# Investigation of Endurance Limits and Analysis of Electric Discharge Machined Surface of Aluminum Alloy 2024 T6

S. Mehmood[1], R. A. Pasha[2], M. Shah[3], A. Sultan[4]

[1,2,3] *Mechanical Engineering Department, University of Engineering and Technology, Taxila*
[4] *Mechatronics Engineering Department, University of Engineering and Technology, Taxila, Sub-Campus Chakwal*
shahid.mehmood@uettaxila.edu.pk

***Abstract*-**Electric discharge machining (EDM) removes the workpiece material by the electro-thermal energy followed by flushing of the molten pool. A portion of this molten material is not removed but resolidifies on the surface of base material and alters the mechanical properties of the material. In this study the endurance limits are investigated for the electric dischrage machined (EDMed) aerospace grade Aluminum alloy 2024T6 for the discharge currents of 3 and 12 amperes. The fatigue tests were performed on 4-point rotating bending machine at the frequency of 50Hz and ambient temperature. These tests were carried out according to the modified stair case method. It is found that the obtained endurance limit for the EDMed specimens at 3 ampere discharge current level is 21% greater than that of 12 ampere. Some surface and subsurface defects are highlighted that can cause high stress concentration.

***Keywords*-**Electric Discharge Machining, Endurance Limit, Scanning Electron Microscopy

## I. INTRODUCTION

The electric discharge machining is a non-traditional machining process that generates high localized thermal energy by discrete electric sparks between workpiece and tool immersed in the dielectric liquid. EDM produces tool face negative geometry on the surface of the workpiece and is mostly used for machining of hard to cut materials in the industry [i]. The generation of the intricate shapes is the advantage of the EDM due to its noncontact machining. The tool side loads and vibrations are not produced in EDM as compared to the conventional machining processes like milling and turning. EDM has got acceptance in the manufacturing industry dealing with soft metals like aluminum alloy in the aerospace and automobile sector due to its high precision and accuracy [ii].

The molten material is rapidly cooled by the dielectric liquid after each discharge, where a portion of molten material is not removed and sticks on the surface of the base metal [iii]. The resolidified surface on the substrate after EDM has different characteristics than the parent material [iv]. This surface is generally recognized as white layer in the literature [v-viii]. Many sub layers of different microstructure and phases are formed in the white layer [v]. Pulse ON-time and discharge current are the important parameters that influence the formation of the white later on the surface of the material [vi]. whereas, it was determined by [ix] that white layer thickness of Al 6061-T6 increases with the current initially but after some certain value, white layer thickness starts to decrease because of intense crack formation that are easily flushed away by kerosene as dielectric liquid. It was reported by [x] that EDM effect is observed only in upper three layers in tool steel, i.e. white layer, heat affected layer and transition layer. Micro-structure of bulk material remained totally unaffected.

Thickness of the white layer and cracks density in it are inversely proportional to the thermal conductivity of the material and directly related to the thickness of workpiece [xi]. The material having high thermal conductivity permits the produced thermal energy to dissipate into surrounding bulk material, due to which the temperature falls in the localized area. The white layer in Ni, Ti and Fe based alloys is brittle and hard [xii]. White layer has micro cracks that often terminate at the junction of the white layer and the base material. These cracks can be avoided by increasing pulse current value and reducing pulse on time value [xii]. The thickness of white layer also depends on the type of dielectric fluid, electrode size and machining parameters [xiii]. It was studied by [xiv] that a thermally affected layer below the white layer that has tempered microstructure and is enriched by the carbon contents that may be absorbed from dielectric liquid or tool electrode. Lower layer has slightly lower hardness than the hardness of WL.

The endurance limit is the fatigue strength of the material at which it can bear infinite number of cycles. Many studies are available for the determination of endurance limit of the hard material but limited work had been performed for soft metal alloys. In the current study, the endurance limit of the Al 2024 T6 alloy has been investigated for the current levels of 3 and 12 ampere. Alongside, the surface conditions are also incorporated with the endurance limit.

