal mechanism. Using conductive powders reveals relatively increased performance when compared to the use of nonconductive powders. Hence, the contribution due to interelectrode gap enlargement and improvement in dielectric circulation is not ignorable but not solely describes the performance increase. The analysis of PMEDM surface and subsurface properties become an essential point to understand the machining mechanism since dispersed discharges give its characteristics impact.

3. SURFACE INTEGRITY

The PMEDM surface describes the interactions between the machined component and its environment. Therefore, it is vital to determine the resultant surface functional performance. Surface integrity in PMEDM includes surface roughness, microhardness, surface and subsurface layers, microstructure, surface cracks. Generally, in conventional EDM, improving surface quality is an important criterion. It is a known fact that the additive of the powder improves the surface roughness. For example, [Mohri et al., 1991] achieved mirror-like surface when adding silicon powder in oil dielectric and using finish EDM conditions. Similarly, the addition of electrically conductive powders decreased the surface roughness and microcrack formation in finishing machining conditions [Ming and He, 1995]. Moreover, they emphasized that additives to kerosene decrease the loss of alloy elements, increase the microhardness and make the resolidified layer thinner. Particular combinations of powder-mixed dielectric produce mirror-finish or glossy machined surfaces [Wong et al., 1998] and point out the alterations in machining mechanism during discharging. The discharges in the spark gap distributed because of the occurrence of the powder in dielectric liquid. Moreover, the breakdown voltage is decreased that allow sparks at a wider inter-electrode gap, improved the flushing conditions and reduced servo movements that result in stable machining conditions. [Chow et al., 2000] claimed that the bridging effect owing to added powders in kerosene that facilities the dispersion of the discharges into several increments. Thus, a single input impulse resulted in several discharging spots (Figure 5). Discrete discharging minimizes the machining debris size, increased the materials removal rates and surface roughness. Similarly, [Yan et al., 2001] have demonstrated that addition of Al and Cr powders into kerosene dielectric liquid leads increased interelectrode gap distance and divide the discharge current which resulted in better EDM performance. Moreover, added powder migrated and penetrated to the machined surface. Addition of Al powder formed a softened resolidified layer while Cr addition hardened the structure due to the migration. [Uno et al., 2001] suggested a new technique to achieve improved surface wear resistance. In their study, they examined nickel and carbon additives for Aluminum bronze, AIBC3, and SKD61 steel work materials using copper and titanium electrodes, respectively. For the first case, they have observed a nickel-enriched resolidified layer. For the second case, a hard TiC layer was formed over the surface. Similarly, [Furutani et al., 2001] observed deposit of titanium carbide under the various electrical conditions when using titanium powder as an additive in kerosene dielectric liquid. The thickness of the TiC layer reached up to 150 µm with a hardness of 1600 HV on carbon steel. The use of silicon powders suspended on dielectric enhances the polishing process performance by producing smooth and high reflective craters on the H13 steel machined surfaces [Peças and Henriques, 2003]. The lowest average surface roughness obtained was 0.09 µm. However, the surface roughness of the work material was found significantly higher due to anodic dissolutions at a low current density on all machining areas when using negative tool electrode polarity in water dielectric liquid [Kozak et al., 2003]. The results obtained revealed the nonlinear and stochastic nature of the process. Therefore, it becomes critical to point out the right combination of materials and electrical combinations of the process for the required surface properties.

