Analyzing The Effect of Machining Parameters For Titanium (Grade 5) Alloy

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ABSTRACT

Titanium alloys are commonly used in industry, automotive, medical and all manufacturing applications.Unconventional machining process which offers lesser micro structural changes and less internal stresses produced during machining compare to traditional machining process. In this project Titanium Grade 5 alloy is machined by using WEDM process with different feed rates and the mechanical property changes are to be investigated. WEDM has since the process' launch emerged as the best option to manufacture micro parts with the highest degree of dimensional precision and surface finish consistency from a simple way to manufacture instruments and die. The machining parameters like kerfs width, material removal rate, feed rate, wire speed, wire tension and voltage are the factors influencing the mechanical properties and micro structure changes. Out of these parameters, the feed rate is varied and the properties like hardness, surface finish and micro structure changes are to be investigated and the best suitable feed rate for machining the titanium grade 5 alloy is to be identified.

Key words: *Titanium alloy, WEDM, Material removal rate, SEM analysis, Hardness.*

I. INTRODUCTION

The attractive material of Titanium and its alloy is the high mechanical and physical properties of a large number of building sectors (for example, high strength to weight; high return stress at lifted temperatures; and excellent erosion imperceptibility). They are increasingly used, especially for oil refining, compound handlery, surgical implantation and contamination management, as part of other modern and business applications. The preservation of radioactive waste and electrochemical and marine applications are also used for titanium alloys. In accordance with the arrangement and the resulting room temperature constituents, the titanium alloys are grouped into four key categories, specifically alpha, close α, α / β and β. Titanium combinations have their innate characteristics that lead to poor usability. Due to low machinability, the surface of the titanium compounds is affected often during machining procedures, harm shows up as micro cracks, formed tip, plastic bending, thermal areas and malleability issues. The high work strength of titanium alloys can also increase the high cutting strengths and temperatures, which may result in a depth-of-cut measurement.

A. Electrical Discharge Machining (EDM)

One of the unconventional techniques is electrical discharge machining (EDM). It is a controlled process for extracting metal from the instrument and operating through electronic spark erosion. A pulsating electrical charge (ON / OFF) of high frequency current is applied to the workpiece through the electrode for the metal removal process. It extracts (erodes) very tiny metal sections at a regulated pace from the workpiece.

B. Wire-Cut Electrical Discharge Machining (WEDM)

Wire cut EDM machining (Electrical Discharge Machining) is an electro thermal production process during which a skinny metal wire in conjunction with de-ionized water (used to conduct electricity) allows the wire to chop through metal by the utilization of warmth from electrical sparks. Due to the process' inherent characteristics, Wire EDM can easily machine complex components and accuracy from hard conductive materials.

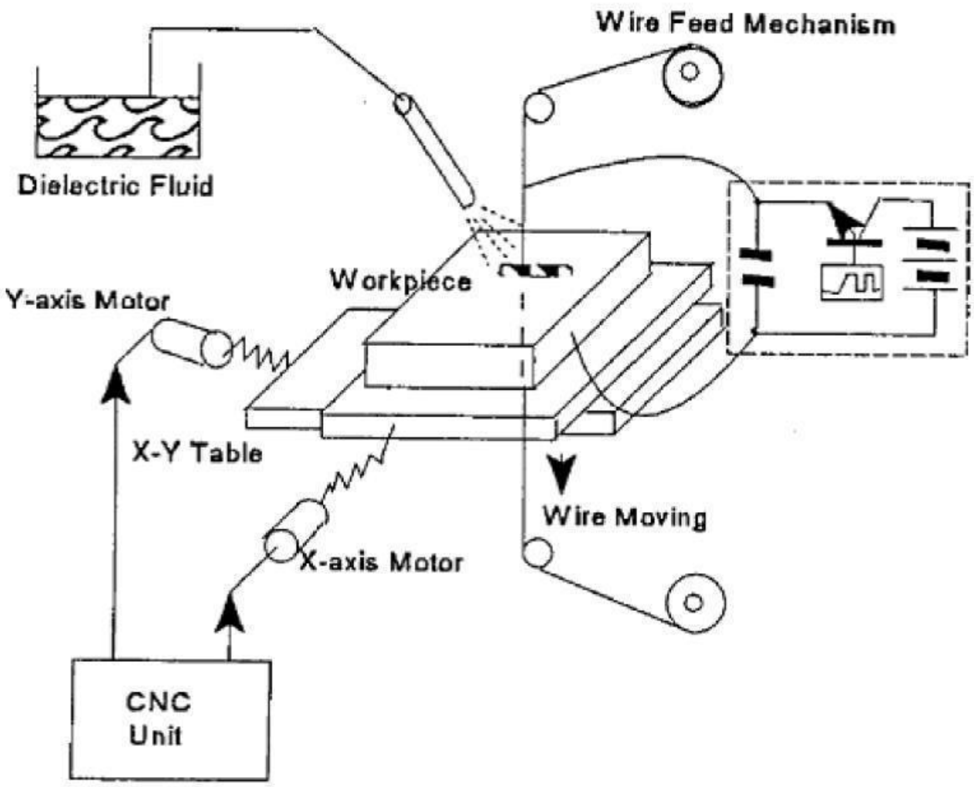


Fig 1.1 Schematic diagram of WEDM

II. LITERATURE REVIEW

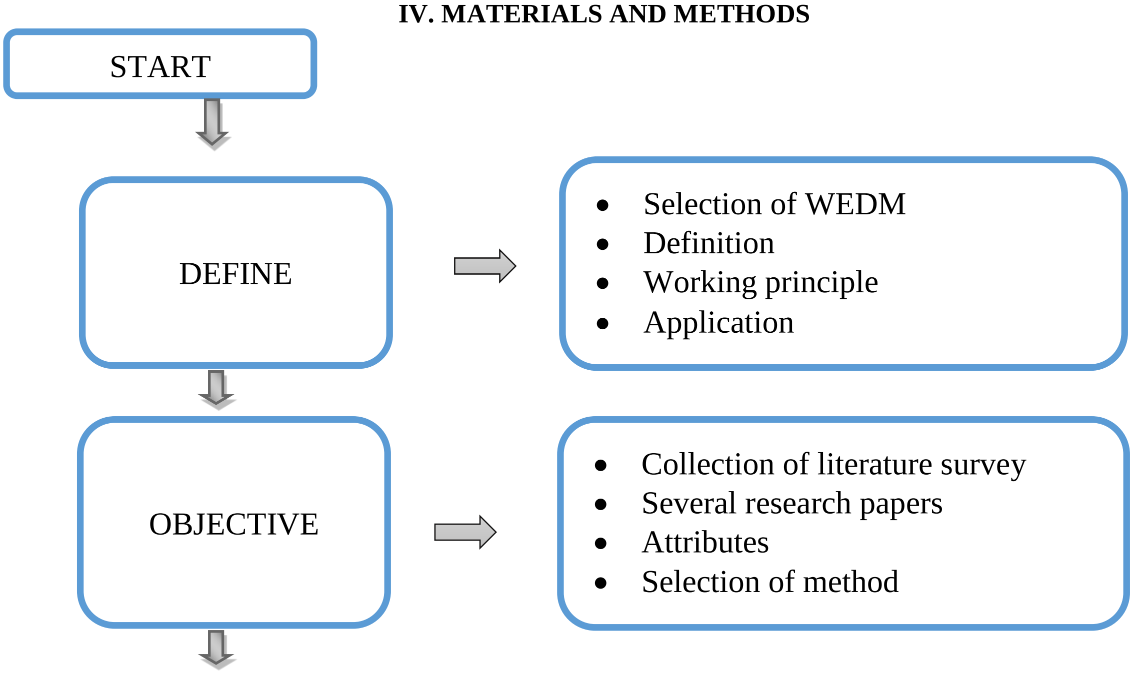
Shanmugam et.al (2004)the process parameters identified were time between two pulses, pulse duration, injection pressure, and wire speed and wire tension. The responses are electrode wear rate (EWR) and Material removal rate (MRR). The study showed that the coated wires are preferred over the uncoated wires.[1]**Newman et.al (2004)**the ultimate goal of the WEDM process is to achieve an accurate and efficient machining operation without compromising the machining performance. This is mainly carried out by understanding the interrelationship between the various factors affecting the process and identifying the optimal machining condition from the infinite number of combinations. [2]

