Investigation of Surface Quality in Cost of Goods Manufactured (COGM) method of μ-Al_2O_3 Powder-Mixed-EDM Process on Machining of Ti-6Al-4V

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Abstract

It is very essential to form such high stregth and hard-to-cut materials by using modern machining methods. It is important to introduce the efforts on modification of the process for improving the machining quality. In the present investigation, an effort was made to analyze the effects of micro size aluminium particles mixed dielectric medium under different powder concentration on machining titanium alloy in electro erosion process. The response-surface-methodology(RSM) based algorithm was utilized to analyze the performance measures by considering machinning time with Cost of Goods Manufactured (COGM) method in PMEDM process. It was found that the micron size powders can significantly help to enhance the surface quality of the Ti-6Al-4V surface during machining in EDM process. The presence of carbon, oxygen elements and the formation of surface oxides and carbides has been found due to the decomposition of dielectric fluid in PMEDM process. The lower deep cavities and uniform machining surface have been produced with the aluminum oxide powder EDM process owing to lower surface cracks density, conductivity. To sum up, investigation and comparison of surface scanning showed that this setting has been implied could be considered by the industries needs more precision.

Introduction

In the recent scenario, Titanium alloys are extensively utilized in aerospace industries due to its low density, high elasticity modulus, high corrision resistance, fatigue resistance and biocompatibility [1]. It is very tedious process to machine such higher strength ,hardness and toughness materials to produce complex shapes using traditional contact machining process. This causes to the growth and development of cutting tools and process mechanism too[2]. The titanium alloys are known as low-machining materials due to the susceptibility of the alloys for the hard working during material removal. It may also possible to chemical react with cobalt adhesives present in most shear tools [3, 4]. The higher hardness of the workpiece can also reduce the speed of economic cutting [5]. It is enough to utilize hard and durable tool materials such as fiber reinforced composites and stellites to cut titanium alloy materials those are costlier than existing tools [6]. It is also very difficult to produce complex profiles in such materials by traditional methods [7]. The better surface quality with lower tolerances, higher production rate, holes with micron size and large aspect ratio may also be required in such processes [8]. These features are generally needed in the products utilized in aerospace and automobile manufacturing fields [9]. Hence modern machining processes such as Electrical erosion process (EDM), Electro chemical machining (ECM), Water-jet-machining (WJM), Electron plasma machining (EBM), Ion beam machining (EBM) and ultrasonic machining (USM) are needed to meet these quality measures. Among the processes, EDM process has merits than other modern machining methods [10]. Nevertheless the process has manu limitations sucha as lower efficiency, higher machining time ands improper surface quality of the specimens [11]. Many technical solutions such optimization algorithm and changing process mechanism in possible ways have been proposed and implemented to overcome such limitations in EDM process [12–14]. The utilization of powder mixed dielectric medium can be used as insulating medium. It can increase the efficiency and surface quality of machined specimen as compared with conventional EDM process [15]. The addition of conductive powders can reduce the resistance of dielectric fracture to reduce the machining time with better surface quality in PMEDM process [16–18]. This has created considerable research directions to improve the machinability of titanium alloy in PMEDM process. Silver nano powder mixed dielectric solution has resulted in better measures of EDM process while machining titanium specimens [19]. It could provide higher machining operating cost in such process. The lower white layer thickness (WLT) was observed in PMEDM process. Many factors such as powder types, concentration and size were contributed to assess performance measures in PMEDM process [20]. It was also observed that the chromium nano sized particles has efficiently contributed than micron sized chromium particles in PMEDM process. Nevertheless, the chromium nano powders used in PMEDM was resulted in four times higher production costs as that of micro chromium powders. The quality indicators in PMEDM using Al_2O_3 powder mixed with different dielectric fluids were analyzed and evaluated [21]. The higher MRR was observed with transformer oil as dielectric medium than distilled water in PMEDM process. The lower electrode-wear-rate (EWR), surface-roughness (R_a) and radial-over-cut (ROC) was observed with kerosene dielectric medium. The MRR, R_a and WLT has been significantly improved in PMEDM with B_4C powder while machining titanium(Ti-6Al-4V) alloy [22]. The MRR was significantly improved with lower R_a and WLT using SiC powder on machining titanium(Ti-6Al-4V) alloy [23]. While utilizing chromium particles combined dielectric medium, the hardness of the layer was increased by two times during the machining of AISI D2 steel in PMEDM process [24]. The size of the cracks, craters and adhesion particles on the machining surface were significantly reduced in PMEDM process while compared with EDM process [25–28]. It was inferred that usage of different particles with the insulating medium could enhance the surface measures of EDM process [29]. Many research directions have been proposed to clarify the process mechanism through optimization of technology factors of PMEDM process to assess the durability of powder[30, 31]. The modeling and optimizing technological parameters in PMEDM is preferred as one of the main research direction by many technical experts[32]. Many computational techniques such as Taguchi, ANN, GRA, Topsis, TGRA, etc were successfully applied to optimization in EDM [33–37]. These techniques have also been used to model and optimize single or multiple targets in PMEDM process. The performance measures in PMEDM process using micro titanium powder have been investigated simultaneously using various optimization techniques to solve different optimal problem results [38–43]. The MRR, EWR and R_a in PMEDM using Al powder were analyzed by fused deposition modeling [44]. It was inferred that the performance measures under optimal conditions were significantly enhanced. The significance of the electrical factors and their interactions in PMEDM using Al_2O_3 powder has been analyzed by RSM[45]. This is suitable solution for modeling and optimization in PMEDM process with the better accuracy and lower computation error.

Although many significant attempts were available to examine the PMEDM process, a comprehensive study has not been conducted about the effects of powders mixed dielectric medium with different properties on the performances in the process. In this investigation, an effort was attempted to examine the effects of micro size aluminium particles combined dielectric medium under different powder concentration on MRR, EWR, surface quality and white layer thickness.

Materials And Methods

The Die sinking EDM - 501- (50A) Spark machine has been used for machining purpose in the present study. The drilling trials for making 1cm of diameter were performed on machining Ti-6Al-4V samples (alpha – beta titanium alloy with dimensions of 5x5x5 cm) in EDM process with copper as tool electrode and kerosene as dielectric medium. The chemical level of specimens is illustrated in Table 1.The percentage of elements has been found and validated using EDS analysis as depicted in **Figure 1**. **Table 2** and Table 3 shows the selection of process factors and other process variables respectively. During the process, PMEDM machining tests are performed in a special tank using aluminum oxide powder mixed in a dielectric. The material removal rate, surface roughness, tool wear rate and machining time were used as measures in PMEDM process. **Figure 2.(a-d)** show PMEDM machining equipment with schematic representation of the PMEDM process. **Figure 3**. shows the machined specimens in the present study. The PS3500 /C/1 digital balance with precision scale of 0.01 g was used to measure the material abrasion rates during before and after machining process.

Table 1. Chemical composition of the titanium alloy

Oxygen	Iron	Copper	Vanadium	Cobalt	aluminium	Carbon	Titanium	Elements
14.53	0.05	0.24	0.44	0.67	3.50	22.05	58.53	Weight percentage (%)

Table 2. Selection of process parameters

Variables	Unit	Symbol	Parameters
Current	A	I	**Input**
Pulse on time	µs	T	
Powder concentration	g/l	C	
Material removal rate	mm^3/min	MRR	**Output**
Tool wear rate	mm^3/min	TWR	
Surface roughness	µm	R_a	
Machining time	min	-	

Table 3. Selection of process variables in the present study

	Variables	Unit	Levels determined
	Peak current	A	15; 20; 25
	Pulse on time	µs	50; 60; 70
	Pulse off time	µs	60
	Open circuit voltage	V_g	220
	Machining voltage	V	70
	Machining time	min	30
	Productive type	-	Iso Pulse
	Polarity of tools	-	Positive
	Dielectric fluid	-	Kerosene
	Powder type	-	Aluminum oxide powders
	Powder concentration	g/l	0; 2.5; 5
	Washing		Immersion

Results And Discussion

The machining experiments were performed to investigate the effects of different parameters more accurately and cost-effectively. Minitab and Expert Design software have been used to perform RSM test design method. The quality measures for all trials are shown in Table 4.

Table 4
Various parameters considered using the RSM method in Minitab software and results.