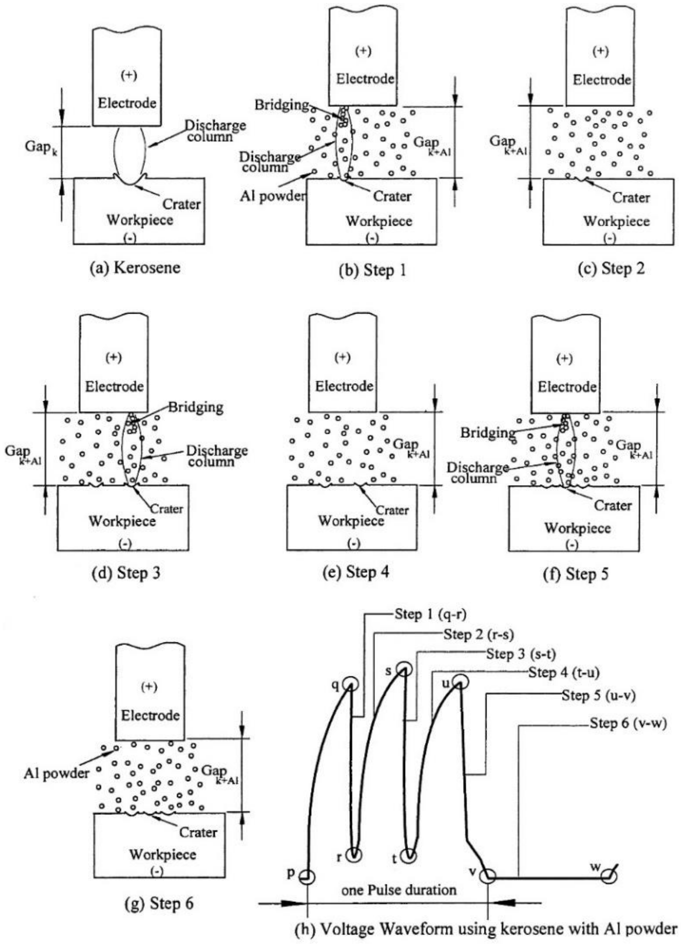


Figure 5 Effect of suspended Al powder on the sparking mechanism: (a) typical sparking model for EDM powder, (b)-(g) sequence of discharging dispersion occurring during one pulse using kerosene with Al powder, and (h) voltage waveform of one pulse using kerosene with Al powder (Chow et al., 2000).

The physical properties of the powder additives play a noteworthy role in changing the resolidified material structure and morphology [Klocke et al., 2004]. For example, the use of Al powder in dielectric liquid leads to thinnest rim zone at small discharge energies. Also, a grey zone beneath the resolidified layer is formed when using Si powder additive in the dielectric liquid. [Yih-Fong and Fu-Chen, 2005] have studied Al, Cr, Cu and SiC powder addition in oil dielectric liquid. In their study, they have observed that smaller particle sizes produce a better surface finish. However, the thickness of the resolidified layer changed inversely with the size of the added powders. So the higher the particle size lead thinner recast layer while producing a rough surface. Among the analyzed powders they have claimed that Al powder produces the best surface finish. Similarly, [Wu et al., 2005] have tried to improve the surface finish by using Al particles and surfactant addition to prevent the agglomeration of the Al powders in oil dielectric liquid. In this way, they have achieved 60% reduction in SR.

Using graphite and boric acid powders (H_3BO_3) in kerosene leads higher hardness values on the steel surfaces than machining in pure kerosene [Cogun et al., 2006]. Similarly [Hu et al., 2008] have demonstrated improvement in wear resistance of PMEDM'ed Ta-W surfaces when using Al powder in kerosene dielectric liquid. Adding silicon powder to the dielectric resulted in the decrease of generated crater sizes in respect to its diameter and depth as well as the resolidified layer thickness. Best results regarding surface morphology are in the range of 2 to 3 g/l powder concentration [Peças and Henriques, 2008a]. They have also presented a linear relationship between the surface quality measures and the tool electrode area [Peças and Henriques, 2008b]. The researchers also noted that the less susceptibility of the surface quality measures to the electrode area when using power additives.

[Furutani et al., 2009] reported that TiC could be accumulated when using smaller discharge energies and power density in Ti powder mixed dielectric oil. They achieved 2000 HV on the deposition besides hardening of the matrix surface. They also found that when discharge current exceeds the critical point for removal of carbon steel, this exceeding leads to melting and evaporating even at low discharge energy. [Kumar and Singh, 2010] studied the manganese powder and found a substantial quantity of material migration from the powder mixed dielectric to the machined die steel surface. The migration leads to an improvement of microhardness up to %73. They noted that long pulse interval (85 µs), the decreased pulse current (4A), pulse-on duration (5 µs) and negative tool polarity are suitable machining conditions for surface alloying. [Tan and Yeo, 2011] have revealed significant alterations in resolidified layer thickness because of the addition of nanosize SiC powder. The decreases in the resolidified layer thickness are between %15 and %30 depending on the use pulse on durations. [Ojha et al., 2011] have studied the addition of chromium powder into kerosene dielectric and indicated improvement in surface roughness when using small sized copper tool electrodes with low peak current.

