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# Fatigue life and Fracture Morphology of Inconel 718 machined by spark EDM process

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**Abstract**

Fatigue life of electric discharge machined and end milled samples of Inconel 718 alloy at high cycle fatigue mode was investigated. The objective of this work is to determine the influence of recast layer formed during the electric discharge machining on the fatigue life of Inconel 718. Data were generated in the fully reversed fatigue mode at ambient temperature using samples fabricated by following ASTM E606 standard. The specimens were machined on a spark electric discharge die sink machine. The specimens were subjected to fatigue, and the resulting fatigue lives and fracture morphology were compared with that of the end milled specimen. The surfaces of the specimens were examined under optical and scanning electron microscopes, and the roughness of the surfaces was measured using a standard surface profilometer. From the results of the investigation, it was concluded that the fatigue life of the samples fabricated by Spark Electric Discharge Machining decreased slightly when compared with that of the end milled sample. The results are explained using the data recorded on recast layer thickness, fracture mechanism observed because of the EDM process, and optical and scanning microscopy.



*Keywords:* Inconel Alloys, Spark Electric Discharge machining, Fracture Morphology, Recast layer Thickness.

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## 1. Introduction

Developments of alloys and heat treatment techniques have led to the evolution of materials with increased inbuilt strength and strength to weight ratios. In turn, this has led to a decrease in the section thicknesses of many engineering components used in weight-sensitive applications and a corresponding increase in surface area to volume ratio. Exposure to severe service conditions indicates that there are possibilities of service failure due to creep, fatigue and stress corrosion cracking. Such failures invariably start at the surface of a component and depend very sensitively on the condition of the surface. In spite of the rapid advances being made in the development of new and improved production techniques, the metal machining process still features prominently in the manufacture of component with good surface features [1]. One of the non-contact metal removal processes is the spark electric discharge machining processes, which is used for machining components with intricate geometry and good surface quality. The type of surface generated in that process depends on several variables: the peak discharge current, material removal rate, and the method, etc [2, 3]. Electric discharge machining continues to grow as a major production tool in most tool-making companies, machining hard to machine super alloys with ease.

The use of electric discharge machining in the production of forming tools to produce plastic moulds, die castings, forgings and precision components for the aircraft and aerospace industry has been firmly established in recent years [4]. The fatigue behavior of high-strength materials and super alloys has been shown to vary with different metal removal methods [5]. Literature reveals that though a number of attempts have been made to study the fatigue characteristics of Inconel 718 using wire EDM [3-5], an approach towards studying low cycle fatigue characteristics of die sink SEDM induced recast layer hasn't been attempted yet. There are no data available at the test range considered to show what effect, if any, SEDM has on the fatigue life of Inconel 718 alloy at various peak discharge current. To address this issue the current research is focused on determining the effect of recast layer formed due to SEDM on the low cycle fatigue life of Inconel 718 alloy. In order to accomplish this objective, the experimental work is planned in two phases. During the first phase, the selected SEDM parameters were used to conduct the experimental trials to acquire the recast layer on the specimen. Based on the available literature, it was identified that Peak Discharge Current, Current Pulse Duration, Gap Voltage and Pulse off time are the parameters that influence the recast layer to a large extent. Therefore, these four parameters at three different levels were used for conducting the experimental trials. In the second phase, the fatigue life of the SEDM samples and end milled sample were compared to determine the influence of recast layer (of various thicknesses) on the fatigue life.

## 2. Experimental Methods

The initial as received Inconel 718 bars are solutionized at temperature close to 950 $^{o}$C and aged at 700 $^{o}$C with tensile property of 1050 MPa. Table 1 shows the typical chemical composition of the work material used in the research.

Table. 1 Inconel 718 composition

| Element | Ni | Fe | Mo | Ti | Cr | C | Nb | Al |
|---|---|---|---|---|---|---|---|---|
| Weight % | Bal. | 18.5 | 3 | 0.9 | 19 | 0.04 | 5.1 | 0.5 |

The methodology included design and fabrication of SEDM tools for machining dog bone shaped fatigue test specimen of Inconel 718 to study the fatigue characteristics of the metal. The tool is made up of copper which is highly conductive, strong in nature and commonly used for EDM process. The Dimension of the as received Inconel 718 material is 20 mm wide, 5 mm thickness and 1000 mm length. The samples are initially cut to 100 mm length each for further processing.