Number	Current	Pluse on time	Concentration of powder	Material removal rate (mm^3/min)	Tool wear rate (mm^3/min)	Machining time (min)	Surface roughness (µm)
1	15	5	0	0.122	0.060	6.2	5.98
2	25	5	0	1.528	0.111	35.45	8.7
3	15	7	0	0.416	0.030	29.27	6.93
4	25	7	0	0.460	0.027	10.26	8.3
5	15	5	5	0.355	0.081	19.7	4.25
6	25	5	5	0.797	0.159	6.02	7.32
7	15	7	5	0.460	0.092	10.43	4.68
8	25	7	5	0.633	0.145	11.05	7.5
9	15	6	2.5	0.491	0.065	8.55	5.26
10	25	6	2.5	2.066	0.275	2.033	7
11	20	5	2.5	1.416	0.189	2.966	8.1
12	20	7	2.5	0.832	0.082	6.85	4.76
13	20	6	0	0.964	0.100	16.8	7.12
14	20	6	5	1.200	0.118	4.75	5
15	20	6	2.5	0.298	0.092	16.13	6.2

The contour plot with tolerance level of 0.05 for the performance measures under the influence of different input factors on machining specimens have been shown in Fig. 4–5. The higher flow rate could increase the amount of MRR, Fig. 4. While the micron powders was included with dielectric insulating medium, the electrical conductivity of insulating medium was also improved. Hence the MRR could be increased significantly. However the powders was mixed with insulating medium further, the dielectric nature was also affected. If dielectric nature of the insulating medium was affected, it could affect the discharge mechanism. This would result in reducing th MRR. Hence the higher MRR has been observed with concentration of 2.5 g/l. However the MRR has been reduced with concentration of 5 g/l. Hence it has been found that 2.5 g/l would be better optimal value of powder concentration. In the mechanism of EDM machining process with powder mixed dielectric medium, the larger and wider electric discharge channel could lead to lower density of the electric power at the electric discharge position. This could reduce the amount of impact forces on the workpiece surface. This has resulted on producing the smaller holes on the machined surface of titanium specimens. The higher thermal conductivity of the particles, was developed more thermal energy outside the machining gap. It has reduced the amount of thermal energy at the electric discharge position and it leads to a reduction in the material erosion from the specimen. The aluminum oxide particles are lighter and more susceptible in the machining gap. The particles could directly produce more heat energy in the gap. consequently, the amount of thermal energy in the electrical discharge channel could be reduced after the optimal value. The aluminum oxide powder due to higher thermal conductivity and lower density creates more drop in the amount of material erosion compared to EDM mode without powder. In order to investigate more deeply and confirm the stated interpretation above more clearly, the interaction diagram of different factors on the erosion rate with constant consideration of parameters, Fig. 5. This diagram comprehensively shows the effects of different parameters in different modes.

The material removal rate during electric discharge depends on the pulse current and duration. The higher electrical discharge energy could produce more erosion in the machining zone owing to higher melting and evaporating temperature. The impact driving force resulting from the evaporation of insulating medium depends on the electric discharge energy. As electric energy increases, the driving force to remove the melting material from the machining cavities is also be increased. It could create larger size of the holes obtained by the spark in the sample. The larger amounts are separated from the workpiece material for each electrical discharge since the current is increased, Fig. 6.

The tool electrode in EDM process should have high melting point and low resistance to electric current. The diagrams related to TWR with combined effects of different initial parameters, Fig. 7–9. The larger current with high pulse duration can generally increase TWR. There is an optimal amount regarding powder concentration according to the diagrams. The more powder particles can reduce the tool erosion by reducing pulse current across the machining zone. The particles combined in the insulating medium can expand the plasma channel to generate the higher thermal energy in EDM process. It could reduce the electric power density which results in the tiny tool erosion. The inclusion of particles in the fluid can transfer more heat across the machining gap. This could reduce the electrical discharge capacity on the tool electrode surface to reduce tool erosion. Hence the best concentration to reduce the tool erosion was found as 2.5 g/l of aluminum oxide powder. The diagram of the interaction of different parameters on TWR with constant consideration of the parameters, Fig. 10. It also indicate the selection of optimal concentration in order to achieve lower TWR with the combined effects of other parameters.

The higher current with pulse time less than 6 units has increased the machining time, **Fig. 11**. During the higher pulse time, the machining time was reduced. The merged effects of current and lower particles concentration could increase the machining time. However, the current was increased to reduce the machining time at higher concentrations 2.5 g/l. Hence the optimal value for the pulse on time should be lower for the effective machining time, Fig. 12–13. The interaction of different parameters on the tool wear with constant consideration of parameters, Fig. 14. It can be stated that the machining time in constant powder concentration was independent and constant owing to the prodcution of intended sparks.

In the different layer recasted on the machined area, there are numwerous changes like phase hanges, thiickness of white layer, material percentage, Mechanical, piysical and chemical properties, and etc. are contaned into the subcategory,Fig. 15. To investigate of fault remanied on the surface, it is imporatn to select what reasons and purpose should be considered

The surface measures of the specimen was described by spark current, electrical discharge time length, gap voltage, electrode polarity, material and workpiece properties, characteristics of dielectric fluid, concentration of chips in fluid and the dimensions of the electrode. The higher pulse current has increased the crack length and the width of the surface cracks, Fig. 16. The cracks formations are owing to the tensile stress developed by the shrinkage of the material during cooling of the workpiece surface after ignition. This higher tensile stress of the workpiece could lead to superficial cracks.The higher current has increased the electrical discharge energy to remove more molten material. The larger and deeper surface cavities could develop higher surface roughness under the larger pulse on time, Fig. 17. As a result of successive electrical discharges on the workpiece surface, cavities are created on the machining surface. These cavities are created by the eruption of molten material on the surface at the end of the pulse time. As the higher pulse duration leads to an increase in pulse energy. The dimensions of the machining cavities on the workpiece surface can also be increased. There are generally prominent edges around the cavities owing to the machining process. The edges surrounding the cavities resulting from machining have beem increased by increasing pulse on time. The quick melting of the workpiece surface in electrical erosion process and the quick freezing of the workpiece during washing with the help of dielectric fluid, surface and heat-affected areas are created on workpiece samples. These surface and subsurface defects could lead to reduce hardness, wear and corrosion resistance of the workpiece surface. The aluminium particles are used in order to maintain the surface measures in power machining mode. The powderless process produces more random and roughness of the machined surface.

The smooth and fine machining surface with uniform surface roughness under aluminum oxide powder mixed dielectric medium, Fig. 18–19. The lower width of the surface cracks was observed as compared with powder-free modes. The aluminum oxide particles led to produce of fine surface quality compared to the machining mode without powder. The higher aluminum oxide powder concentration with the dielectric fluid can increase the particles in the gap between the tool and the workpiece. It produces the instability in electric discharge machining due to production of the higher short-circuit or arc pulses. Hence the powder concentration more than 2.5 g/l, the machining surface could develop more rough and random surface by increasing the powder concentration powder. The instability in the process could also produce more random spark energy distribution owing to density of the electric power. Consequently, the impact force from the electric discharge on the workpiece surface could be generated as more heterogeneous. It was viewed that the process of topographic changes of machining surface under different concentrations was quite similar to the process of machining time under different concentrations.

Topography of machined surface without and with powder mode, Fig. 20. It can be seen that the powder mode has produced the better quality level compared to the powder-free mode. The more rough and uneven surface was observed by increasing the powder particles concentration due to the instability in the erosion process. It was also observed that the process of topographic changes of machining surface for different concentrations is quite similar to the production mechanism of surface roughness under different concentrations in PMEDM process.

The significance of different parameters on surface measures have also been investigated in order to investigate performance measures and tabulated in Table 4. In PMEDM process, the chips are almost spherical that separated from the surface of workpiece due to uniform sparking during electrical discharge.

The larger current increase the surface roughness owing to the higher discharge energy. The higher impact forces on the machining surface has caused more molten material to produce deeper and larger cavities. After the molten material erupts from the cavities, the remaining molten material around the cavities freezes and produces a rough surface during cooling due to the flow of dielectric fluid. The lower current could produce lower surface roughness due to the lower depth of the cavities. Figure 21–22 show the main effects of the input parameters on the roughness values of the machining surface. The main reason for larger craters are owing to energy from electric discharge as mentioned earlier. The surface roughness of the specimens under different concentration in the dielectric fluid, **Fig. 23**. The better smoothness was observed with aluminium particles mixed dielectric medium due to the higher conductivity and low density of aluminum oxide. The lower electrical resistance can increase the spark gap whereas high thermal conductivity causes more heat to be transferred out of the discharge position. Both of these factors could lead to a decrease electric power density and impact force from the electrical discharge on the workpiece surface. It has resulted in producing lower deep cavities from machining on the workpiece surface. The addition of conductive or semiconductor powder particles into the plasma channel, the resistivity of the fluid fracture decreases. Hence the EDM feed mechanism could increase the gap between the two electrodes compared to the conventional EDM machining mode to create more stable electrical discharge conditions. The production of larger and wider electric discharge channel which leads to decrease the electric power density at the electric discharge position. It has created less deeper cavities on the machining surface and resulted in the lower surface roughness. The higher thermal conductivity of the powder particles could lead to a lower thermal energy at the electric discharge position.

The optimization of the electrical discharge process when adding aluminum oxide powder with values that are considered as the ultimate justifiable goal. The range of changes considered, the weight to determine the value of the parameter and the degree of importance, Table 5.