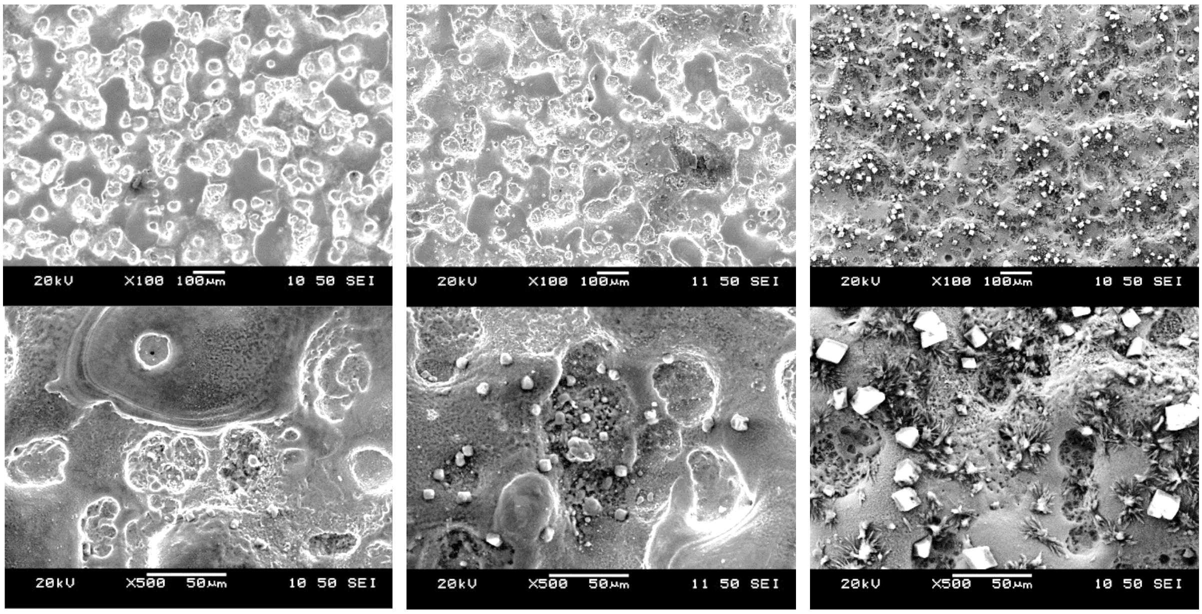
[Janmanee and Muttamara, 2012] claimed formation of a titanium layer onto Tungsten carbide work material by adding titanium powder suspension into the dielectric. They evaluated the completeness of the surface and found less number of microcracks that filled with titanium powder and carbon decomposed from the hydrocarbon-based dielectric liquid. The covered layer hardness was found to be reached up to 1750 HV. They attributed micro crack reduction and hardness increase to the diffusion of atoms during discharging. Similarly, [Kumar and Batra, 2012] have revealed a substantial quantity of material migration from the powder added dielectric liquid under appropriate machining conditions when using tungsten powders. In this way, 3.25% tungsten enrichment on the surface could be achievable. Moreover, powder particles carburize the surface due to released products of the cracked dielectric. Carbon migration results in a more than 100% hardness increase within the resolidified layer for steel work material. Small discharge currents below 5A, smaller pulse-on time below 10 µs, the extended pulse-off time above 50 µs when using negative tool electrode polarity suggested favorable machining conditions. [Ekmekci and Ersöz, 2012] tried to explain the role of SiC particles on the surface morphologies of Interstitial Free (IF) steels. They have pointed out the penetration of suspended particles on the machined surfaces due to the dynamic behavior of the particles during discharging. Under specific operational conditions particles located about an electrical discharge channel hurried up and achieved adequate velocity to infiltrate the molten pool previous to solidification due to the negative pressure generated at the end of discharge. Also, they have claimed that such penetration mechanism prevents the formation of penetration cracks. [Bhattacharya and Batish, 2012] indicated accumulation of materials and formation of complexes. The cooling rate plays a primary function in the development of grain size of machined work materials. For example, using low melting point powders in the dielectric liquid causing a finer structure of the grains due to decreased cooling rates. [Syed and Kuppan, 2013] have revealed low thickness of white layer around 17 µm when using a high concentration of Al powder and low peak current in water dielectric.

[Hu et al., 2013] examined the surface properties of SiCp/Al composite machined by PMEDM using Al powder in kerosene with Cu electrode. The SR decreased about 31.5%, the surface cracks are less, the corrosion and wear resistance is better, when compared to conventional EDM. Therefore, they proposed the PMEDM as a promising method for metal matrix composites. [Bhattacharya et al., 2013] studied the influence of the different type of powder, a dielectric liquid, electrode material and electrical parameters in powder mixed EDM to understand their relations during the process. They noted that adding powders into the dielectric meaningfully enhance the SR and microhardness of the machined surface. Powder concentration, current, pulse on time and electrode material, in that order, were the primary contributing factors affecting microhardness. Using tungsten powder in dielectric and brass electrode lead decreased SR whereas using W-Cu tool electrode provided greater microhardness. They also noted a considerable amount of material migration from the tool electrode and powder mixed dielectric liquid. [Yaşar and Ekmekci, 2013] examined SiC powder addition in water dielectric and emphasized that material transfer mechanism to the machined surface not be a random process. The mechanism is related to the secondary discharges and depending on operational parameters. [Jabbaripour et al., 2013] evaluated the influence of different powder types (Al, Cr, Gr, SiC and Fe) on SR and topography, MRR and corrosion resistance. Best results regarding SR and MRR was achieved with Al powders. The researchers found that the samples machined with graphite and chrome powders in dielectric liquid were about three and two times higher than the samples machined without powder addition regarding electrochemical corrosion resistance. [Sidhu et al., 2014] examined the surface modification of three different types of particulate reinforced metal matrix composites using PMEDM. They noted that using copper electrode instead of graphite resulted in the higher amount of oxides because of advanced conductivity and reactivity of copper that influencing the microhardness on the machined surface. Additionally, carbon migration increases when using high pulse energies. Finally, they have also noted that PMEDM is an appropriate machining technique for metal matrix composites to improve surface quality. Conductive powder addition to dielectric liquid influences the sparking efficiency and energy distribution due to decreased dielectric strength. The resolidified layer microhardness increases on EDM'ed superalloy Super Co 605 work material with the use of graphite powder in the dielectric. Additionally, high current pulses cause deteriorated surface quality because of solidified droplets on the machined surface [Singh et al., 2015a].