Taguchi's L9 orthogonal array was followed to design the experiments and the experimental observations are tabulated in Table 2. Fig 1 shows the SEDM setup used for fabricating the fatigue samples. Fig 2 shows the tool mount and the sample jig fixture setup. Fig 3 shows the machined Inconel 718 sample after the SEDM process. Fig 4 shows the Instron Universal Testing Machine (UTM) setup used to conduct the low cycle fatigue test of the samples processed by SEDM. The spark EDM process was started and continued until the formation of profile and the same process was repeated on the other side to fabricate the specimens. Fig 5 shows the specimen prepared for the fatigue testing. The machined samples were cut into pieces to observe under Scanning Electron Microscope

(SEM) to validate the microstructure of Inconel 718 and to study the recast layer thickness. The pieces were then cleansed ultrasonically in an acetone solution and were then dried up. The SEDM surfaces were examined in optical and scanning electron microscopes over a wide range of magnification. Rockwell hardness measurements were made on the SEDM surfaces produced from different experimental trails. Five measurements were made on each sample and the average of readings was taken for comparison. Surface roughness was measured using Mitutoyo 178-923E Sj210 Series Surface Roughness Tester. The machine used in conducting the low cycle fatigue test was Instron UTM. The machine is equipped with a load cell that is adjusted automatically by static force motor and hydraulic units. The cyclic load was adjusted automatically up to 80 kN. The test frequency of the machine was maintained constant at 10 Hz (600 cycles/minute). A stress ratio of R=0, a fully reversed condition was followed. The fully reversed load of 160 MPa and 460 MPa were used to evaluate the fatigue behaviour of the SEDM samples at load below and close to yield point. All tests were conducted at room temperature.