The overlay plot diagram can decide the most optimum range of the input factors within determined range. The material removal rate should attain the maximum value whereas tool wear rate, surface roughness and machining time should reach the minimum level. The shaded area is known as the area outside the determined specifications. The yellow region area is known as the safe area for achieving optimization goals called the "sweet spot", Fig. 24. The overlay plot diagram while adding aluminium powder under different concentrations in the electrical discharge process to reach optimal range of input and output parameters. The results have shown that the optimal process parameters including I = 22 A, Ton = 7 µs and C = 5 g/l, and quality indicators such as MRR_{opt}=0,867 mm^3/min, TWR_{opt} = 0.126 mm^3/min, SR_{opt} = 5.86 µm and T_{opt} = 12.542 min.

Table 5
Constraints of process parameters in EDM

Constraints						
		Lower	Upper	Lower	Upper	
Name	Goal	Limit	Limit	Weight	Weight	Importance
A: Peak current	is in range	15	25	1	1	3
B: Pulse on Time	is in range	5	7	1	1	3
C: Concentration of powder	is in range	0	5	1	1	3
MRR	maximize	0.121678	2.06591	3	1	5
TWR	minimize	0.0268531	0.275456	1	2	3
SR	minimize	4.25	8.7	1	3	5
Machining time	minimize	2.033	35.45	1	1	3

Machining Time Mangament is known as a criteria for assessing of the performance of a process. To be more precie, it is a good option to take place a process in a high or poor efficiency. Making a surface with high quality at least Cost of Goods Manufactured (COGM), simultaneously, it is investifated in this study. Figure 25 shows that my investigation has been done in three stage of concentration of powders (C_p = 0–5 g/l). the descreasing procedure of machning time is visble while the without powder is compared with added powder conditions. It is the sign of improving machining time in PMEDM process.

In short view, by considering the achiviements obtained of adding Al_2O_3 that is shown on Fig. 26, it could be visible that the PM-EDMed Ti-6Al-4V workpeice is usable in sensitive industried like aerospace and medicine processes. The surface that has a predictable charactereistics is needed in any industries. Indeed, analyzing of time and cost management shows that the surface could be considerable in different stage of production and manufacturing when it has had a priority of quantity and quality.

Conclusion

An effort was made to analyze the influence of micro size aluminium oxide ($Al_2O_{3)}$ powder mixed dielectric medium under different powder concentration on machining titanium alloy. The RSM based algorithm has been utilized to analyze the performance measures in PMEDM process. From the detailed experimental investigation, the following conclusion have been made.

- The amount of material removal rate compared to powder-free EDM mode initially increases and then decreases due to the addition of Al_2O_3 powder.
- The micron sized Al_2O_3 powders can significantly produce low surface roughness of the titanium alloy surface.
- The presence of carbon, oxygen elements and the formation of surface oxides and carbides has been found owing to the decomposition of dielectric fluid in PMEDM process.
- The possibility of instability in electrical discharge owing to high arc production under high pulse current and duration in PMEDM process.
- The lower deep cavities and uniform machining surface can be produced with the aluminum oxide powder EDM process owing to lower surface cracks density, considerable electrical and thermal conductivity across the machining gap.
- The optimal process parameters in PMEDM using Al_2O_3 powder were found to be I = 22 A, Ton = 7 µs and C = 5 g/l among the chosen factors. The quality indicators such as MRRopt = 0,867 mm3/min, TWRopt = 0.126 mm3/min, SRopt = 5.86 µm and Topt = 12.542 min and variables with an accuracy of 9.4%.

Declarations

Compliance with Ethical Standards

Ethical Approval: There is no ethical approval needed in the present study.

Consent to Participate: There is no consent to participate needed in the present study.

Consent to Publish: There is no consent to publish needed in the present study.

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Figures

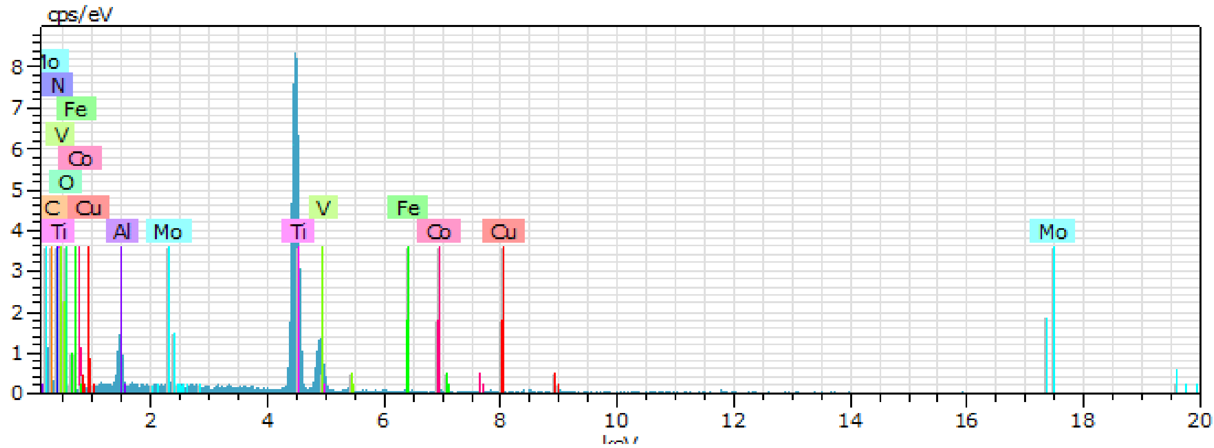

Figure 1

EDS analysis of composition percentage of Ti-6Al-4V workpiece.

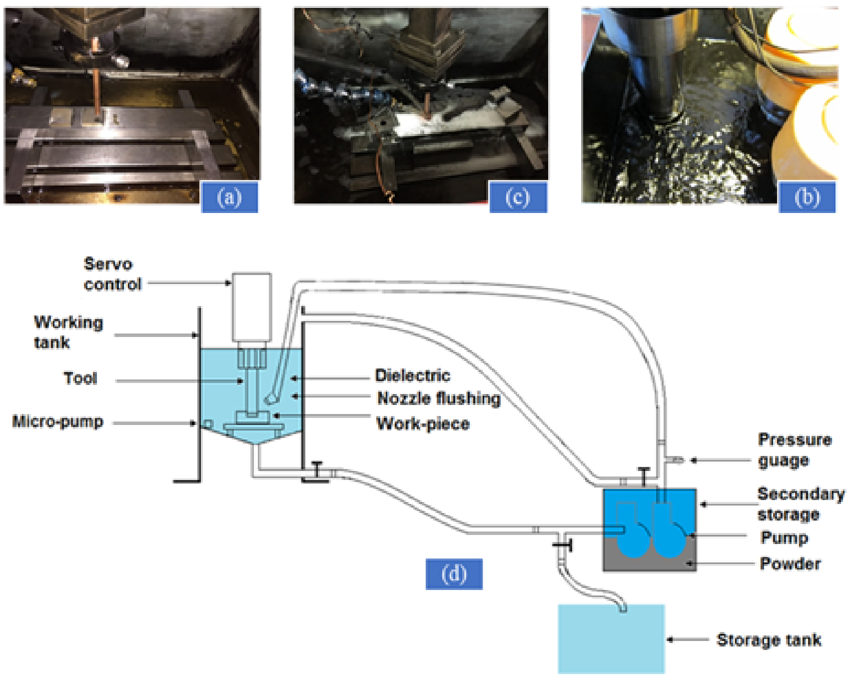

Figure 2

PMEDM process arrangement with schematic representation

Figure 3

Machined titanium specimens using PMEDM process.

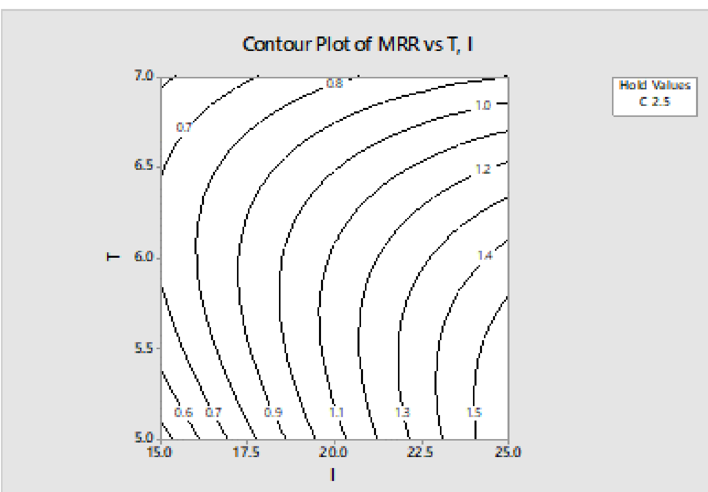

Figure 4

Combination effects of I and Ton in MRR.