The surfactants can be added into dielectric to increase the conductivity, regulate discharge conditions for suspended debris particles and enhance overall machining efficiency by preventing agglomeration of powder and sediment particles. Therefore, surfactant-mixed dielectric (EDM oil, 14 g/L graphite powder and Span 20 surfactant, C18H34O6) provide reduced resolidified layer thickness and surface crack density [Reddy et al., 2015] as well as the improved SR and MRR [Kolli and Kumar, 2015b].

By adding Ti nanopowder to the dielectric, surface micro defects, including voids, droplets, and cracks were reduced and resulted in slighter craters with low-height ridges were observed [Marashi et al., 2015]. They also indicated that Ti atoms accumulated on the PMEDM'ed surface in higher amounts around the surface microcracks.

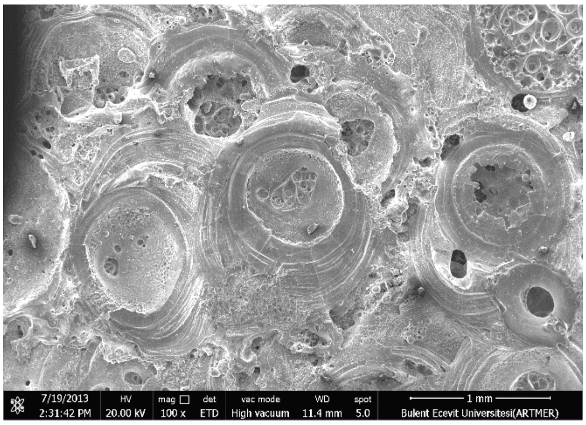
PMEDM is expected to improve MRR, TWR, microhardness and to reduce SR. Besides this, material migration takes place between the workpiece and the tool electrode. The powder additives penetrate the workpiece surface during processing. Added powders break the electrical pulse and support the formation of sub-discharges that promote the material deposition on the machined surface (Figure 6). This situation does not occur randomly, but depends entirely on powder concentration, pulse on duration and pulse current [Ekmekci et al., 2015]. The powder penetration to the surface is only happening under specific machining conditions. In this respect, several forms of secondary discharges and the impact on the machined surface indicated five different forms of discharges in SiC powder mixed water dielectric liquid when machining Ti6Al4V work material [Ekmekci et al., 2016]. [Talla et al., 2016] have investigated the effects of different types of powder added to the kerosene dielectric in PMEDM on Inconel 625 work material. They obtained significant improvement in MRR, SR, and surface hardening while decreasing the cracks on the surface compared with conventional EDM. They showed that highest MRR was obtained with Al powder whereas Si powder has the potential to enhance surface integrity characteristics. [Li et al., 2017] have observed an increase in thickness of the hardened layer by the rise of pulse current. Moreover, they claimed a quality increase in a resolidified layer by the rise in pulse-on time. TiC and $TiSi_2$ phases increased the microhardness from 310 to 630 HV that indicates a two-fold increase in hardness concerning the base material. [Amorim et al., 2017] used suspended Mo powders in hydrocarbon-based dielectric liquid and detected Fe-Mo, MoxC, and Mo in solid solution in the resolidified layer. This phases and ingredients increased the microhardness four times fold concerning based tool steel materials.



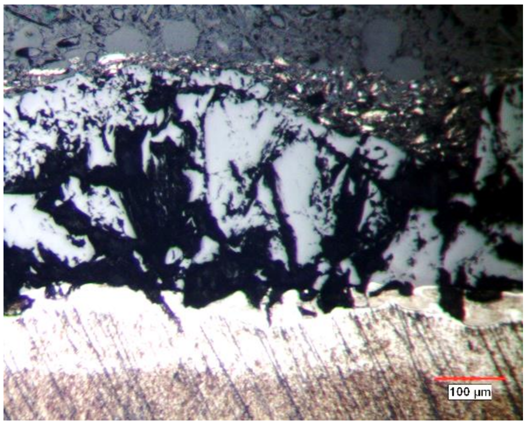
a) b) c)

Figure 6 Effect of the powder concentration on the surface topography (Pulse on time: 100 µs and Pulse Current: 14 A) a) 5 g/l b) 10 g/l c) 15 g/l SiC in water dielectric liquid (Ekmekci et al., 2015).