## II. MATERIAL AND EXPERIMENTATION

The materials used in this study is Aluminum 2024 T6 in the form of rods. Initially the specimens are prepared by turning operation on the lathe machine. Then the specimens are further machined by the electric discharge machine at the selected conditions. Dog-bone shape specimen of gauge length 96 with 12mm diameter are prepared on numerical control lathe machine with a centered peripheral notch of 10mm diameter and 0.8mm depth Fig. 1. A Carbide tip Cutting tool has been used for lathe machining. Initially rough and then finish cut is performed with the machining parameters as described in Table I.

TABLE I
NC-LATHE MACHINING PARAMETERS

| Type of cut | RPM | Feed *mm/s* | Depth of Cut *mm* | Tool nose radius *mm* |
|---|---|---|---|---|
| **rough** | 1000 | 0.12 | 1 | 0.5 |
| **finish** | 1200 | 0.08 | 0.2 | 0.2 |

Fig. 1. Picture of the specimen prepared by turning operation.

The surface is generated in the notch of the specimen by the Die-sink Electric discharge machine (NEUAR) and the depth of the notch is increased to 1 mm as described in Fig. 2. The machining is performed at 3 ampere and 12 ampere by keeping all other parameters same. In current study, only two levels of discharge current are investigated which are usually used for finish machining. The industrial grade pure copper is used for the tool electrode. The kerosene oil is used as dielectric liquid. The dielectric pump of EDM can generate a pressure of impingement equal to 0.9 kg/cm$^2$ on the surface of the workpiece. But in present work this option is not adopted. Instead, the flushing is occurs by the rotation of the workpiece.

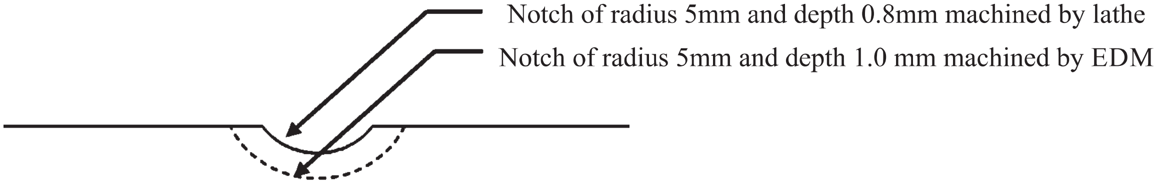


Fig. 2. Machining of Notch

The typical surface of the EDMed specimen is shown at three different magnifications (1x,3x and 10x) as shown in Figure 3. The surface is composed to hemispherical cavities that are termed as crater in the literature. The size of the crater is directly proportional to the discharge energy which reveals the dependence of the surface roughness on it.