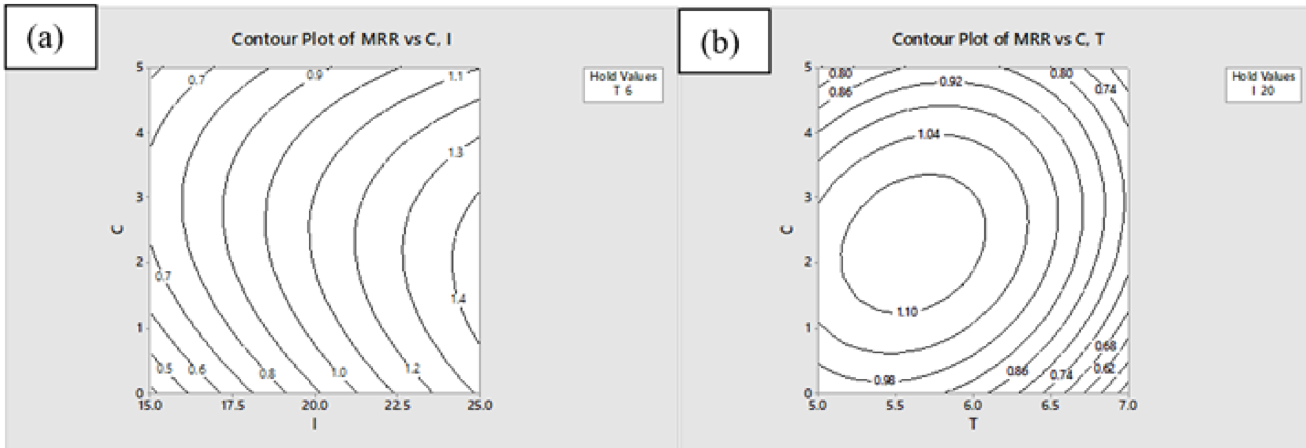

Figure 5

Combination effects of different parameters on MRR a) C and I b) C and Ton

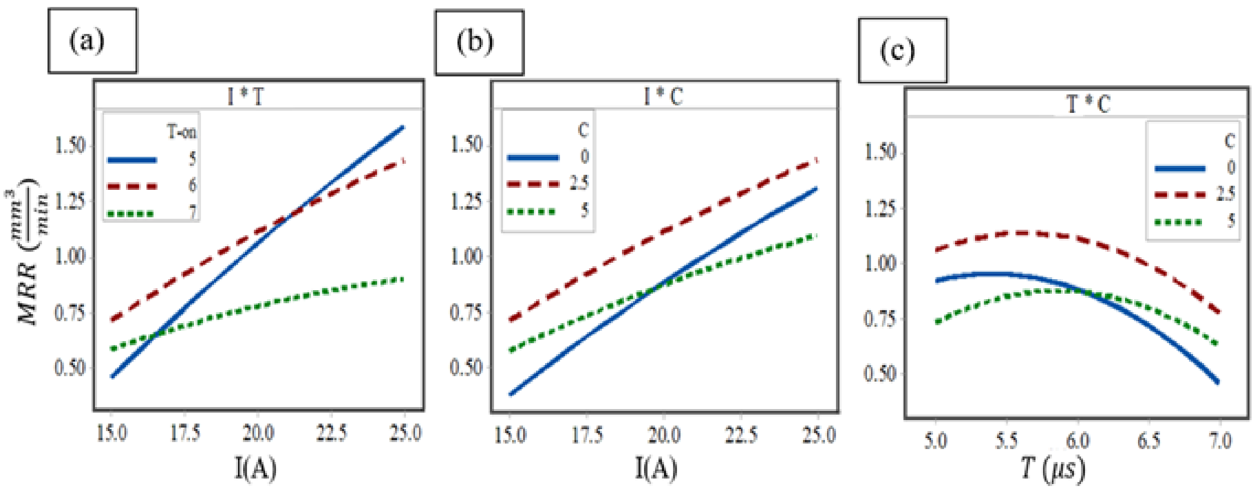

Figure 6

Interaction diagram of different parameters on MRR a) I at constant Ton b) I at constant C c) Ton at constant C.

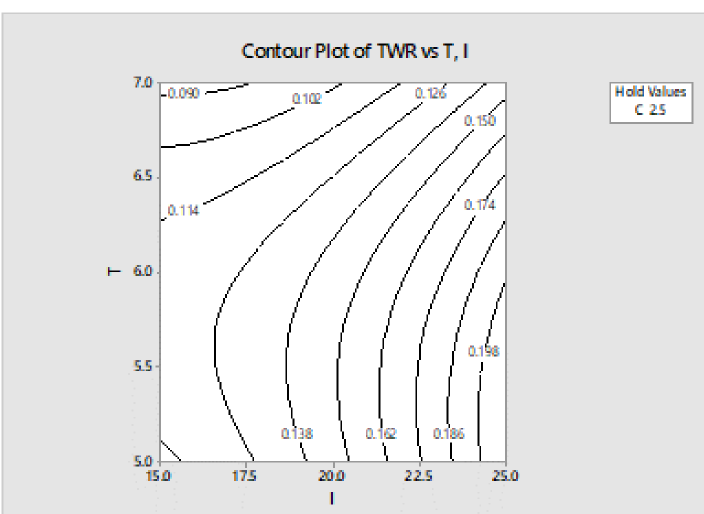

Figure 7

Combination effects of I and Ton on TWR.

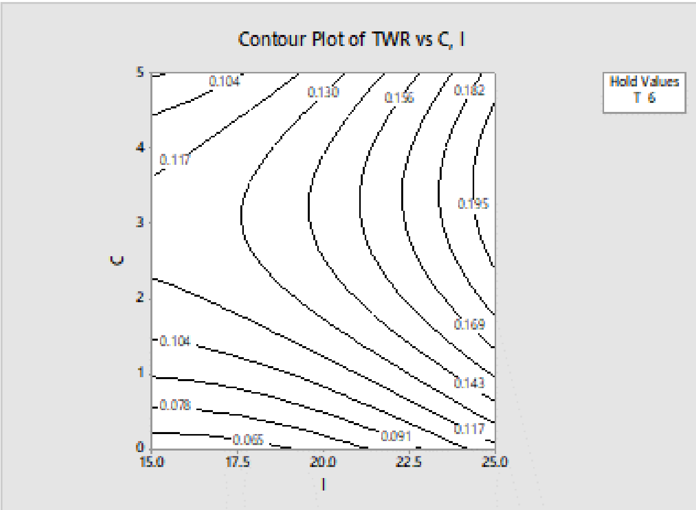

Figure 8

Combination effects of C and I on TWR.

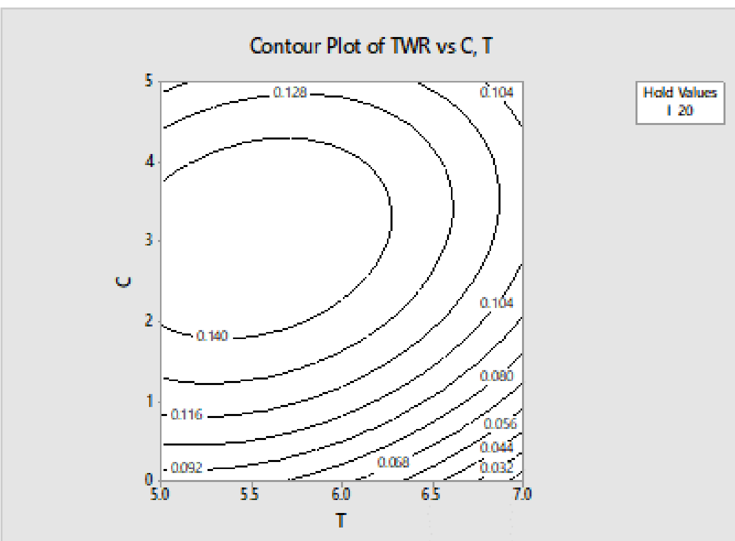

Figure 9

Combination effects of C and Ton on TWR

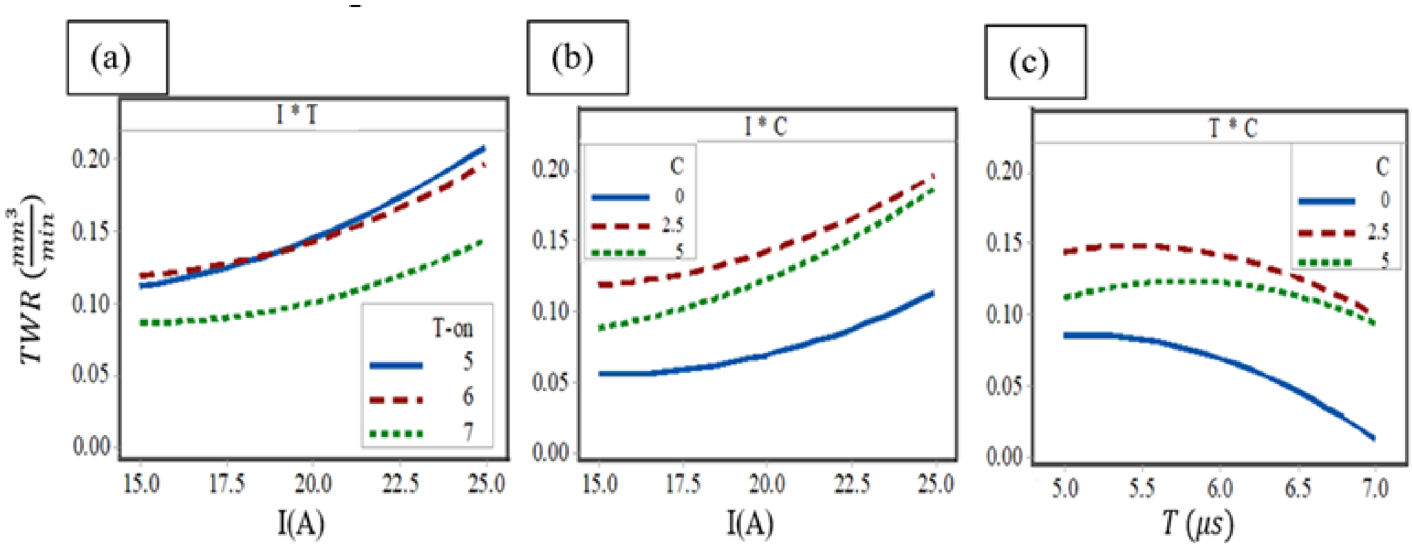

Figure 10

Diagram of interaction of different parameters on TWR. a) I at constant Ton b) I at constant C c) Ton at constant C