Electrostatic forces direct the motions of the fine powders in the dielectric liquid owing to the stable electrical filed generated during discharging. The presence powders result in deviation of the electric field in the discharge gap. Positive and negative ions collected on the powders due to the effect of open gap voltage. Therefore, the primary discharge channel is divided into different shapes because of changed inter-electrode gap situations and produce distributed heat sources on the machined surface. The conclusion also designates the dependence on the electrical parameters and the forms of discharge division that produce the particular surface, and consequent heat affected layers (Figure 7). Hence, surface topography and damage become a crucial matter to understand the machining mechanism.



a) SEM view



b) Section view

Figure 7 SEM and Section views of PMEDM'ed Ti-6AL-4V (Powder: SiC, Concentration 20 g/l, Mesh no: 800, Dielectric: Deionized Water, Pulse Current: 7A, pulse on time: 1600 μs).

The possibility of particle accumulation under particular machining situations reveals the prospect of producing functional surfaces. Migration sometimes observed as penetrated particles or as a modified resolidified layer. The result is exceptional attention from the researchers to develop surfaces for specific needs. Nowadays, among the specific needs, production of biocompatible surfaces offers an exciting prospect to the researchers.

4. FUNCTIONAL SURFACE AND BIOCOMPATIBILITY

Machined surfaces interact with the environment where they inside and need to be developed to work in harmony with the ambient. For this purpose, materials surface coated or deposited with different types of elements or compounds by EDM in many studies concerning to improve corrosion resistance, wear resistance, fatigue performance, and recently biocompatibility has been done. Conventional EDM applications are included in respect to convey the completeness of biocompatibility issues in the process. [Chen et al., 2008] have studied Fe-Al-Mn work material EDM in kerosene dielectric liquid without powder addition. They figured out the formation of γ phase and κ carbide in the resolidified layer that significantly progressed the formation of microstructure oxide layer. Therefore, they concluded that electric discharge machining increased the work material biocompatibility (Figure 8) by forming nanostructure oxide on the surface. Similarly, [Peng et al., 2010] have indicated the formation of γ-hydride microstructure in the resolidified layer and claimed a transition of, $\alpha \rightarrow (\alpha+\delta) \rightarrow (\delta+\gamma) \rightarrow \gamma$ during conventional EDM. Additionally, they revealed the formation of nanoporous TiO_2 on the surface when using short pulse durations that yields bioactive titanium. [Harcuba et al., 2012] investigated the biocompatibility of the EDM'ed Ti–6Al–4V samples without powder additives in hydrocarbon oil. They have shown that EDM surfaces offered advanced substrates for the bond, development, and practicality of MG 63 cells than the TiO2 layered surface by plasma spraying. They achieved a carbon-enhanced surface layer and suggested the EDM process for producing biomedical implants. [Yang et al., 2013] and as well as [Lee et al., 2013] have observed nanoscale pores in anatase TiO_2 surface when EDM of Ti-6Al-4V work material in a distilled water dielectric liquid. They have examined cell culture, alkaline phosphatase activity and osteocalcin response of the EDM'ed surface and indicated a significant increase in biocompatibility when compared to untreated surfaces. Moreover, using increased peak pulse currents and pulse durations during discharging yielded multiple osteoblast functions. [Lee et al., 2016] EDM'ed Ti Grade II work material using Ti electrode with water dielectric liquid to form enhanced biocompatible surfaces. Experiments were carried out with 10A, 29A and 29A followed by 2.4A (29 + 2.4A) pulse currents at 21 μs of a pulse on time. The most improved biocompatible surfaces are the ones EDM'ed with the multi-current application. Also, a contaminant-free TiO_2 layer with a few micrometer thicknesses was observed on the surfaces EDM'ed with the use of pure water instead of oil.