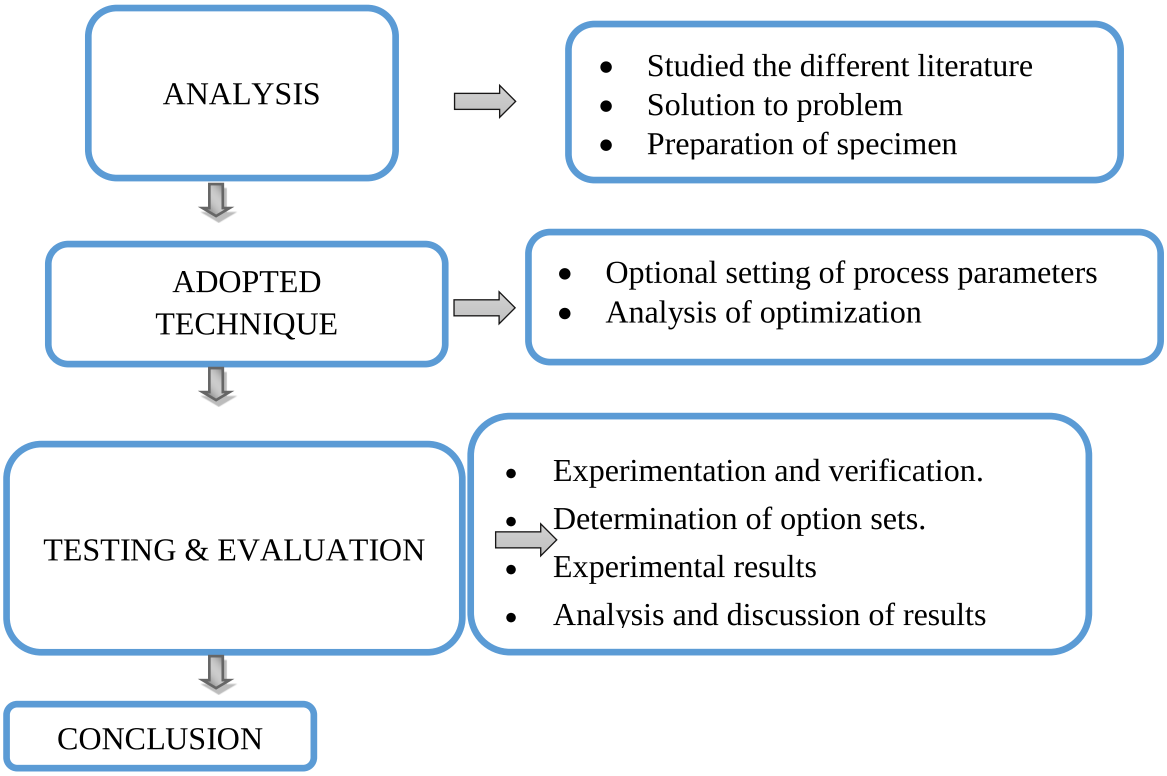
Vamsi Krishna pasam et.al (2004) Ignition pulse current (A), Short pulse duration (B), Time between two pulses (C), Servo speed(D), Servo reference voltage(E), Injection pressure(F), Wire speed (G) and Wire tension(H) on surface finish was studied using Taguchi parameter design. A mathematical model is developed by means of linear regression analysis to establish relationship between control 20 parameters and surface finish as process response. An attempt is made to optimize the surface roughness prediction model using Genetic Algorithm (GA) [3]**Bulan Abdullah et.al (2012)**The process parameters identified were machine feed rate (4 mm/min), wire speed (8 m/min), wire tension (1.4kg) and voltage (60V). The responses are kerf width, material removal rate and surface roughness. The main goal is the maximum MRR with the minimum kerf and surface roughness. [4]**PragyaShandilya et.al (2012)**The process parameters identified were pulse-on time (TON), pulse-off time (TOFF) and wire feed rate (WF)). The response is kerf width. The study showed that there is considerable decrease in surface roughness with decrease in voltage and this reduction is of the magnitude of approximately 59.27% in the taken range of voltage. [5] **Rajurkar et.al (2013)**it is found that the cutting speed increases with peak current and pulse interval. Surface roughness was found to increase with pulse width and decrease with pulse interval. [6]**Prohaszka et al. (1997)**three kind of wire material namely Mg, Sn and Zn were selected to perform the experiments. It was concluded that the materials used for the fabrication of wire electrodes must be characterized by a small work function and high melting and evaporation temperatures. [7]**Spedding and Wang (1997)**the pulse-width, pulse duration, wire tension and injection set point were selected as input parameters. [8]**Lin et al. (2001)**Multi-variables fuzzy logic controller was designed to determine the reduced percentage of sparking force. The objective of the total control was to improve the machining accuracy at corner parts, keeping the cutting feed rate at fair values. [9]**Liao et al. (2002)**the developed model could successfully estimate the work piece height. Based on the on-line estimated work piece height, a rule-based strategy for adaptive parameters setting was proposed to maintain stable machining and to improve the machining efficiency. [10]**Kali Dass, S. R. Chauhan (2011)**the factorial design was utilized to obtain the best cutting condition which leads to the minimization of the surface roughness and tangential force. The half normal plot and ANOVA indicate that the (B) feed rate (f) is the most significant factor followed by (C) depth of cut (ap) and (A) cutting speed (vc). [11] **G. Dongre, J. Shaikh(2017)** the cutting performance of Mist lubrication machining is better than that of conventional dry and flooded lubrication machining. Mist lubrication has improved tool life and also gives better finished surface. The overall experimental results showed that the surface finish, cutting forces, and tool wear are related to the heat generated at the cutting zone and the friction between tool and work surface and to get better MRR, surface finish and minimum tool wear one must use effective lubrication method during machining. [12] **BogdanSłodki, WojciechZebala (2019)**the aim of the presented research was to analyseMach inability of the Grade 5 ELI titanium alloy with tools made of sintered carbides with defined chip breaker geometry in the condition of high pressure cutting fluid. The main aim of the analysis was to determine the areas of correct work of the chip breaker for the finishing turning process. The component values of the total cutting force depend on the feed rate and depth of cut and do not depend on the cutting speed; the obtained chip form depends on the range of feed rates and depth of cut, shape of the chip breaker and on the value of the cutting fluid pressure. [13] **Mohammed Nouari and Hamid Makich (2014)**in this research work, a detailed experimental approach for the comprehension of machining titanium alloys has been presented. Several analyses confirmed that differences in machinability and microstructure of tested titanium alloys can have an important impact on tool wear. The low machinability of titanium alloys due to the low thermal conductivity and high micro hardness of these materials leads to severe and premature tool wear. The machining of titanium alloy Ti-55531 has been compared with that of Ti-6Al-4V alloy. To do this study, the mechanical, thermal, metallurgical and physic-chemical aspects were analysed in depth.[14] **PatilAmit S et al., (2015)** Coated carbide cutting tool gives maximum material removal rate with high pressure through spindle lubrication system. Surface finish is directly depending upon machining conditions. Good surface finish obtained at minimum depth of cut, maximum R.P.M., with low cutting speed in wet machining. Dry machining should be avoided for saving tool life and surface texture. Rigid clamping is necessary for avoiding effect of low modulus of elasticity of Titanium alloy for chatter free surfaces [15].