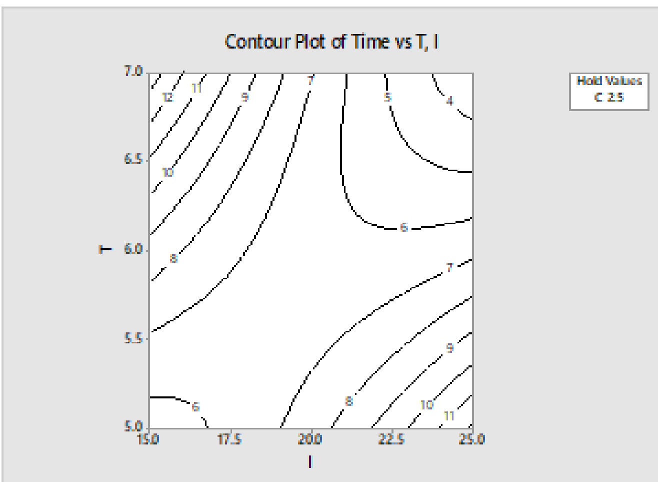

Figure 11

Combination effects of I and Ton on EDM machining time.

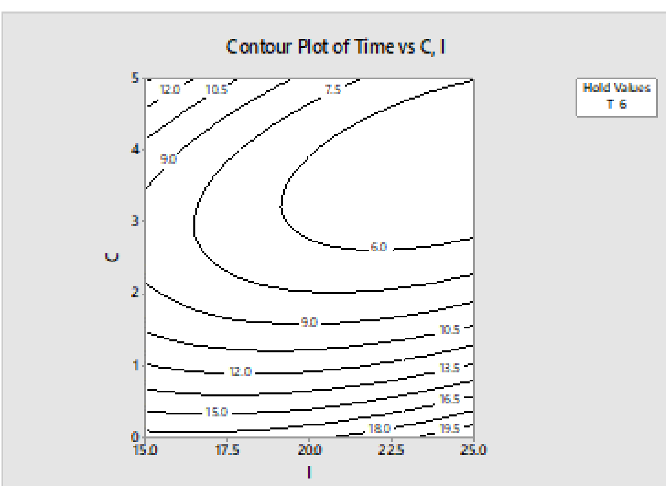

Figure 12

Combination effects of C and I on EDM machining time.

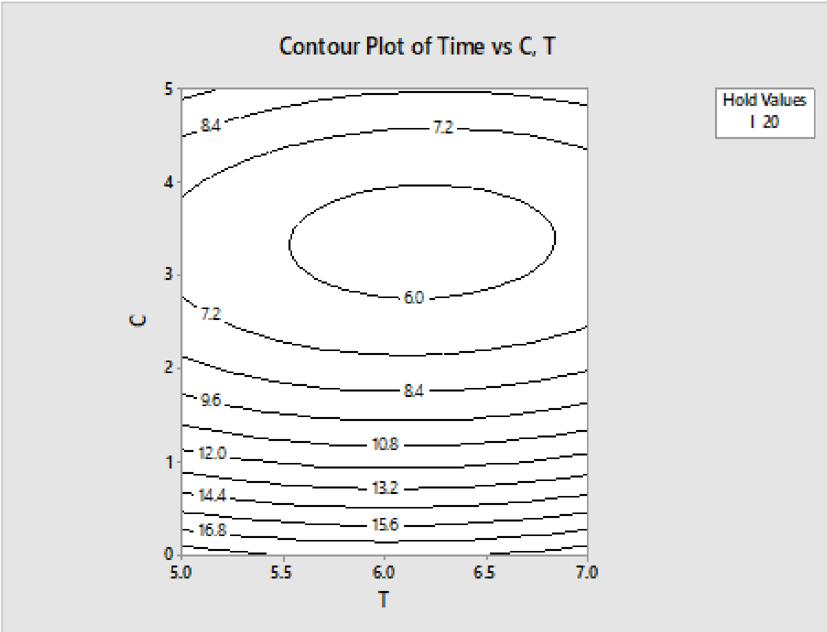

Figure 13

Combination effects of C and Ton on EDM machining time.

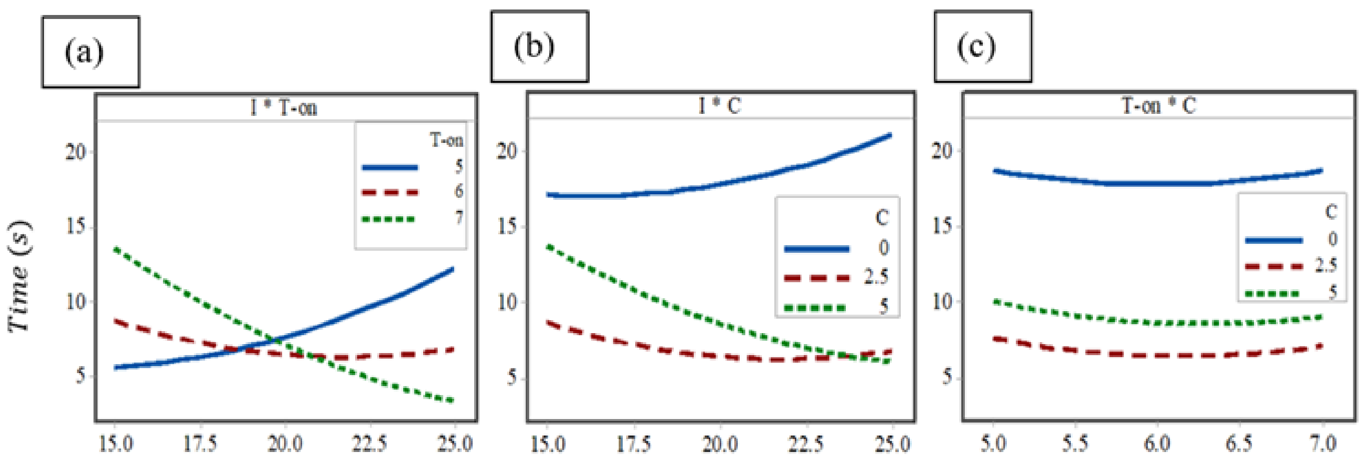

Figure 14

Diagram of the interaction of different parameters on TWR a) I at the constant Ton b) I at constant C c) Ton at constant C