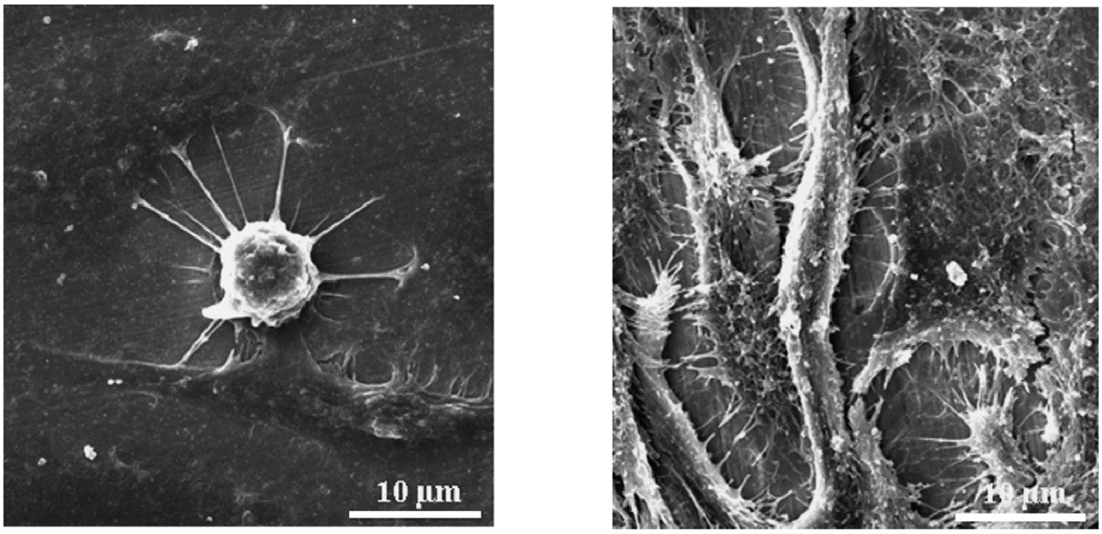


Figure 8 SEM micrographs demonstrating cellular morphology of EDM'ed Fe–Al–Mn alloy after various culture times: (a) 8 h, (b) 24 h (Chen et al., 2008).

Powder additive cases also indicated promotional biocompatibility issues. [Murali and Yeo, 2004] have studied the potential of micro-EDM of Ti-6Al-4V for producing biocompatible devices and demonstrated that the surface roughness is between the recommended values for biological studies. [Chen et al., 2014] have examined the consequences of the intensity of Ti powder mixed in water dielectric liquid on the EDM'ed surface of Grade 4 pure titanium. They observed the TiO phase within the recast layers in case of all Ti powder concentrations. Decreasing peak current and pulse duration result in lower surface cracks in 3 g/l Ti powder added dielectric liquid. However, increasing the powder concentration to 6 g/l produces the surface without any cracks. They also indicated that using 0.1 A pulse current with 30 μs and 50 μs pulse duration leads to a Ti modified hydrophilic surface with no cracks thus could be considered to use as biomaterials for dental implants application. [Prakash et al., 2015] generated a biomimetic nanoporous surface containing a combination of bioceramic oxides and carbide phases on β-Ti (Ti-35Nb-7Ta-5Zr) surfaces when using SiC additives in the dielectric liquid. Presence of carbide phase (TiC, SiC, and NbC) had superb metallurgical adhering and resulted in higher hardness on surfaces. On the other hand, oxide phases (TiO_2, Nb_2O_5, ZrO_2, and SiO_2) advanced the biocompatibility of the surface. Moreover, bioceramic oxide layer has excellent corrosion resistance properties. They also emphasized that the PMEDM'ed nanoporous surface show a higher grade of bioactivity (cell attachment, distribution, and proliferation) comparing with the non-treated surface.

Hydroxyapatite (HA) is one of the hardest molecules, and its crystal structure is similar to that of the human skeletal system so that it can be used instead of bone. Similar to the structure of the bone, the ratio of calcium to phosphorus (Ca / P) is around 1.67. The studies on the use of HA for medical applications in powder mixed EDM were first carried out in 2013 [Ekmekci and Ekmekci, 2013]. In their study, they performed HA precipitation on Ti alloy when using HA additives in the dielectric liquid (Figure 9). The most suitable parameters are high pulse current and low pulse duration. In their continuing work, they have indicated that secondary sparks have made deposition more effective [Ekmekci and Ekmekci, 2016b]. A Hydroxyapatite (HA) containing coating also generated by [Ou and Wang, 2016] using HA powder mixed EDM in distilled water on Ti-Ta alloy following hydrothermal treatment. This coating includes Ti and Ta oxides, Ca and P. By hydrothermal treatment; the incorporated Ca and P were precipitated to petal-like HA crystals on the coated surfaces. They emphasized that the HA-containing coating show enhance wettability results. [Aliyu et al., 2017] have observed a hard biocompatible layer on metallic glass surface when using HA as powder additive in hydrocarbon-based dielectric liquid. [Ou and Wang, 2017] performed PMEDM on Pure Ti and Ti-Ta alloys using bioactive HA powder mixed in water dielectric liquid. They observed that lowest values of MRR, TWR, SR, and thickness of recast layer was obtained at 5 g/l concentration of HA powder and these values increase gradually with increasing powder concentration. Moreover, they determined Ti, Ta, O, Ca, and P in the recast layers on the titanium-tantalum alloys which their amounts decreased when the discharge current was increased. Therefore, the PMEDMed surfaces exhibited greater hardness and anti-scratch properties when compared to that on pure titanium. Machining performance and SR are inversely proportional to the thermal conductivity and melting point of the material that changes the amount of Ta in Ti-Ta alloys. [Prakash and Uddin, 2017] achieved a natural bone-like nano-porous surface topography without cracks on the β-Ti implant surface using the HA additives. On the β-Ti implant surface, they produced a layer including of Ti, Nb, Ta, Zr, O, Ca and P elements and formed biocompatible phases, for instance, $Ca_3(PO_4)_2$, $CaZrO_3$, Nb_8P_5, CaO, TiP, Nb_4O_5, TiO_2 and TiH which were useful for osseointegration and bioactivity. This biocompatible recast layer has excellent metallurgical bonding with the substrate surface and shows improved hardness up to 1275 HV which is 3 times higher than the untreated surfaces. The researchers also noted that HA deposited layer showed superior corrosion resistance as compared to EDM'ed without powder and untreated samples in simulated body fluid. In briefly the in-vitro bioactivity results confirmed that the nano-porous HA-containing layer has excellent biocompatibility, e.g., adhesion, growth, proliferation, and differentiation of human osteoblastic cells.