III. SCOPE AND OBJECTIVE OF THE PROJECT

- The titanium alloy is machined with different feed rates in WEDM.
- The hardness of the titanium alloy is to be tested at the machine.
- Surface roughness is to be verified by using SEM.
- Then the micro structure of the titanium alloy at the machined area is tested by scanning electron microscope.
- It will give good surface finish and accuracy to the product

IV. MATERIALS AND METHODS





MATERIAL SELECTION

Titanium alloys are alloys containing a blend of titanium and other chemicals. These alloys are highly durable and have high tensile strength. They are lightweight, extremely resistant to corrosion and are capable of resisting extreme temperatures. The high cost of raw materials and manufacturing, however, limits them to military applications, aircraft, spaceships, motorcycles, medical devices, jewellery and highly stressed parts such as rods on luxury sports cars or other high-quality sportive devices and consumer electronics.

Properties

- Density - 4.42 g/cm^3
- Tensile Strength - 900 ksi
- Elastic Modulus - 114 Gpa

V. EXPERIMENTAL WORK

A. Effect of Cutting Speed

The speed of cutting is significant to minimize surface roughness (17.49 percent). The machined component's surface roughness decreases with increased cuts. It is because, in combination with the higher cutting temperature, a high spindle speed increases the softening of the material in the work piece and reduces the cutting forces and thus the finish on the surface.

B. Effect of Feed Rate

The feed rate contributes greatly to the surface ruggedness reduction. In general, the surface roughness increases in warm, flooded and MQL environments when feed rate increases. However, due to the pressure applied by the supply of MQL, which in turn removes chips (debris) from the cuttings zone, the MQL showed a reduction in surface roughness in comparison to dry and flooded conditions. As is evident as feed rate increases, even surface roughness increases as the heat from the cutting zone is less usable, a high quantity of material removal rate and a chip build-up between the sections of the tool work.

C. Analysis of Hardness

During machining, work hardening will make the material's surface and immediate surface harder. Temperature, time and mechanism for relaxing stress internally are the determined effect of internal work hydration. The internal process of Harding the heating build-up takes place with the use of a tool to cut the working part material and accumulation for refrigeration happens with the disengagement of the tool from the working part material.

D. Machine Tool

The wire-cut EDM of titanium alloy was carried out on a wire-cut EDM machine (ELEKTRA MAXICUT) of Electronica Machine Tools Ltd. Table 5.1 illustrates technical specification of the MAXICUT WEDM.

Table 5.1 Technical specification of the MAXICUT WEDM

Max. Table Size	440 x 650 mm
Max. Work piece height	200 mm
Max. Work piece weight	300 kg
Max. Taper cutting angle	±15°/100 mm
Resolution	0.001 mm
Wire diameter	0.25mm(standard) 0.15, 0.2, 0.3 mm(Optional)
Simultaneously controlled axes	X,Y, u, v
Input Power supply	3 phase, AC 415 V, 50 Hz
Average power consumption	3.5 to 5 kW
Dielectric fluid	De-ionized water

E. Selection of Titanium Alloy

Titanium Ti 6Al-4V is the most commonly used titanium alloy workhorse of all Ti 6Al-4V, or Grade 5 titanium alloys. It represents 50 % of the world's total use of titanium. Their value lies in their many advantages. To increase its strength, Ti 6Al-4V can be heat treated. The soldered building is used at service temperatures of up to 600 degrees F. This alloy combines its high strength with a light weight, useful formability and high resistance to corrosion.

F. Material Removal Rate (MRR)

The MRR maximum is a significant cost and efficiency indicator. However, increasing MRR cannot be desired for all applications because it can scarify the surface integrity of the workpiece. The product of rapid removal rates is a rough surface finish. The material removal rate (MRR) for WEDM can be obtained from the expression,

MRR =VMM ……… (1)

MRR – Material Removal Rate (mm^3/m)

VMM – Volume of the Material Removed (mm^3)

T– Time taken or machining (min)

G. Surface Roughness (SR)

The surface produced by WEDM process consists of a large number of craters that are formed from the discharge energy. The quality of surface mainly depends upon the energy per spark. The surface roughness of the machined work piece is measure with the help of surface roughness instrument and its specification.

H. Factors and Levels

The levels of the machining parameters were selected and listed in the Table 3.9.1 to perform the experimental design

Table 5.2 Factors and Levels

S. No	Factors / Levels	1	2	3
1	Pulse on time (μs)	1	2	3
2	Pulse off time (μs)	8	9	10
3	Peak Current (A)	4	5	6
4	Wire Tension (Kg.f)	300	600	900

I. SEM Analysis

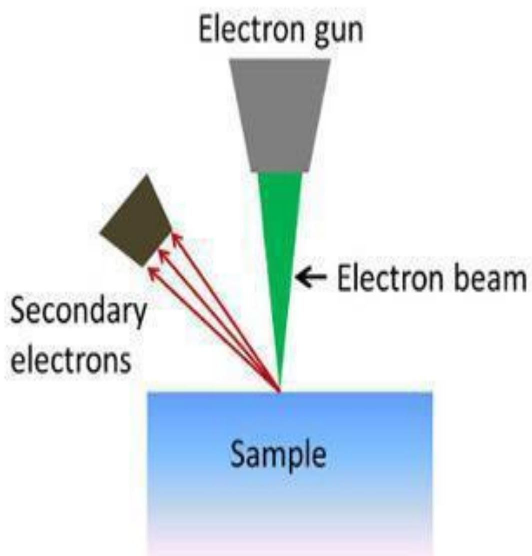


Fig 5.1 SEM analysis diagram

The scanning electron microscope (SEM) uses a focused beam of high energy electrons to generate a variety of signals at the surface of solid specimens. After machining, the plate form sample was produced from 'Electronica (Maxi cut)' the wire electro discharge machining (WEDM); the microstructure of the machined surface of titanium work-piece was obtained for each machined sample by using scanning electron microscope (SEM). The microstructure of each machined sample was obtained in order to perform a detailed study of the machined surface.

The SEM images of titanium alloy under different lubricant strategies. Depicts the surface generated under dry mode with cutting speed of 50 m/min, feed of 0.35 mm/rev, nose radius of 0.4 mm and depth of cut of 0.25 mm and the recorded surface roughness of 3.25 mm. The higher surface roughness is due to dry mode and high feed rate of 0.35 mm/rev. The surface roughness measured under flood lubrication with cutting speed of 150 m/min, feed of 0.35 mm/rev, nose radius of 0.6 mm and depth of cut of 0.25 mm is 2.65mm.This is because of high feed rate and high nose radius. The surface generated with a better surface finish of 0.89 mm under MQL condition with cutting speed of 150 m/min, feed of 0.15 mm/rev, nose radius of 0.4 mm and depth of cut of 0.5 mm. The better surface finish is attributed due to MQL condition, low feed and high cutting speed.

VI. EFFECT OF TITANIUM (grade 5) ALLOY

A. EFFECT AND ANALYSIS OF PARAMETERS FOR MATERIAL REMOVAL RATE

a) Effect of Pulse-on-Time on Material removal rate

Normally, Material removal rate increases with increase in the pulse on time. The expressions show that discharge energy is increases with increases in the pulse on time.

$$E = P \times T$$

$$P = V \times I$$

$$E = V \times I \times T \quad \text{………………………..} (2)$$

Where,

E - Energy
P - Power
V-Voltage
I – Current
T – Time

In this experiment pulse on time is kept low. So, there is no drastic change in the material removal rate with respect to the pulse on time.

b) Effect of Pulse-off-Time on Material removal rate

Increase in Pulse off time reduces the material removal rate. If time between two pulses is increase discharge of energy due to spark is reduced. So, Material removal rate is reduced when pulse off time is increased.

c) Effect of Peak Current on Material removal rate

The expressions clearly shows that discharge energy increases with increases in the peak current which leads to uniform cooling and heating. Peak current is the most affecting parameter in calculating material removal rate. If Peak current increases material removal rate also increase.