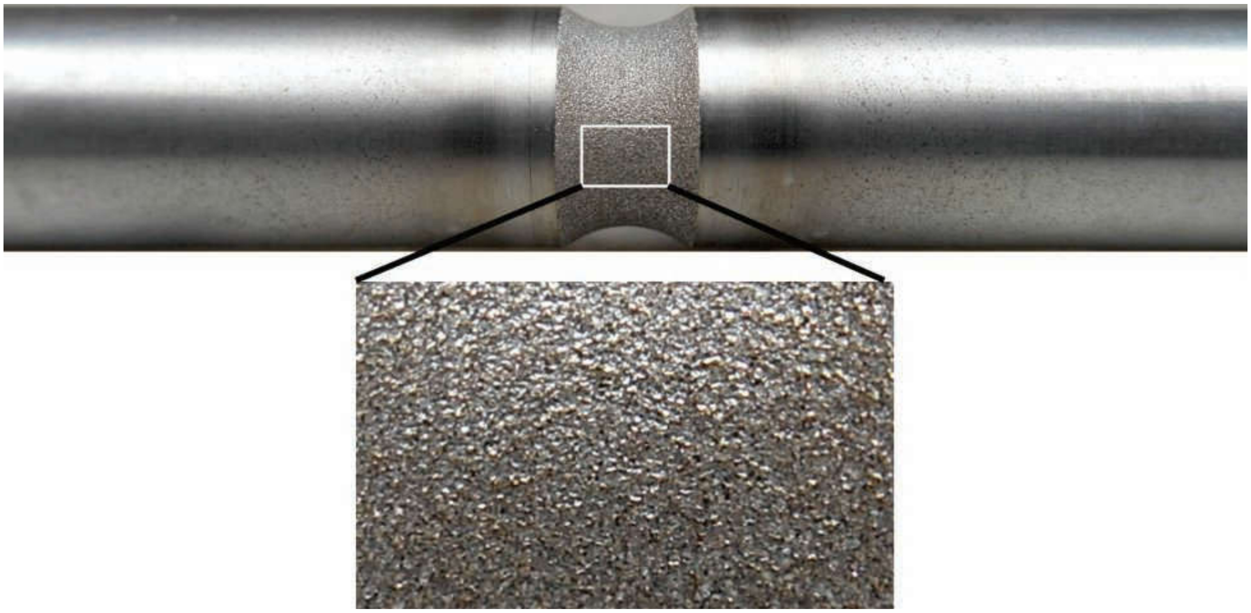


Fig. 3. Typical surface appearance of the EDMed surface of the specimen.

The procedure for preparation of specimens for microscopic examination is shown in Figure 4. After EDM machining specimen are cut at the middle of the notch so that each part contains half notch. Again 12mm length is cut from the side of half notch. EDM surface have free carbon particles and oil contents that need cleaning by placing samples in acetone liquid in ultrasonic chamber for five to ten minutes. Then each piece is placed in the center of small portion of pipe. Araldite® LY 5052/Aradur® 5052 is used with the ratio of 70:30 is poured into the gap between specimen and pipe. This solution is allowed to dry completely in sunshine or open air. After epoxy gets hardened, grinding is performed by emery paper with grit sizes # 350, 600, 1000, 1200, and 2000. Then further mirror like polishing is achieved by using abrasive paste of 1 micron on buffing paper. To avoid reflection of light during microscopy these polished specimens are etched by HF solution for 40 seconds. Immediately after etching, specimens are rinsed with running water and dried in open air.

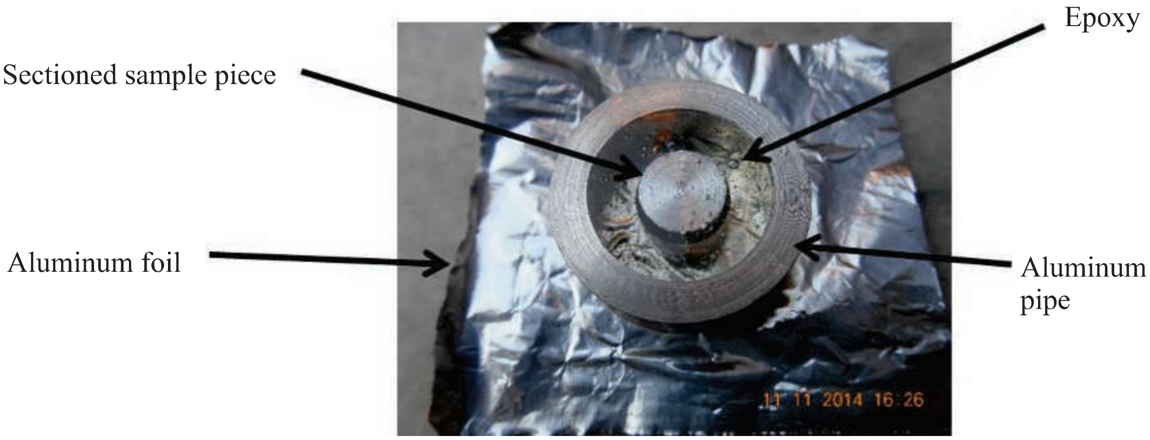


Fig. 4. sample preparation for optical microscopy and micro-hardness test

## III. DETERMINATION OF ENDURANCE LIMITS

The Modified Staircase Method was used since it needs only six experiments and is recommended by Japan Society of Mechanical Engineers (JSME) standard for its results being very close to that of conventional Staircase method [xv]. Fatigue tests were performed for the run-out of 1E7. Load step of 10 N was applied for 3 A and 5 N for 12 A. The mean endurance limit 'μy' was obtained by