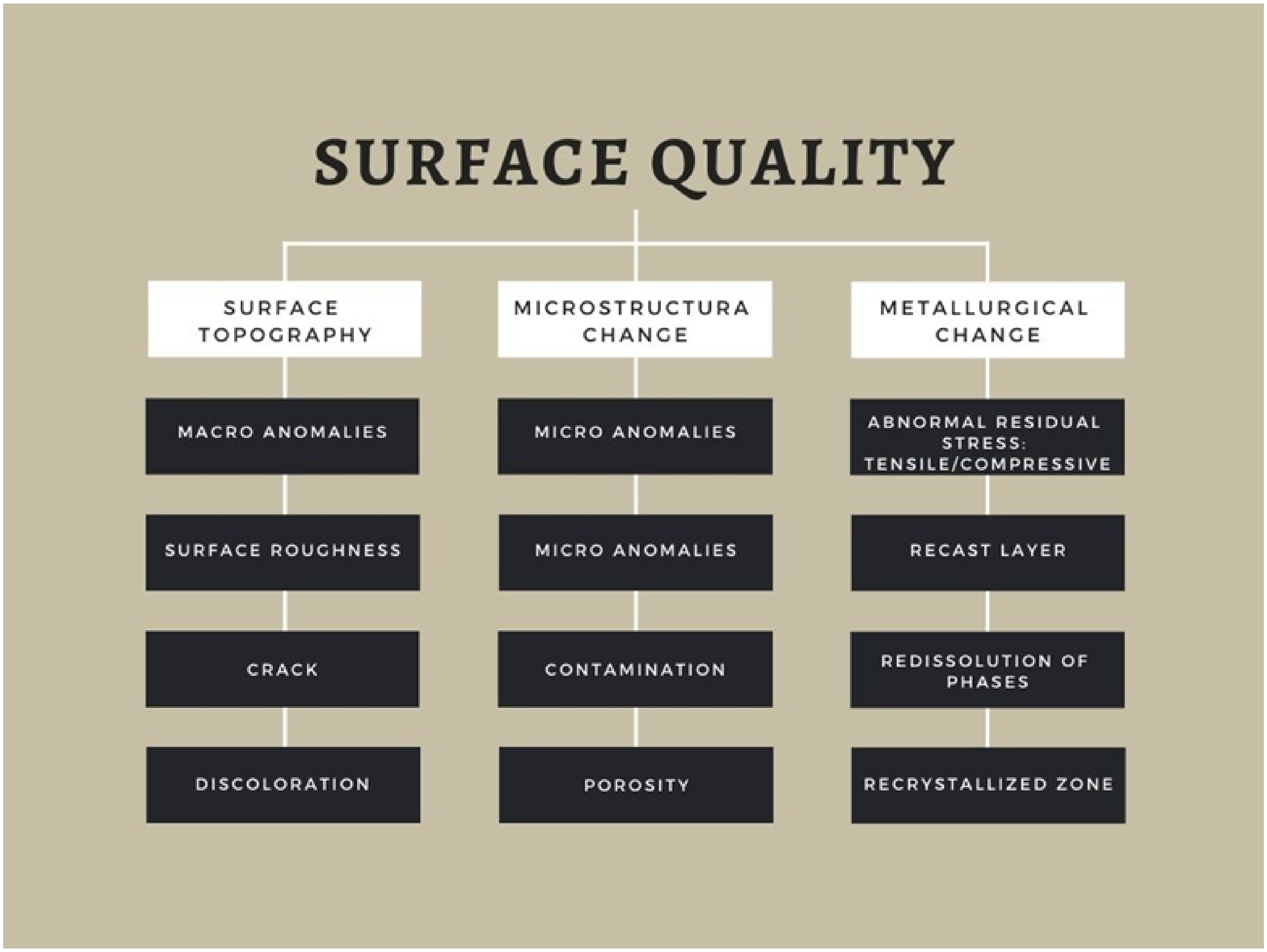

Figure 15

Diagram of the interaction of different parameters on TWR a) I at the constant Ton b) I at constant C c) Ton at constant C

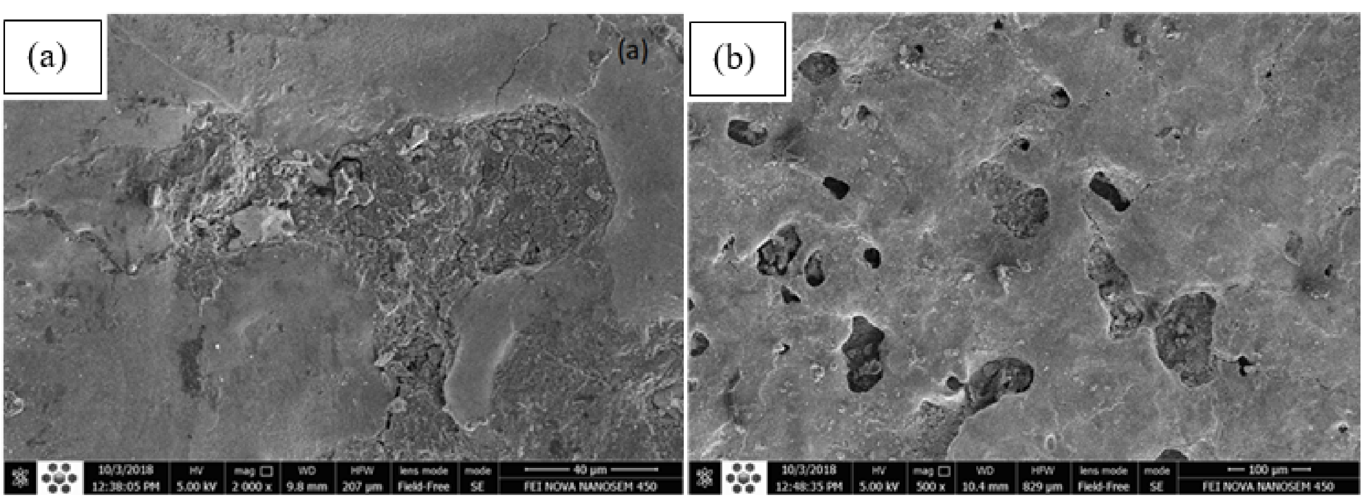

Figure 16

SEM images of machining surface in EDM without adding powder a) Ip= 15A, Ton = 50 μs b) Ip= 25A, Ton = 60 μs.

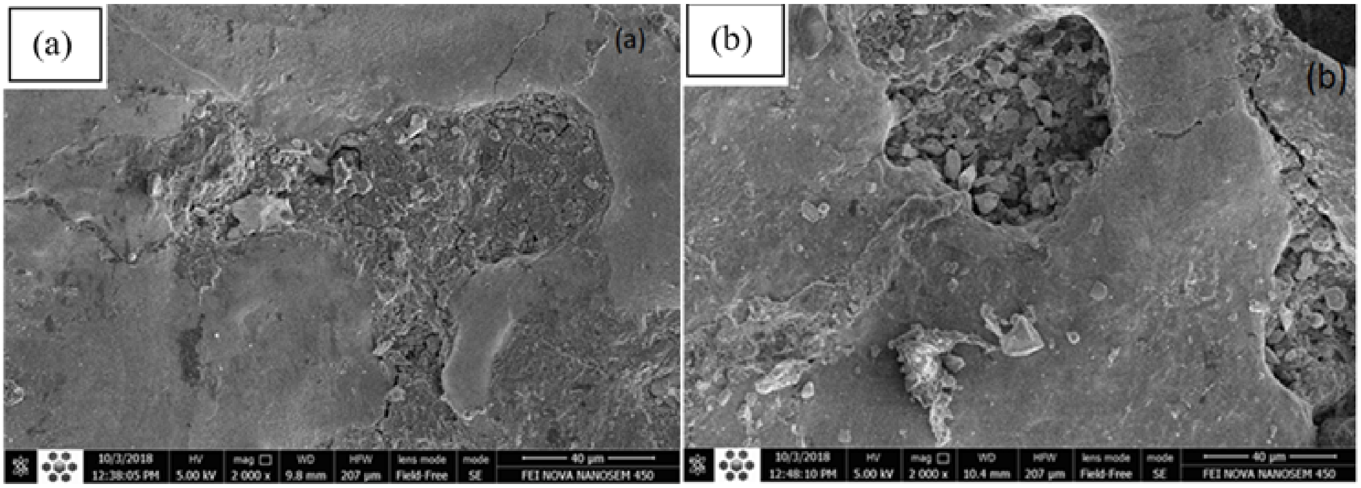

Figure 17

FE-SEM images of the machining surface in EDM without adding powder a) Ip= 15A, Ton = 50 μs b) Ip= 15A, Ton = 70 μs.

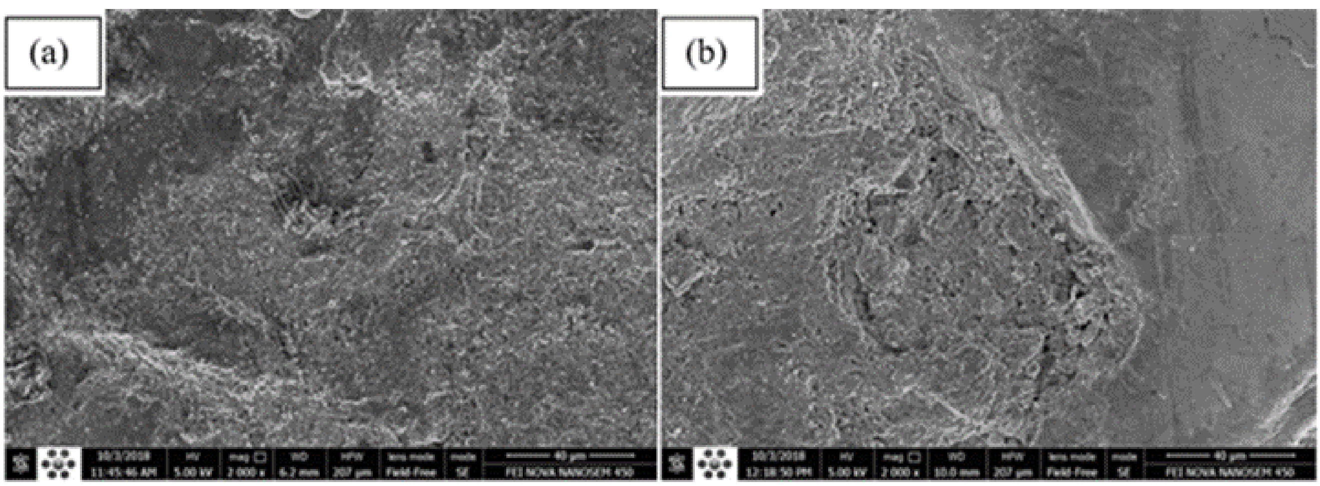

Figure 18

FE-SEM of machining surface in EDM adding powder a) Ip =15, Cp = 2.5 g /l, T= 60 μs b) Ip = 25A, Cp = 2.5 g/l, T= 60 μs.