B. EFFECT AND ANALYSIS OF PARAMETERS FOR SURFACE ROUGHNESS

a) Effect of Pulse-on-Time on Surface Roughness

Surface Roughness decreases with decrease in the pulse on time. The surface quality of WEDM is associate with the material removal per discharge, which is determined by the pulse energy per discharge. The value of surface roughness increases as the pulse width increases. The increased pulse width results into longer discharge time, which leads to higher discharge energy. The machined surface gets deteriorated owing to increased diameter and larger depth of craters.

b) Effect of Pulse-off-Time on Surface Roughness

Increase in Pulse off time reduces the Surface Roughness. If time between two Pulses is increase discharge of energy due to spark is reduced. So, Formation of craters on the surface of the work piece is reduced.

c) Effect of Peak Current on Surface Roughness

If Peak current increases it increases in the discharge energy. As a result, Surface Roughness valve is increased with increase in the peak current. The surface quality of WEDM is associate with the material removal per discharge, which is determined by the pulse energy per discharge. The value of surface roughness increases as the pulse width increases. The increased pulse width results into longer discharge time, which leads to higher discharge energy. The machined surface gets deteriorated owing to increased diameter and larger depth of craters.

C. SURFACE MICROGRAPHS

a) Material Removal Rate

SEM examination reveals some micro-cavities in the untreated brass wire. The brass wire develops residual stresses during its manufacture and crystal molecules develops non-uniform pattern. As the temperature decreases in chamber, the atomic bond becomes weak and the crystal structure of brass reverts to its original state. Any residual stress gets eliminated. Therefore, more uniform and compact pattern is maintained. The wire electrode strength might have been enhanced owing to the fine grains and less micro-cavities. This adversely affects the material capacity of heat transmission and electrical conductivity.

However, the quantity of the micro cavities in brass wire electrode after deep and shallow cryogenic cooling is clearly less than that before cryogenic cooling. The heat transmission and electrical conductivity is increased and soundness of wire electrode is obviously increased. A good conductivity wire allow for applying high energy to the process. Therefore, higher current will be delivered to wire by voltage generator of the WEDM. Owing to increase infrequency of discharge, the faster sparking in discharge channel takes place.

It may be assumed that “chain of discharges” takes place within single discharge and several discharging pulses takes place within single pulse. Owing to the bridging effect, the insulating strength of the dielectric decreases. Early explosion of the plasma channel takes place owing to short circuiting. The series of discharge starts along the wire electrode surface area. The increase in frequency of discharges causes faster erosion from the work piece surface.

D. SURFACE ROUGHNESS

The machining with more conductive cryogenic treated wire electrodes makes the discharge passage enlarged and widened. The generated debris from the spark gap is easily evacuated. The discharge is uniformly distributed in the discharge channel in the gap, which results into reduction in the relative difference in electric field between micro-peaks. The smaller and shallow craters are produced due to discharge of micro-current at each potential discharge point. The surface quality of WEDM is associate with the material removal per discharge, which is determined by the pulse energy per discharge. The value of surface roughness increases as the pulse width increases. The increased pulse width results into longer discharge time, which leads to higher discharge energy. The machined surface gets deteriorated owing to increased diameter and larger depth of craters. Increase in wire tension causes slight increase in surface roughness but further increase causes improvement in surface roughness due to decrease in cut width.

VII. RESULTS AND DISCUSSIONS

A. EXPERIMENTAL RESULTS

The Experiment was conducted by selecting four parameters namely, Pulse on time, Pulse off time, Peak current and Wire tension and setting the parameters in three different conditions on L9 orthogonal array. The calculated values from the experiments are tabulated in the Table 7.1 shown below.

Table 7.1 Experimental Results of WEDM

Ex. No	Ton (µs)	T off (µs)	IP (A)	SV (V)	SP mm/min
1	116	60	230	20	2
2	122	58	230	20	3.58
3	126	54	230	20	4.56

B. BRINELL HARDNESS TEST

In this test consists a hardened steel ball into a test specimen. In thisusually steel ball of diameter (D) under a load (P) is forced in to the test piece and the mean diameter d of the indentation left in the surfaces after removal of load is measured. According to ASTM specification a 10mm diameter ball is used for the purpose. Lower loads are used for measuring hardness of soft materials and vice versa. In the brinell hardness test is obtained by dividing the test load P by curved surface area of indentation.

Brinell hardness number = $2P / \pi D (D-D\sqrt{D^2 - d^2})$

Where,

P = load applied in kgf.
D = diameter of the indenter in mm.
D = diameter of the indentation in mm.

Table 7.2 Observation of Brinell hardness test

S. No	Feed rate (titanium alloy) (mm/min)	Diameter of Indenter (mm)	Load (kgf)	Diameter of impression (mm)	Brinell Hardness number (BHN)
1	2	5	750	2.08	220.02
2	3.58	5	750	2.15	223.56
3	4.56	5	750	2.20	218.65

C. SURFACE ROUGHNESS TEST

Table 7.3Observation of Surface roughness

S.NO	FEED RATE (mm/min)	Ra			Rz		
		L1	L2	L3	L1	L2	L3
1	2	1.84	1.84	1.84	9.63	9.63	9.63
2	3.58	1.89	1.89	1.89	9.69	9.69	9.69
3	4.56	1.92	1.92	1.92	9.75	9.75	9.75

D. SEM ANALYSIS RESULT

SEM images of machined sample surface at 100X and 10X magnification of WEDM test specimen are shown in figures (fig. 7.1 to 7.3). Several surface defects are considered by this result. Here a SEM image shows the irregular morphology for WEDM test specimen (titanium grade-5). The examination of the deformed microstructure reveals very fine sizes of grains in the (Ti).

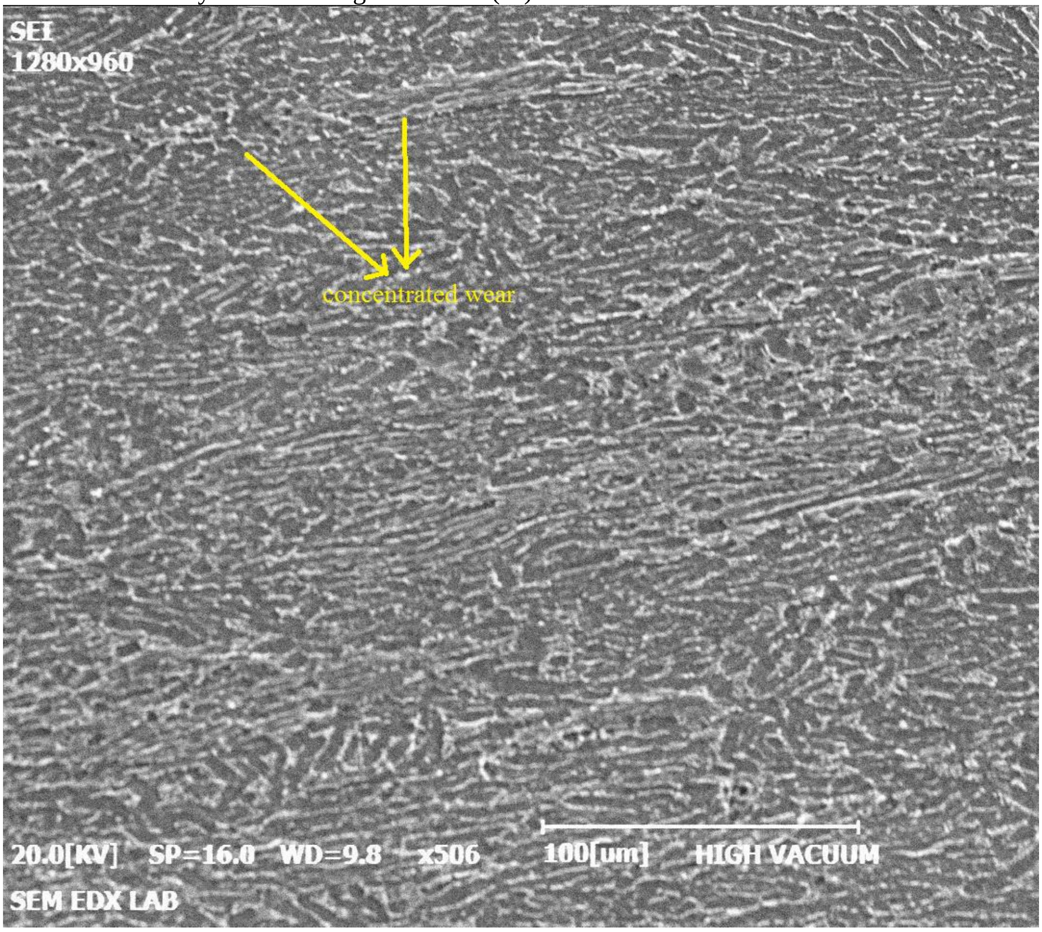


Fig. 7.1 (a)