$$\mu_y = \frac{\sum_{i=2}^{n+1} S_i}{n} \qquad (3)$$

Where,

S = Magnitude of alternating stress (MPa)

I = Experiment no.

n = total no. of experiment

## IV. RESULTS AND DISCUSSIONS

### A. *Endurance Limits*

The results obtained by the fatigue tests according to modified-stair-case method are presented in the form of experiment suspended and specimen broken for 3 ampere and 12 ampere as shown in Table 2 and Table 3 respectively. Endurance limits for 3 ampere and 12 ampere has been found equal to 89.1 MPa and 73.6 MPa respectively. If machining is performed at 3 ampere then the endurance limit is improved by 21% as compared to 12 ampere.

TABLE II

STAIR-CASE TEST DATA FOR 3 AMPERE

| Load (N) | S#1 | S#2 | S#3 | S#4 | S#5 | S#6 | S#7 |
|---|---|---|---|---|---|---|---|
| 160 | | | x | | | | |
| 150 | | o | | x | | x | |
| 140 | o | | | | o | | estimated |

o = Suspended, x = Broke

TABLE III

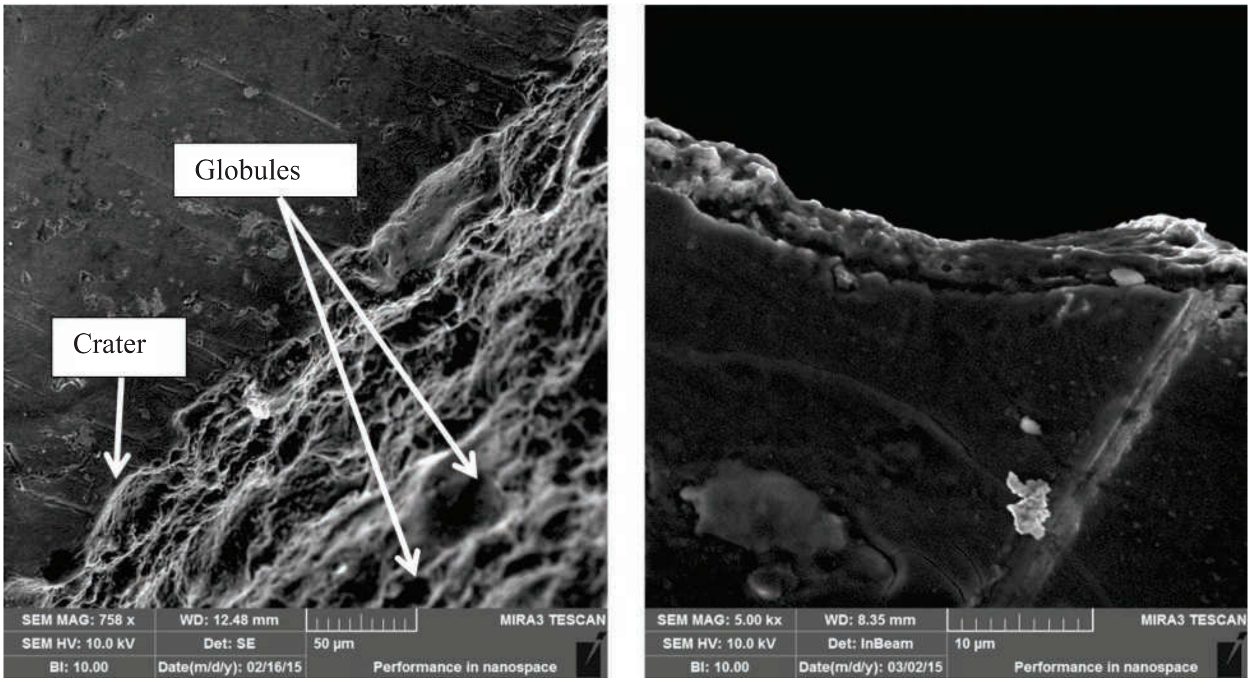