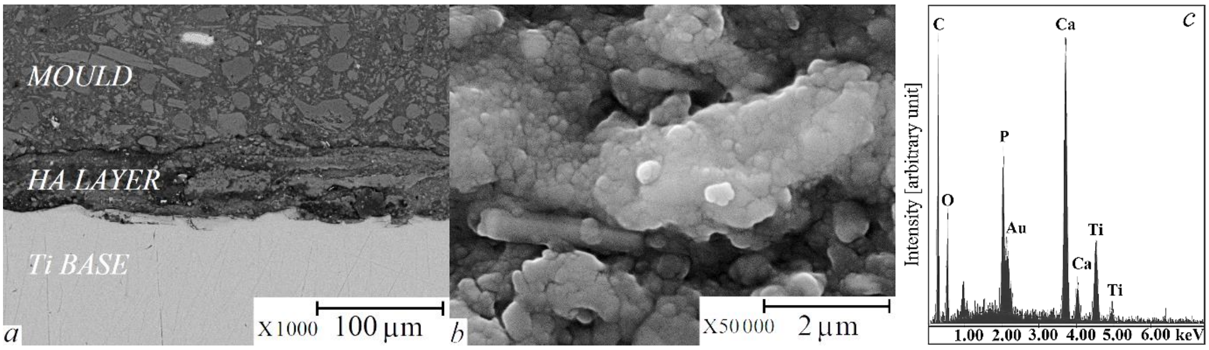


Figure 9. Section SEM images of Ti6Al4V surface HA powder mixed EDM in deionized water. Pulse-on time: 12 µs, pulse current: 22 A a) General appearance b) Grain structure of HA-coated surface c) EDS peaks of the surface [Ekmekci and Ekmekci, 2016b].

[Prakash et al., 2016a] tried to predict optimum conditions to improve surface quality, and hardness of the machined surface with Si powder in EDM oil mixed EDM on β-Ti work material. They found that by this technique surface microhardness increased about 184% and surface roughness near 1.02 µm with optimum conditions of peak current 13 A, pulse duration 5 µs, duty factor 8% and powder concentration 8g/l. They also observed a thin recast layer without micro cracks on the machined surface. Similarly, [Prakash et al., 2016b] examined the fatigue performance, and bioactivity of β-Ti in Si powder mixed EDM. They observed less amount of surface defects like microcracks, pits, and voids which improved the surface quality and fatigue performance. They evaluated the fatigue endurance as 280 MPa which is adequate for orthopedic applications. They promoted the bioactivity and biocompatibility (cell adhesion and proliferation) via micro and submicron porosity on the PMEDM'ed surface. [Prakash et al., 2017a] pointed out the effects of Si powder addition in hydrocarbon-based dielectric liquid on EDM of the β-Ti alloy. Their studies confirmed the formation of carbides and oxides enriched surfaces that indicates favorable surface conditions to enhance the biocompatibility. Moreover, the generation of surface porosities could be controlled by the process parameters to increase the hydrophilicity of the β-Ti alloy surface. For example, when machining with 15 A pulse current, 50 µs pulse-on time, 8% duty cycle and 8 g/l Si powder addition leads approximately a nanoporous surface with pore size ranging between ~200–500 nm. [Prakash et al., 2017b] suggested PMEDM for the generation of nano-porous biocompatible surfaces in the β-phase Ti alloy that allows enhanced conditions for the tissue to grow within the bone and enable to the robust interface. They have also shown the improvement in bone/implant interface strength by finite element method. Their results imply that the smaller craters produced by PMEDM enhance the bonding strength between the implant surface and surrounding tissues.