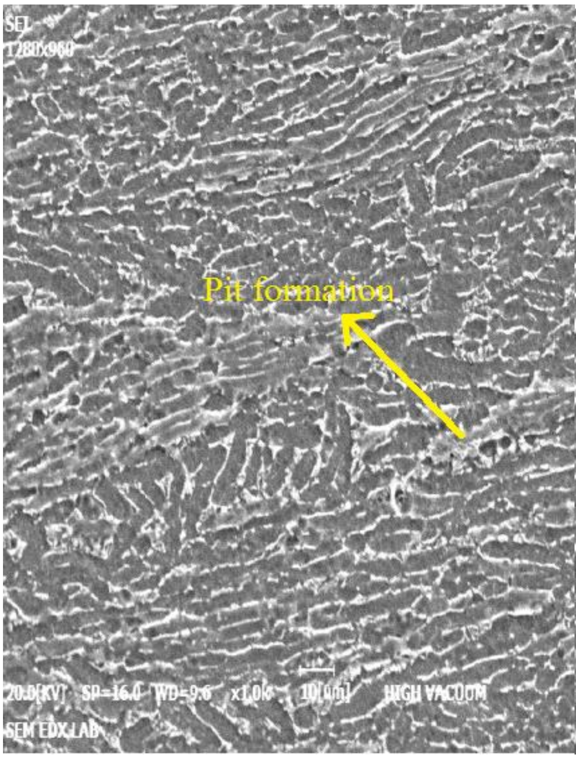


Fig. 7.1 (b)

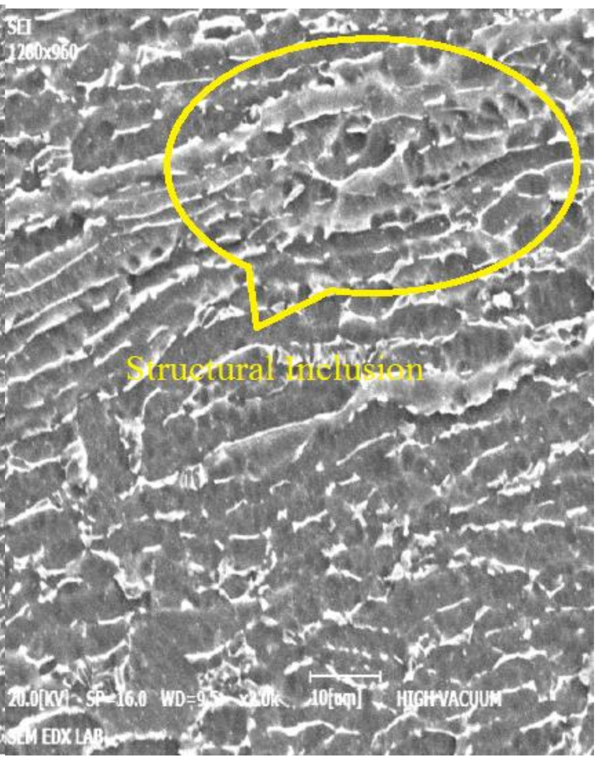


Fig. 7.1 (c)

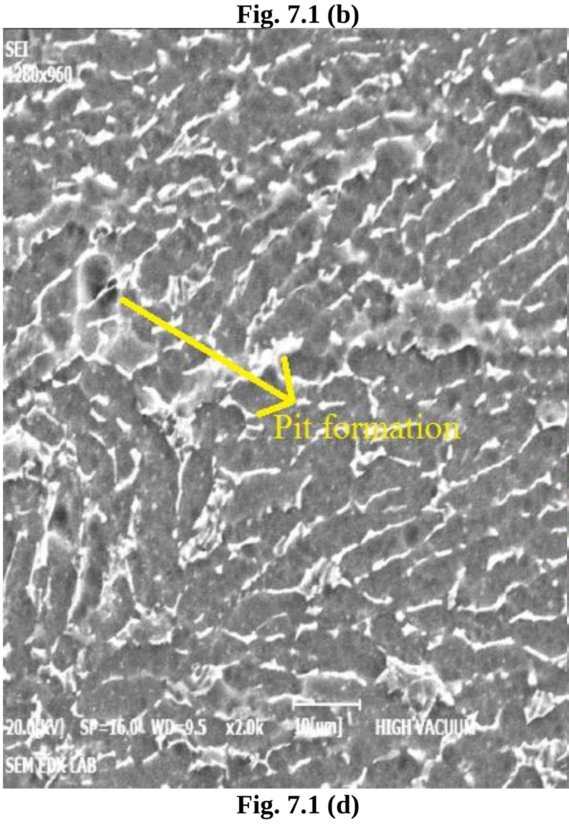


Fig. 7.1 (d)

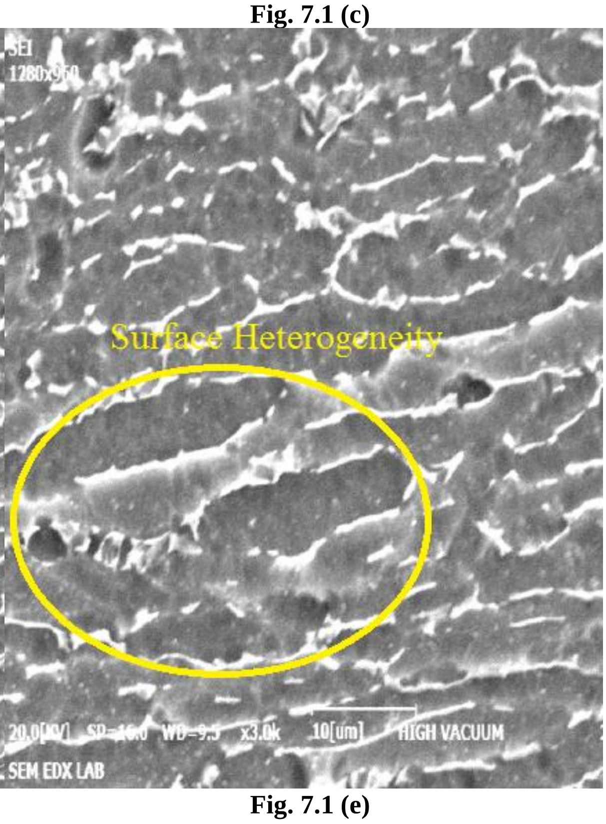


Fig. 7.1 (e)

On fig. 7.1 SEM micrograph shows the different defects on microstructural surfacefeed rate 2. (a) it specifies the creation of concentrated wears. (b) Formation of pits in magnified view. (c) Positioning of structural inclusions. (d) Formation of pits. (e) Formation of different surface heterogeneities.