STAIR-CASE TEST DATA FOR 12 AMPERE

| Load (N) | S#1 | S#2 | S#3 | S#4 | S#5 | S#6 | S#7 |
|---|---|---|---|---|---|---|---|
| 130 | | | x | | | | |
| 125 | | o | | x | | | |
| 120 | o | | | | x | | Estimated |
| 115 | | | | | | o | |

o = Suspended, x = Broke

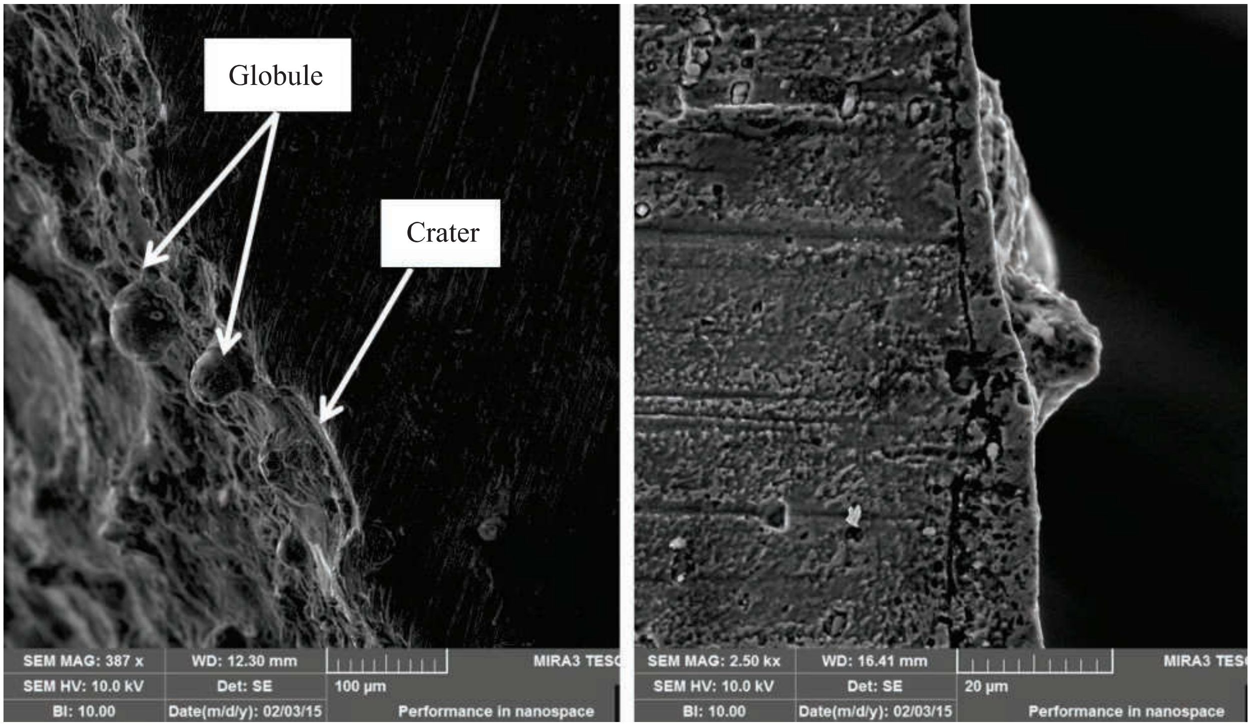
### B. *Microscopy*

The tangential observations of the white layer are investigated by the scanning electron microscope and metallurgical microscope. In Fig. 5, comparison between 3 and 12 amperes discharge current level is performed by the images of the scanning electron microscope. It is seen that the craters and globules are produced on the surface and the size of these features is small at 3 ampere as compared to 12 ampere. The white layer at 3 ampere discharge current level is relatively uniform as compared to the 12 ampere discharge current level, where the white layer thickness is increasing from top side of image to the lower side of the image.