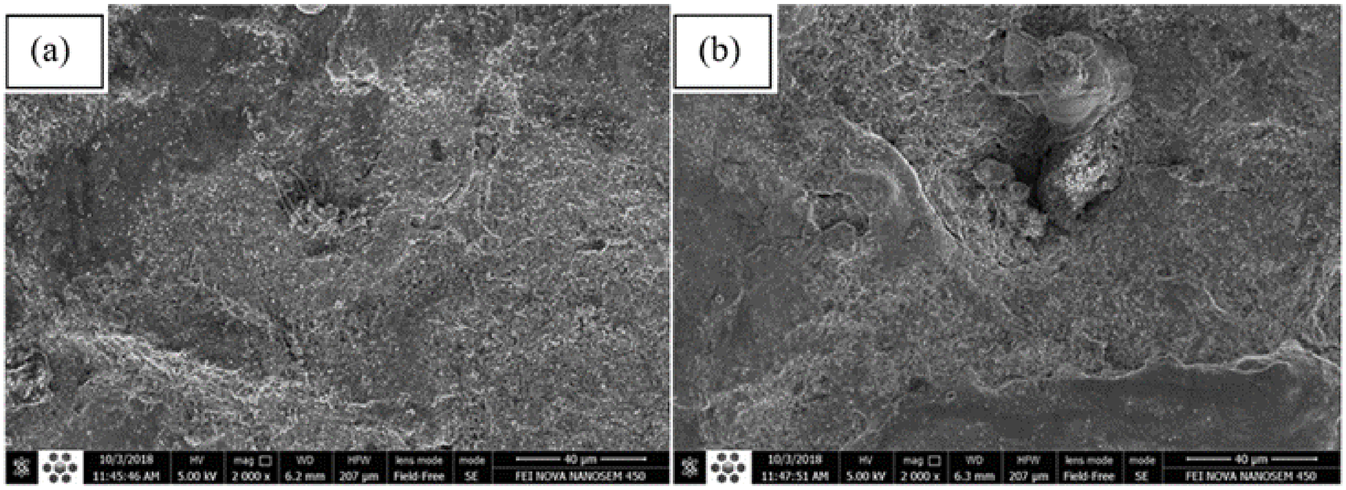

Figure 19

FE-SEM images of machining surface in EDM adding powder a) Ip =15A, Cp = 2.5 g /l, T= 50 μs b) Ip = 15A, Cp = 5 g/l, T= 50 μs.

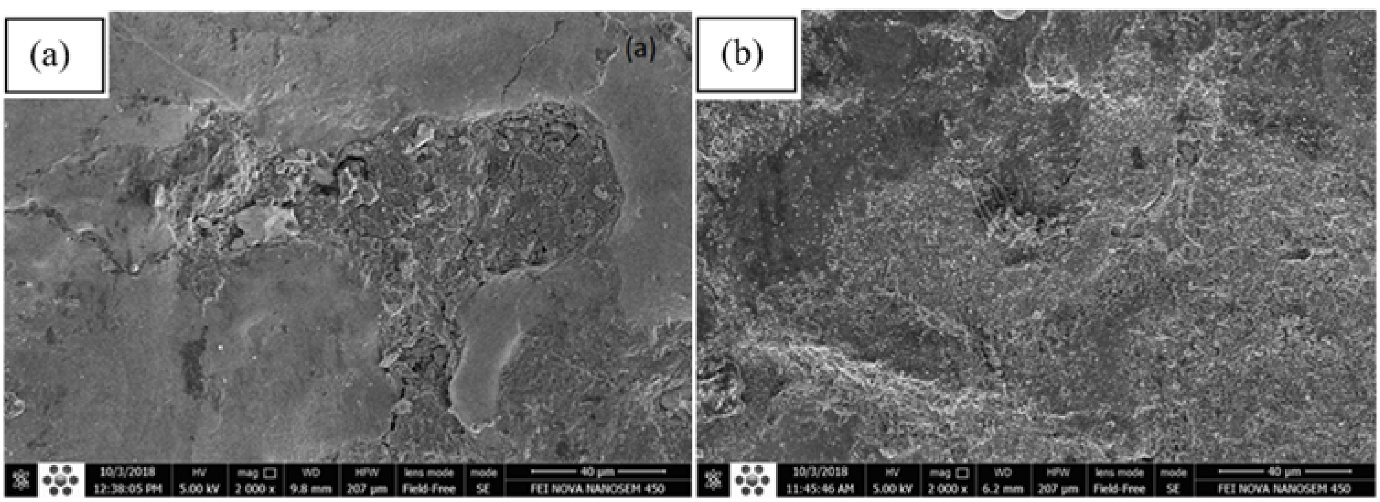

Figure 20

FE-SEM images of machining surface in EDM without powder (a) Ip=15A, Cp= 0 g /l, T= 50 μs (b) Ip= 15A, Cp= 2.5 g/l, T = 50 μs.

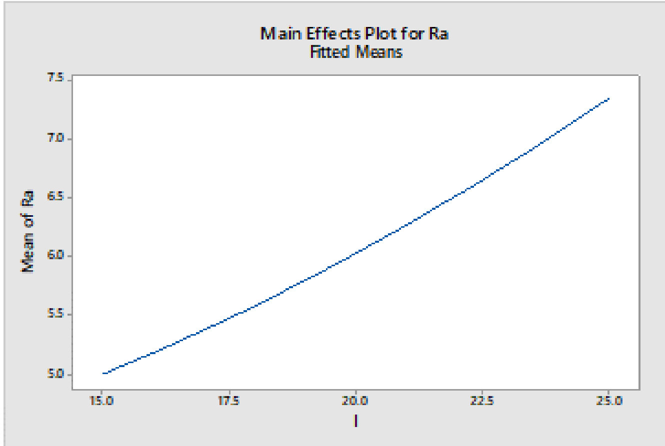

Figure 21

Effects of I on Ra of EDM pieces

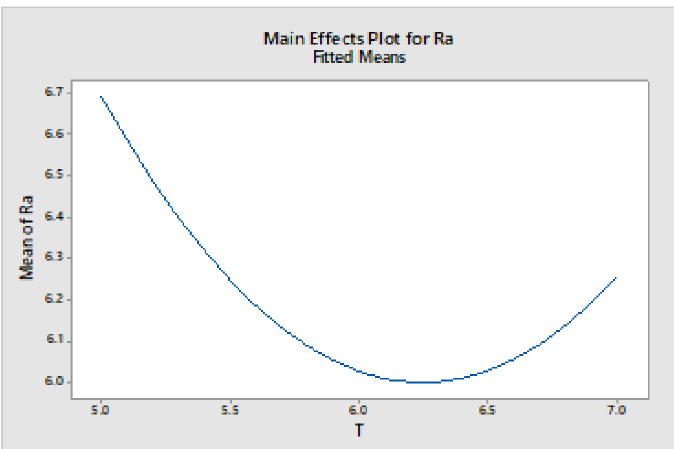

Figure 22

Effects of Ton on Ra.

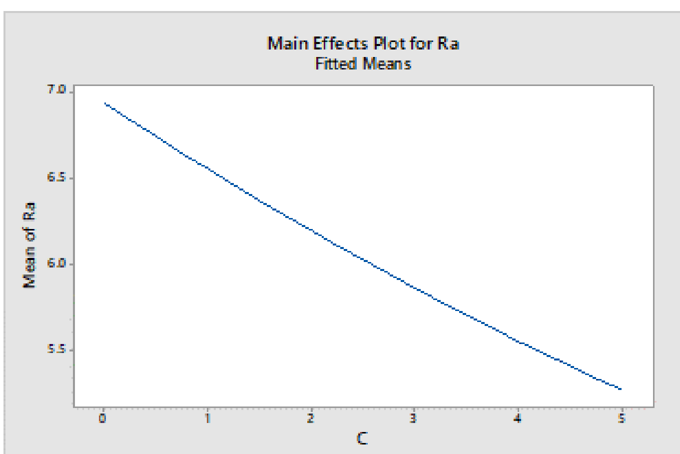

Figure 23

Effects of C on Ra

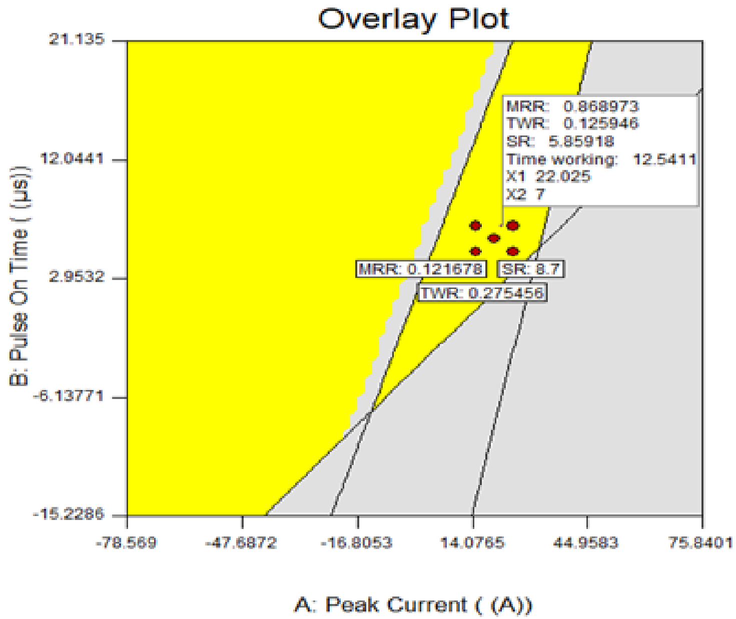

Figure 24

Optimization Model of the EDM process.