Fig. 1 Die sink EDM machine

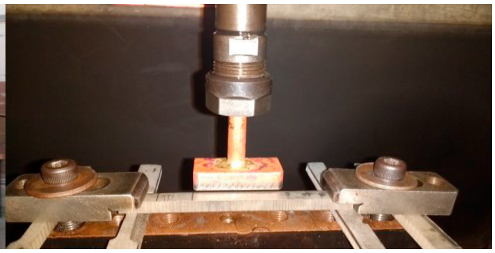


Fig. 2 Fatigue sample after EDM process

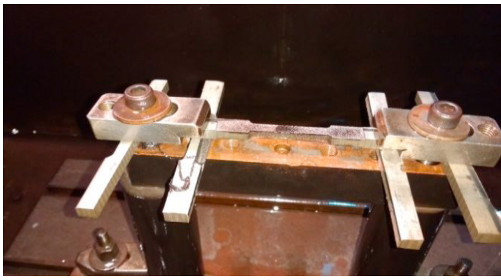


Fig. 3 Tool setup for the EDM process


Fig. 4 Fatigue Test

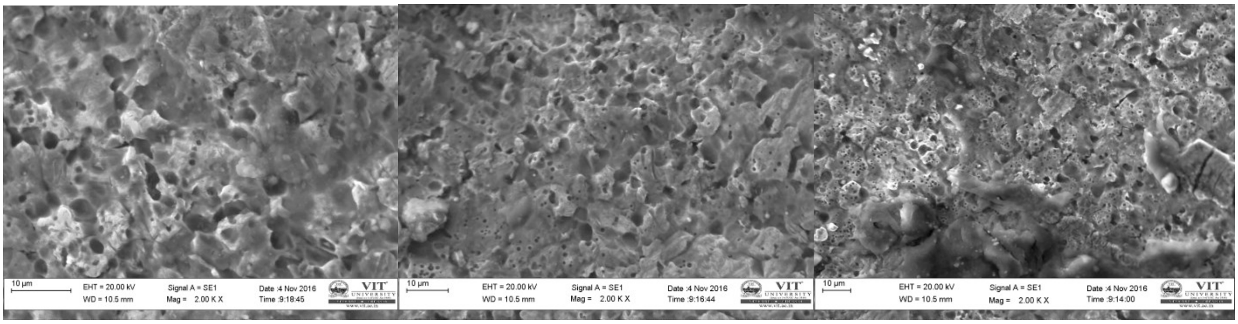
Table 2: Experimental observation

| Sample No: | Peak Discharge Current, $I_p$(A) | Current Pulse Duration, Ton (µs) | Gap Voltage, | Pulse-Off Time, off(µs) | Hardness, HRC | Tensile Strength, MN/m2 | Surface Roughness, (microns) | Recast layer thickness (microns) | Fatigue Life at 160 MPa | | Fatigue Life at 500 MPa | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $E_g$(V) | | | | | | Stress (KN) | Life Cycles | Stress (KN) | Life Cycles |
| 1 | 6 | 200 | 4 | 150 | 33 | 827 | 10.4 | 25.7 | 8 | 176897 | 23 | 50128 |
| 2 | 6 | 400 | 8 | 100 | 31.5 | 811 | 11.7 | 18.4 | 8 | 169153 | 23 | 48981 |
| 3 | 6 | 810 | 6 | 200 | 30.9 | 810 | 12.2 | 35.2 | 8 | 142577 | 23 | 45933 |
| 4 | 12 | 200 | 4 | 100 | 30 | 788 | 6.7 | 30.8 | 8 | 137068 | 23 | 52791 |
| 5 | 12 | 400 | 6 | 150 | 29.3 | 763 | 9.0 | 45.2 | 8 | 111631 | 23 | 47827 |
| 6 | 12 | 810 | 8 | 200 | 28 | 755 | 8.7 | 52.6 | 8 | 110235 | 23 | 50287 |
| 7 | 20 | 200 | 6 | 150 | 27.2 | 841 | 5.9 | 24.3 | 8 | 102040 | 23 | 64351 |
| 8 | 20 | 400 | 4 | 200 | 28.4 | 772 | 10.4 | 68.2 | 8 | 92040 | 23 | 49800 |
| 9 | 20 | 810 | 8 | 100 | 29 | 759 | 11.0 | 55.7 | 8 | 89247 | 23 | 45233 |
| End milled sample : HRC 35, Tensile Strength 967 MPa | | | | | | | | | | | | |


Fig. 5 ASTM E606 Fatigue Standard Samples.

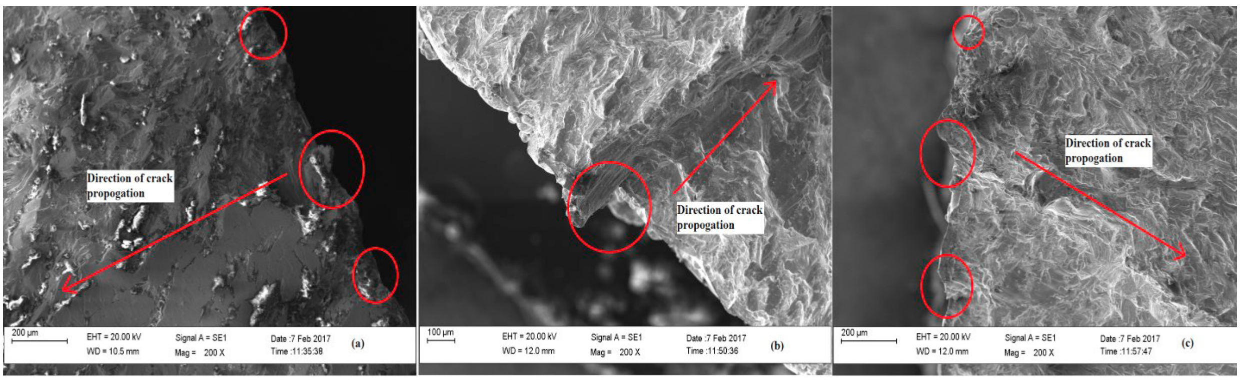
## 3. Results and Discussion

### *3.1. Surface observations and fracture study*




(i) 6A (ii) 12A (iii) 20A

Fig. 6 SEM images of Inconel 718 after SEDM process.