(a) 3A

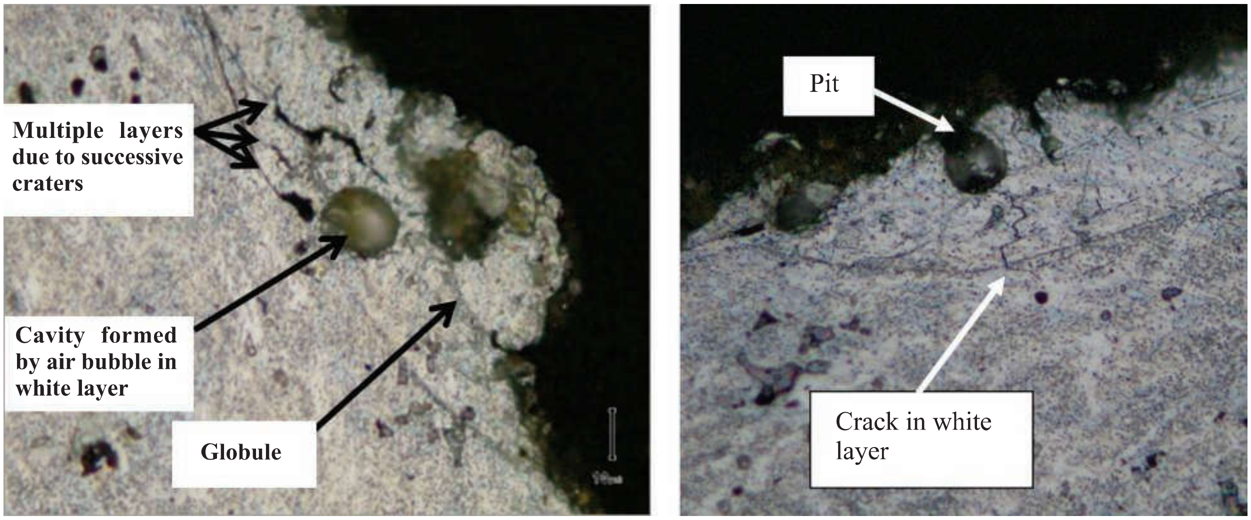
(b) 3A



(c) 12A (d) 12A

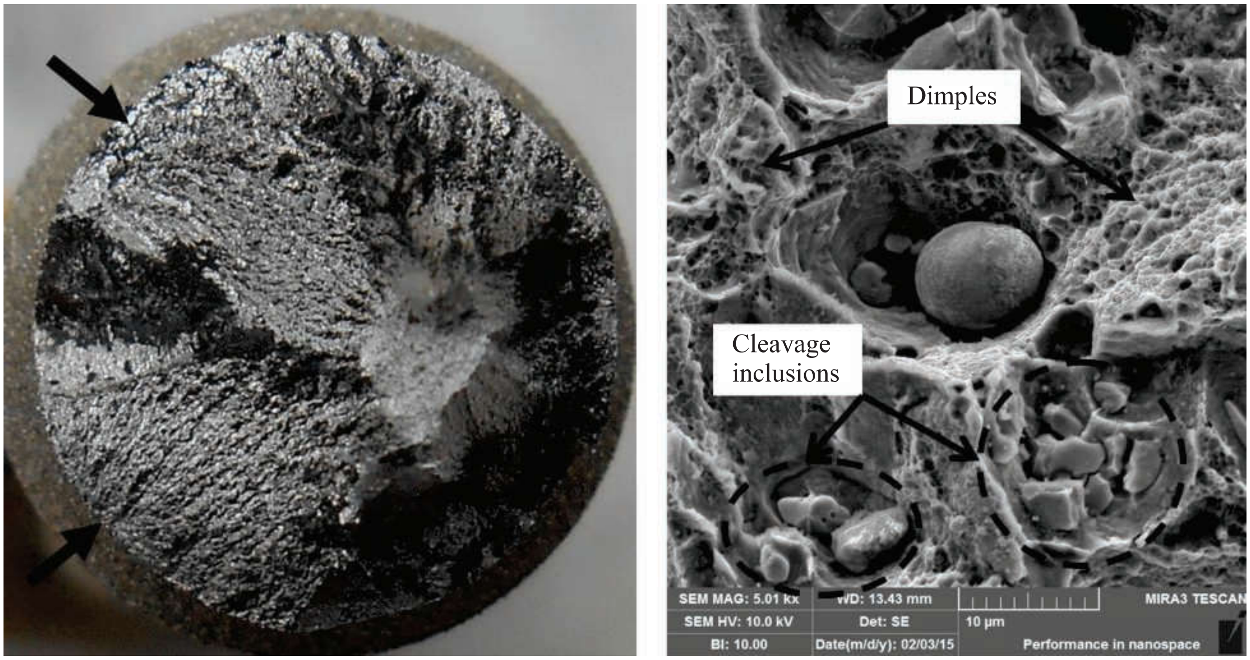
Fig. 5. SEM cross-sectional image of the white layer by at 3A and 12A

A white layer is shown in Fig. 6(a), three overlapping layers are seen due to formation of successive crater after each discharge. A spherical cavity is observed which is possibly due to entrapped gas bubbles during EDM. A globule of approximately 25 µm diameter is seen. In Fig. 6(b), a pit or pockmark is formed on the surface of white layer and below this pit a crack is formed due to stress concentration at this area. Near to this pit a very sharp discontinuity in the white layer is also observed that may become a stress raiser.



(a) (b)

Fig. 6. (a) Defects in white layer, (b) crack propagation from white layer to base material; (1000X)



(a) (b)

Fig. 7. Fractrographs (a) Multi-cite crack initiating from white layer (10x), (b) Nature of fracture (5000x)

In Fig. 7, Fractographic observations of the fractured surface at the lowest stress level are shown. Multiple crack initiation cites are observed from the EDMed surface and cracks are propagating radially inward as shown in Figure 7(a). Figure 7(b) conforms the nature of fracture in the crack propagation region. Round and rectangular cleavage facets of the intermetallic inclusions are observed at the bottom of cavities. These inclusions are comprised of secondary phase particles such as silicon, ferrous and magnesium, which show weak bonding with the matrix. Micro-voids appear from these inclusions and the size of micro-voids keeps on increasing by the repeated stresses and finally merge to form a crack that ultimately caused rupture of the material. Many dimples are seen on the surface which reveals inter-granular ductile fracture.

## V. CONCLUSIONS

In Electric Discharge Machining, amount of molten material is directly proportional to discharge current. Rapid cooling thereafter in hydrocarbon oil, changes the characteristics of machined surface. Effect on fatigue strength is investigated in this study for different surface conditions generated by two discharge current levels conventionally used in EDM. Knowledge of fatigue strength for different surface conditions generated by EDM will necessarily help design engineer when designing components exposed to repeated loading.

The conclusions of the investigation are

1. The electric discharge machining at 3A discharge current level resulted an improvement of 21% in the endurance limit as compared to that of 12 ampere discharge current.
2. The surface generated at 12 ampere discharge current produced craters and globules of larger size than that of 3 ampere discharge current
3. The resolidified surface layer contains overlapping sub-layers which have gaps at the junction of these layer. Also the entrapped air bubbles and surface pits are possible stress raisers that can cause early crack initiation.
4. Multi-site cracks are initiated from the electric discharge machined surface which radiate radially inward.