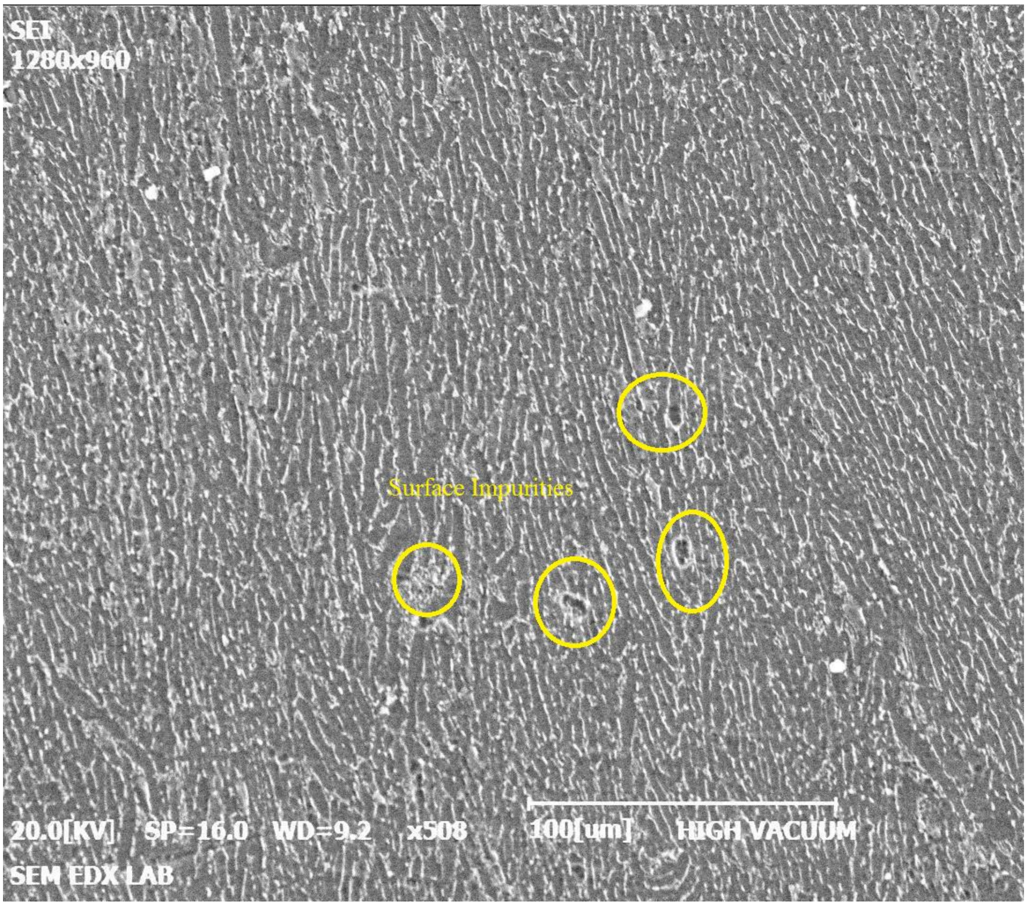


Fig. 7.2 (a)

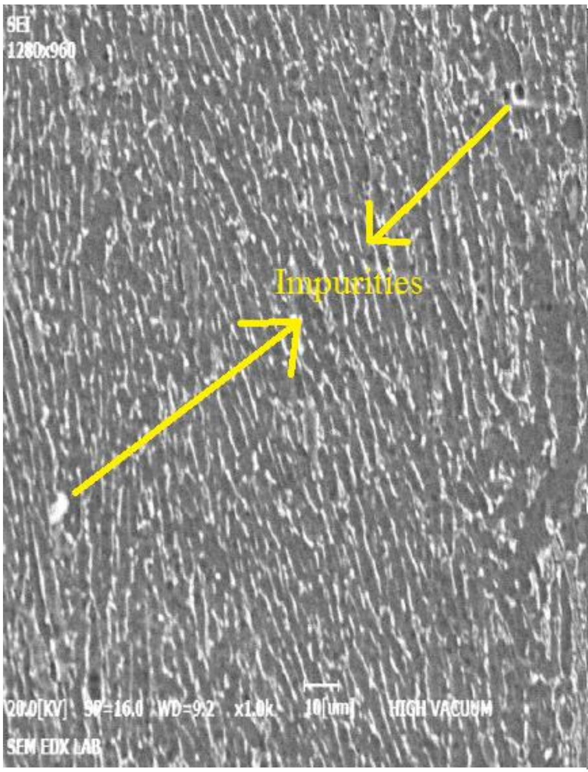


Fig. 7.2 (b)

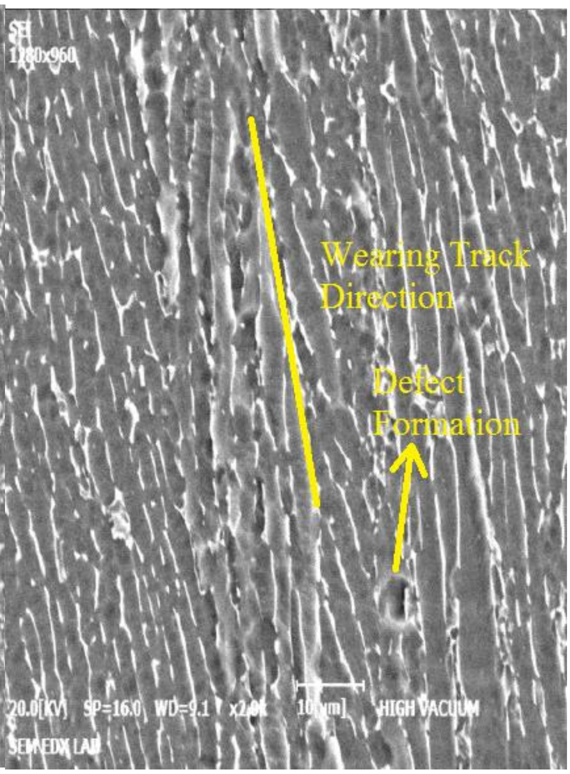


Fig. 7.2 (c)

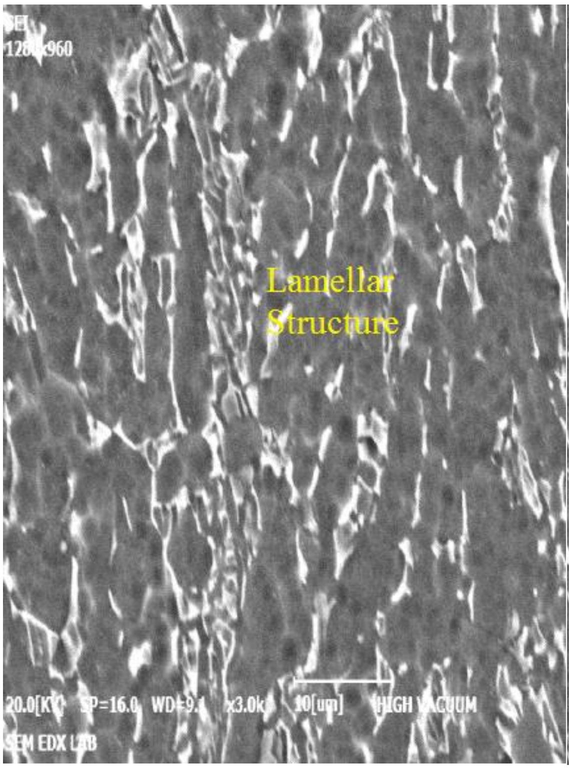


Fig. 7.2 (d)