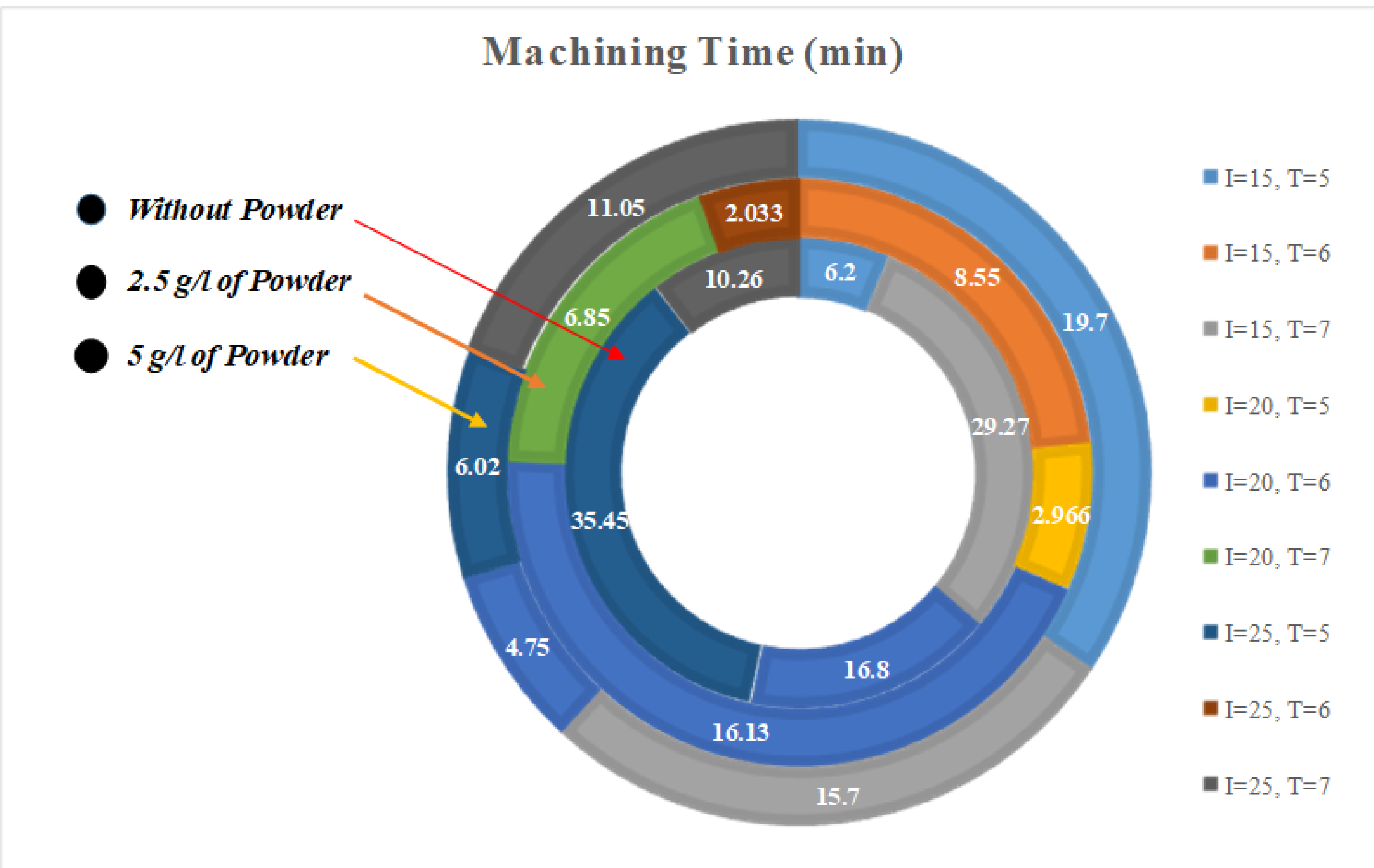

Figure 25

Machining Time Management of PM-EDM in three level of concentration of powder

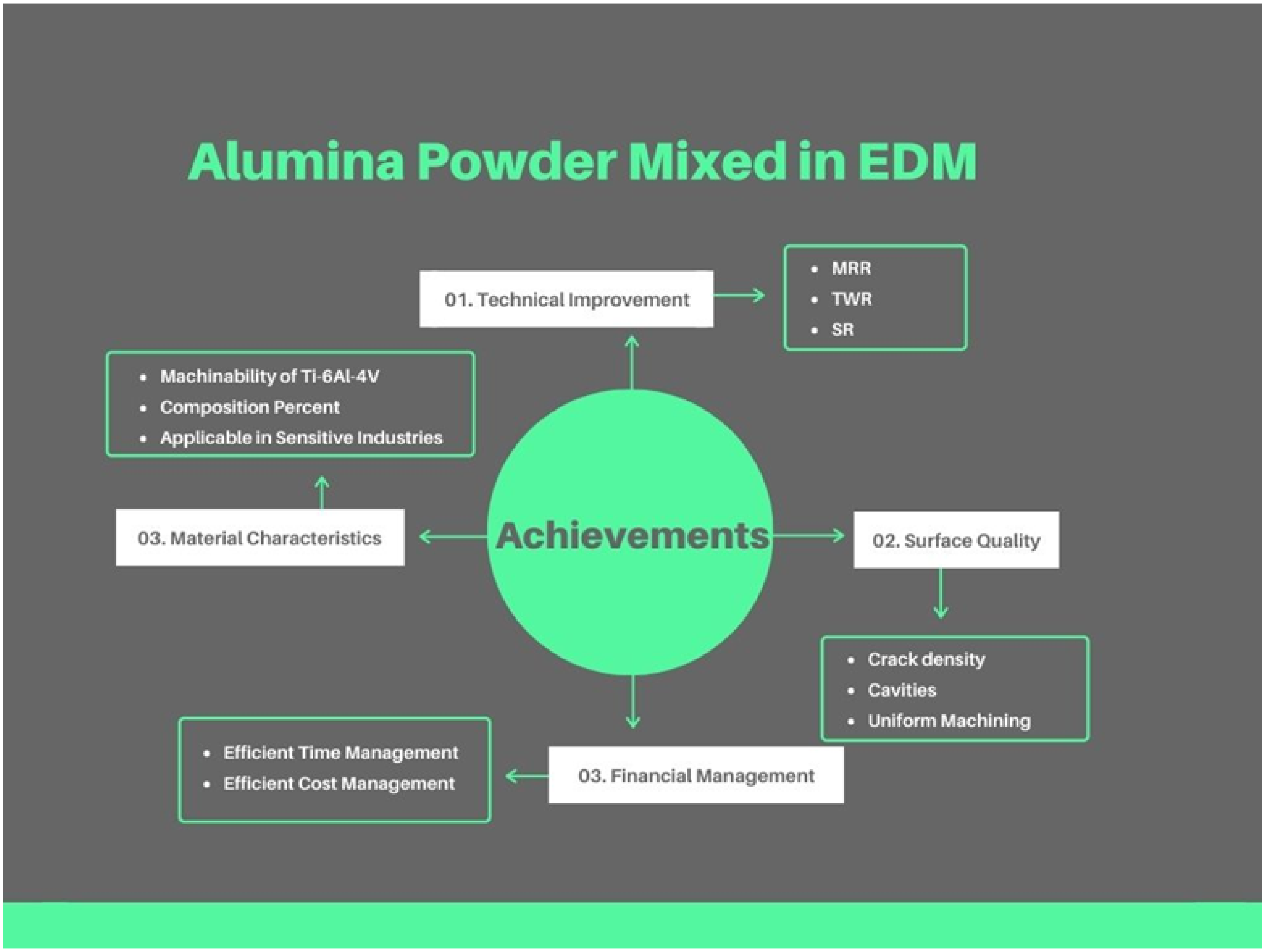

Figure 26

Achievements of Adding Alumina in EDM process