5. CONCLUSIONS

The advancement in material science result in the development of high strength and hardness materials, and therefore machining industry confronts with cumulative requirements to achieve high productivity and accuracy. EDM is one of the standard non-traditional production technique to machine electrical conductive high strength and hardness materials. However, several issues regarding the surface integrity such as microstructural alterations, microcracks, and topography limit the surface quality for industrial applications and arise the need for post-surface treatments to remove defected surface layers. Addition of suspended powder in dielectric liquid during EDM was first suggested to increase the machining performance and then figured out that surface quality improvement is possible to overcome the limitations. Researchers have examined several arrangements of work, tool electrode, dielectric and powder materials. Addition of conductive powders into dielectric liquid has resulted in substantial improvement in MRR due to decreased dielectric liquid strength and increased gap distance during EDM. The decrease in the heat affected layer thicknesses with relatively less number of surface defects pointed out the possibility of producing high surface quality by proper selection of the materials and electrical parameters evolved in the process. Therefore, the influence of added powders on discharge characteristics and the impacts on the surface becomes a vital issue for further improvements. The impacts powders on discharging expressed as the dispersion of sparks due to the formation of similar breakdown regions during PMEDM. The term dispersion also arises further questions regarding its intensity, homogeneity and its geometrical forms. Previous studies in this sense indicated several different forms of dispersed discharges that result in exciting surface topographies over the surface (Figure 10). Therefore, it could be concluded that the relation between the powders in dielectric liquid and the machining parameters that lead different forms of discharge dispersions became a crucial issue to understand the process.

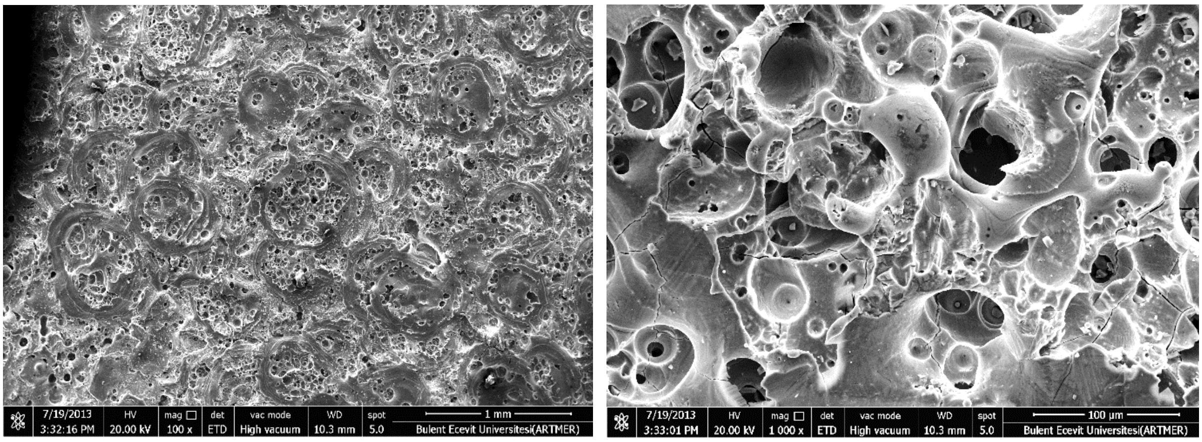


Figure 10 SEM views of PMEDM'ed Ti-6Al-4V (Powder: SiC, Concentration 20 g/l, Mesh number 800, Dielectric: Deionized Water, Pulse Current: 2A, pulse on time: 100 µs).

The nature of sparking provides high local temperatures and pressures that are difficult to obtain by other known techniques. Suspended powders in the dielectric liquid are under the influence of high temperatures and pressures induced during the process. The adjacent suspended particles to a spark heated rapidly and forwarded to the melted cavity with the closure of the spark due to the induced negative pressure. Therefore, migration of suspended particle material besides the products of cracked dielectric liquid to the machined surface is possible under specific machining conditions. The obtained results promise an easy technique regarding generation functional surfaces for specific needs. However, the non-linear and stochastic nature of the process adds difficulty to figure out the right combinations of the machining parameters to achieve required surface quality. The main shortcoming of the conducted studies is the lack the effects powder size and geometry on the machining performance and surface integrity. Therefore, extensive studies with a variety of combinations of powder size and geometry, work, tool electrode and dielectric material are needed to elaborate the process.

Surface treatment for biomedical applications is an essential issue for biocompatibility. Numerous surface modification techniques are in use for the purpose such as physical and chemical deposition techniques. However, most of these techniques have numerous weaknesses such as un proper bonding strength with the substrate and final production costs. Recently, PMEDM has introduced a potential alternative technology to machine and modify biomedical components such as implants. The mechanism of material transfer in PMEDM allows forming tough, nanostructured, and nanoporous layers that improve the osseointegration and cell adhesion. Recent studies indicate that HA powder mixing during EDM provides surfaces with an improved cellular response. Factors affecting these improvements could be attributed to the HA migration, formation of fine oxide and carbide phases with proper surface roughness, and hydrophilic characteristics. Further work could be needed to find optimal conditions, in vitro, biological tests to investigate the cell adhesion, proliferation, and differentiation on the PMEDM surfaces.

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