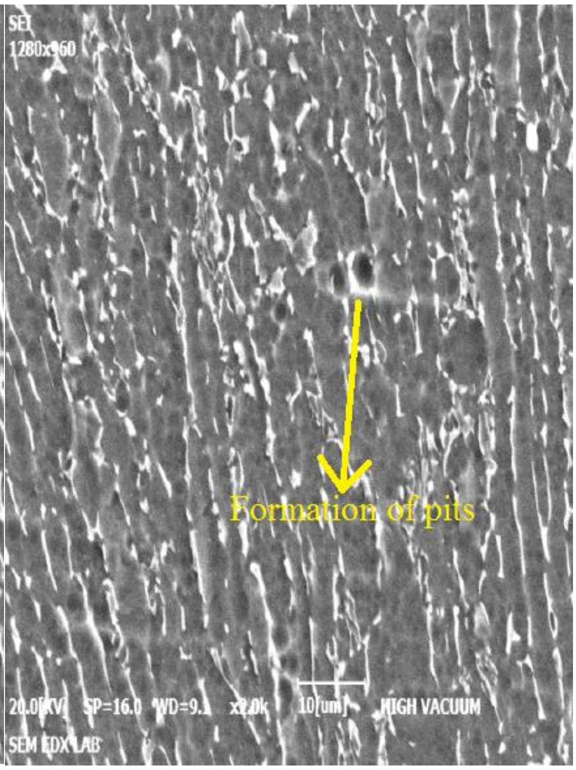


Fig. 7.2 (e)

On fig. 7.2 SEM micrograph shows the different defects on microstructural surface at feed rate 3.5. (a) Surfaceimpurities. (b) Magnified view of surface impurities. (c) Defect formation and wear tracking direction. (d) Lamellar structure. (e) Formation of pits.

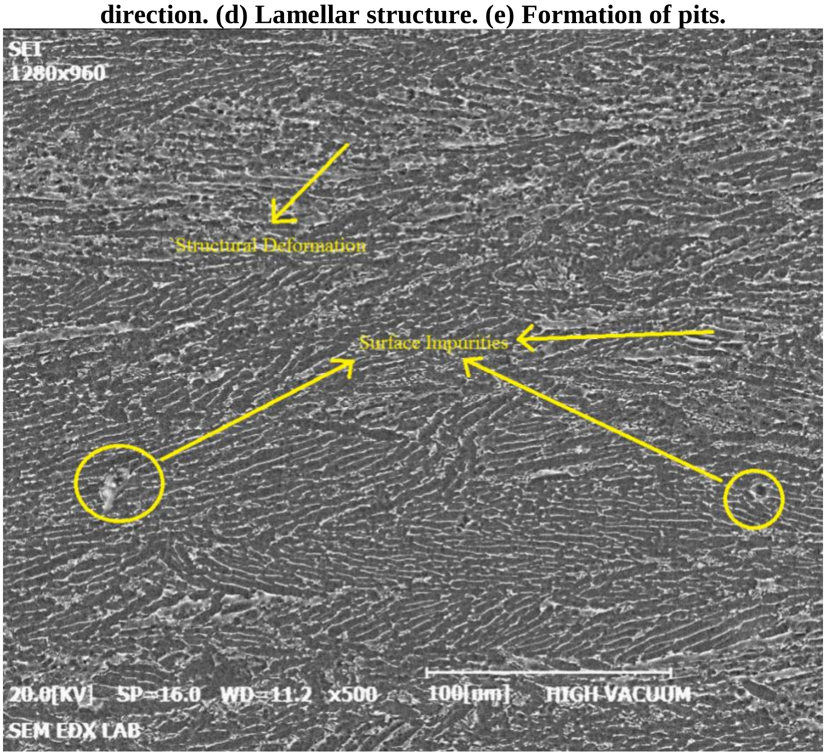


Fig. 7.3 (a)

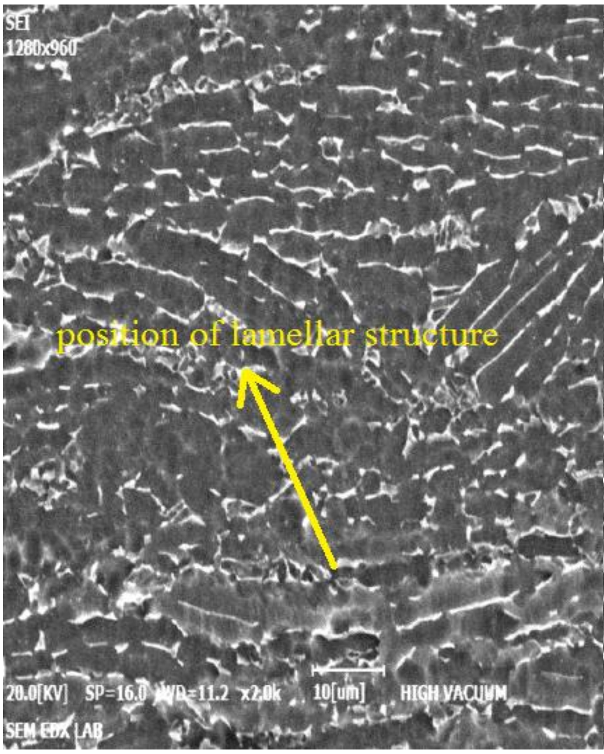


Fig. 7.3 (b)

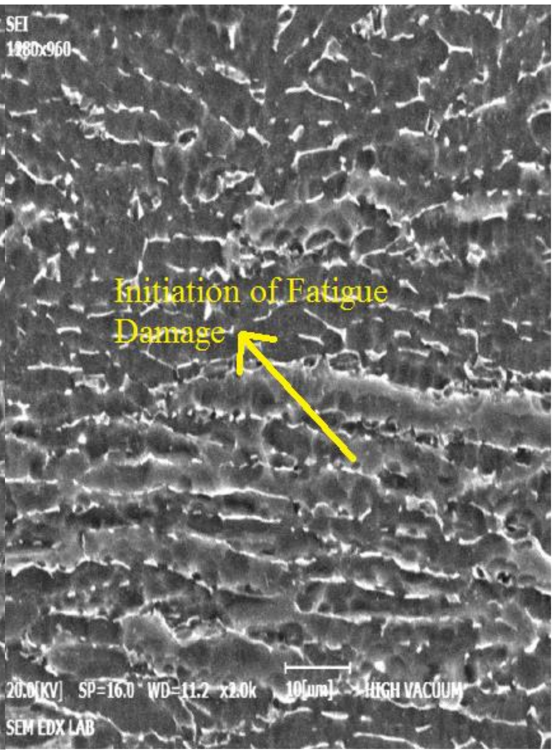


Fig. 7.3 (c)

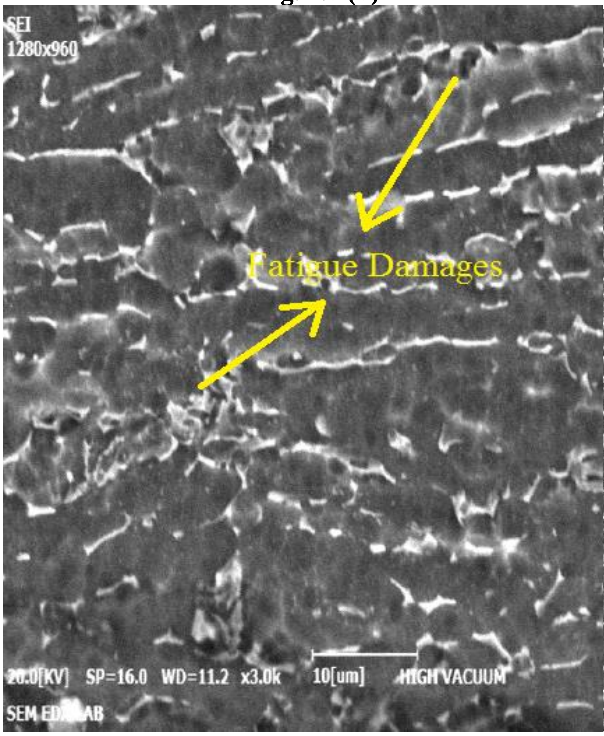


Fig. 7.3 (d)