## RERFERENCES

[i] A. Torres, I. Puertas, and C. J. Luis, "Modelling of Surface Finish, Electrode Wear and Material Removal Rate in Electrical Discharge Machining of Hard-to-Machine Alloys," *Precision Engineering,* vol. 40, pp. 33-45, April, 2015.

[ii] E. B. a. L. I. Andrea Gatto, "Performance Optimization in Machining of Aluminium Alloys for Moulds Production: HSM and EDM," in *Aluminium Alloys, Theory And Applications*, T. Kvackaj and R. Bidulsky, Eds., ed: InTech, February, 2011, pp. 355-376.

[iii] S. Chakraborty, V. Dey, and S. K. Ghosh, "A Review on the Use of Dielectric Fluids and their Effects in Electrical Discharge Machining

Characteristics," *Precision Engineering,* vol. 40, pp. 1-6, April, 2015.

[iv] Y. Zhang, Y. Liu, R. Ji, and B. Cai, "Study of The Recast Layer of a Surface Machined by Sinking Electrical Discharge Machining Using Water-in-Oil Emulsion as Dielectric," *Applied Surface Science,* vol. 257, pp. 5989-5997, January, 2011.

[v] G. Cusanelli, A. Hessler-Wyser, F. Bobard, R. Demellayer, R. Perez, and R. Flükiger, "Microstructure at Submicron Scale of The White Layer Produced by EDM Technique," *Journal of Materials Processing Technology,* vol. 149, pp. 289-295, 2004.

[vi] M. Shabgard, M. Seyedzavvar, and S. N. B. Oliaei, "Influence of Input Parameters on the Characteristics of the EDM Process," *Strojniški vestnik – Journal of Mechanical Engineering,* vol. 57, pp. 689-696, June, 2011.

[vii] H. Ramasawmy, L. Blunt, and K. P. Rajurkar, "Investigation of the relationship between the white layer thickness and 3D surface texture parameters in the die sinking EDM process," *Precision Engineering,* vol. 29, pp. 479-490, 2005.

[viii] F. Ghanem, H. Sidhom, C. Braham, and M. Fitzpatrick, "Effect of near-surface residual stress and microstructure modification from machining on the fatigue endurance of a tool steel," *Journal of materials engineering and performance,* vol. 11, pp. 631-639, 2002.

[ix] S. Arooj, M. Shah, S. Sadiq, S. H. I. Jaffery, and S. Khushnood, "Effect of Current in the EDM Machining of Aluminum 6061 T6 and its Effect on the Surface Morphology," *Arabian Journal for Science and Engineering,* vol. 39, pp. 4187-4199, 2014.

[x] K. Tamil Mannan, A. Krishnaiah, and S. P. Arikatla, "Surface Characterization of Electric Discharge Machined Surface of High Speed Steel," *International Journal of Advanced Materials Manufacturing and Characterization,* vol. 3, pp. 161-167, 2013.

[xi] L. C. L. L.C. Lee, Y.S. Wong and H.H. Lu, "Towards a Better Understanding of the Surface Features of Electro-Discharge Machined Tool Steels," *Journal of Materials Processing Technology,* vol. 24, pp. 513-523, 1990.

[xii] T. Tai and S. Lu, "Improving the Fatigue Life of Electro-Discharge-Machined SDK11 Tool Steel via the Suppression of Surface Cracks," *International Journal of Fatigue,* vol. 31, pp. 433-438, 2009.

[xiii] A. K. Jha, K. Sreekumar, and P. P. Sinha, "Role of electro-discharge machining on the fatigue performance of 15–5PH stainless steel component," *Engineering Failure Analysis,* vol. 17, pp. 1195-1204, 2010.

[xiv] B. Ekmekci, O. Elkoca, and A. Erden, "A comparative study on the surface integrity of plastic mold steel due to electric discharge machining," *Metallurgical and Materials Transactions B,* vol. 36, pp. 117-124, 2005.

[xv] R. D. Pollak, "Analysis of methods for determining high cycle fatigue strength of a material with investigation of Ti-6Al-4V gigacycle fatigue behavior," DTIC Document2005.