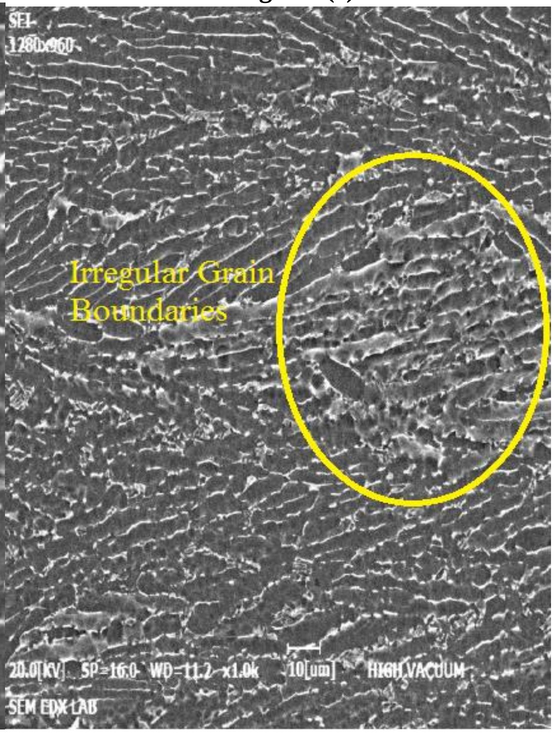


Fig. 7.3 (e)

On fig. 7.2 SEM micrograph shows the different defects on microstructural surface at feed rate 4.5. (a)Structural deformation and surface impurities. (b) Position of affected lamellar structure. (c) Initiation of fatigue damage. (d) Structurally damaged spots (fatigue). (e) Location of irregular grain boundaries.

Based on the SEM results different feed rates are taken for the microstructural analysis. by that result at feed rate 2 (fig.7.1 (a)), they exhibit some microstructural impurities such as pits, wear at magnified view of 100µm and further that is taken for four individual magnified areas (fig. 7.1 (b), (c), (d), (e)) at the scale of 10µm. each of that results are describes defects and its defect origins. It founds some microstructural inclusions, wear and formation of pits on the testing surfaces.Similarly, the result of feed rates 3.5 & 4.5 are generated by scanning electron microscopic analysis. At feed rate 3.5, the result (fig. 7.2 (a)) shows micro level physical impurities at scale of 100 µm. Result of SEM images (fig. 7.2 (b), (c), (d), (e)) describes common defects like pits, initiation of fatigue damages on the micro structure and direction of wear track and high surface roughness. At feed rate 4.5, the results (fig. 7.3 (a)) shows that high level defects of tested surface at 100 µm. Result of SEM images at the magnification scale of 10µm (fig. 7.2 (b), (c), (d), (e)) describes the structural deformation, position of lamellar surface, introduction of fatigue damages and irregular grain boundaries of micro surface. From these above results feed rate 4.5 having higher structural damages when compared to other feed rates of WEDM machine for titanium grade 5 alloy.

VIII. CONCLUSION

The Experiments were conducted by selecting four parameters namely pulse on time, pulse off time, peak current and wire tension at three different settings. Hence, the observations were made from the results are as follows

1. Peak current is the most influencing parameter for material removal rate which shows that increase in peak current will increase the material removal rate and surface roughness.
2. Pulse on time is the most influencing parameter for surface roughness which shows that decrease in pulse on time will increase the surface finish and reduce the material removal rate.
3. Wire Tension has effect on both Material removal rate and Surface roughness. Optimum wire tension results in high MRR and low surfaceroughness.
4. Factors machine feed rate have been found to play an important role in this experimental work. The outcome of this study will help in improving the quality of Titanium Ti-6Al-4V products as well as minimizing the machining cost to realize the economic potential to the fullest.
5. The signals that derive from electron sample interaction reveal information about the sample including external morphology (texture), chemical composition, and crystalline structure and orientation of materials making up the sample.
6. The SEM is also capable of performing analyses of selected point locations on the sample this approach is especially useful in qualitatively or semi quantitatively determining chemical compositions crystalline structure, and crystal orientations.
7. The main goal is the maximum MRR with minimum surface roughness in setting the machining parameters.
8. While, machining the titanium grade 5 alloy the respective feed rates have been changed. So, that the surface roughness is changed to maximum when attaining “4.56 feed rate”.

REFERENCES

[1] Y.S. Liao, J.T. Huang, Y.H. Chen (2004) “*A study to achieve a fine surface finish in Wire EDM*”, Journal of Materials Processing Technology, Vol.149, pp. 165–171

[2] ShajanKuriakose, M.S. Shunmugam (2004) “*Characteristics of wire electro discharge machined Ti6Al4V surface*” Materials Letters, Vol.58, pp. 2231-2237.

[3] Vamsi Krishna Pasam, SurendraBabuBattula, MadarValli P, Swapna(2004) “*Optimizing surface finish in WIER -EDM using the Taguchi parameter design method”* GITAM University.

[4] K.H. Ho, S.T. Newman, S. Rahimifard, R.D. Allen (2004) “*State of the art in wire electrical discharge machining (WEDM) ”*, International Journal of Machine Tools & Manufacture, Vol.44, pp. 1247–1259.

[5] Scott F. Millera, Chen-C. Kaoa, Albert J. Shiha, Jun Qub (2005) “*Investigation of wire electrical discharge machining of thin cross sections and compliant mechanisms*” , International Journal of Machine Tools & Manufacture, Vol.45, pp. 1717–1725.

[6] S. Sarkar, S. Mitra, B. Bhattacharyya (2005) “*Parametric analysis and optimization of wire electrical discharge machining of titanium aluminidealloy*”, Journal of Materials Processing Technology, Vol.159, pp.286–294.

[7] Neeraj Sharma, Rajesh khanna(2010) “*Optimization of process parameters of cryogenic treated D-3 in WEDM by Taguchi Approach*”, International Journal of Engineering Research and Applications (IJERA)Vol. 1, pp.546-553.

[8] Okada, Y. Uno, M. Nakazawa, T. Yamauchi (2010) “*Evaluations of spark distribution and wire vibration in wire EDM by high-speed observation*”, Department of Manufacturing Technology, CIRP Annals - Manufacturing Technology, Vol.59, pp. 231–234

[9] AnizaAliasa, BulanAbdullaha, NorlianaMohdAbbasa (2012) *“Influence of machine feed rate in WEDM of titanium TI-6AL-4V with constant current (6A) using brass wire*”,International Symposium on Robotics and Intelligent Sensors, Procedia Engineering, Vol.41 pp. 1806 – 1811.

[10] PragyaShandilya, P.K.Jain, N.K. Jain (2012) “*Parametric optimization during wire electrical discharge machining using response surface methodology*”, Procedia Engineering Vol.38, pp.2371 – 2377.

[11] Kali Dass, S. R. Chauhan (2011) “*Machinability Study of Titanium (Grade-5) Alloy Using Design of Experiment Technique”*, Research gate, Page no: 609-621.

[12] G. Dongre, J. Shaikh (2017) “*Analysis for Machining of Ti6Al4V Alloy Using Coated and Non-Coated carbide tools, Advances in Intelligent Systems Research*, Page no: 134-141.

[13] BogdanSłodki, WojciechZebala (2019) “*Turning Titanium Alloy, Grade 5 ELI, With the Implementation of High Pressure Coolant”*, Production Engineering Institute of the Mechanical Faculty, Cracow University of Technology, Page no: 2-14.

[14] Mohammed Nouari and Hamid Makich (2014) “*On the Physics of Machining Titanium Alloys: Interactions between Cutting Parameters, Microstructure and Tool Wear*”, University of Lorraine, Page no: 338-358.

[15] PatilAmit S et al., (2015) “*Machining Challenges in Ti-6Al-4V.-A Review*”, International Journal of Innovations in Engineering and Technology, Page no: 6-23.

PHOTOGRAPHY