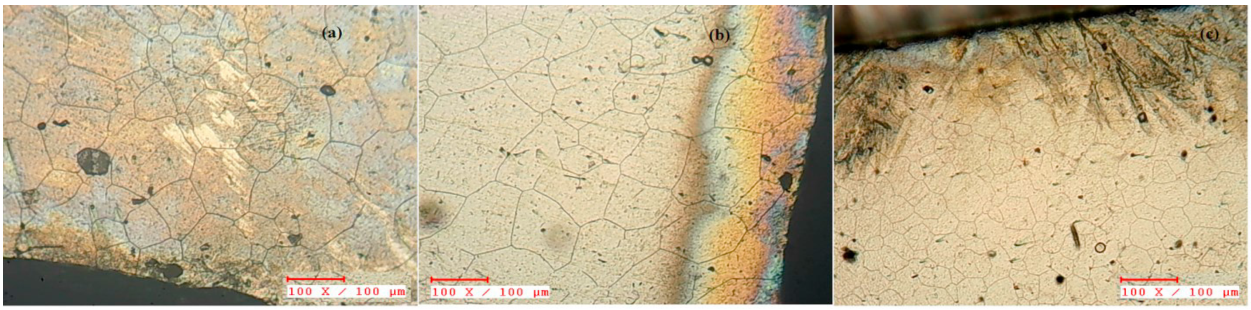

(a) 6A (b) 12A (c) 20A

Fig. 7 Fractographs after fatigue test.

Fig. 6 shows the SEM images for samples processed with peak currents 6A, 12A and 20A respectively. Then, Ra increased with the increase in discharge current with all 200, 400 and 810 µs Ton conditions. This phenomenon is inferred that when Ton time is increased the material removal takes longer time to erode of which leaves a huge defect in the surface, which is reflecting on the increase in the surface roughness. By increasing Ip, the amount of energy in the SEDM process will increase. Therefore, the melting and vaporizing of the work piece will produce the larger and deep crater as indicated in Fig. 6. It can be used to prove our experimental result that as the peak discharge current is increased; the surface roughness is also increased. Fig. 7 shows the SEM images of the fatigue-tested samples processed with peak discharge currents 6A, 12A and 20A respectively. The 6A sample shows very few spots for crack initiation compared to the other two samples because for the 6A sample the roughness is comparatively less and this leads to less chance for the crack to propagate. But several crack initiation spots were observed for the samples that are dealt with Ip values close to 12 A and 20 A.

From the optical microscope image as shown in Fig. 8 also it is clearly observed that, the depth of the valley/craters with various shapes of recast layer was formed and this condition was contributed to the high Ra value at higher Ip than the lower Ip. Images shown in Fig 6 depict that, as the peak discharge current (Ip) increases the surface roughness of the work piece sample also increases as viewed in the microstructure and Table 2. Images presented in Fig. 7 show the crack formation in the samples operated under different peak currents. There are only a few crack initiation zones in the 6A SEDM samples, whereas there are several crack initiation zones for the 12A and 20A SEDM samples. Zones are those parts in a fatigue-tested sample from where the crack has high possibility to propagate. The main theory of failure observed after the SEDM process is Orowan's theory of fatigue failure where the work piece is observed to have small, weak regions which served as areas favourable for slips to occur and areas for high tensile stress concentration leading to fatigue life reductions. After SEDM process the samples are observed with severe surface pitting, small weak regions which are acting as the potential crack initiation zones, which reduced the fatigue life of the SEDM samples compared to end milled specimens. The small surface defects develop as a crack as the load is repeatedly applied. The crack creates a stress concentration and this forms a new localized plastic region in which the process repeated over and over which resulted in crack growth and indeed a brittle failure as shown in Fig 6 and Fig 7.

The samples are cut into 3mm pieces to analyze the grain boundaries at the heat-affected zones after the SEDM process. It is observed that heat affected zones are seen in all the samples produced during 9 experimentations. Some induced stress is evident from the microstructure of the samples. From Fig. 8 it is observed that dense grain boundaries are present near the heat-affected zone, which confirms the localized melting and rapid solidification took place during the material removal by the SEDM process on the samples [13]. From the microstructure it is understood that the grain boundaries are large in size at the center of the samples and clear as shown in Fig. 8.




(a) (b) (c)

Fig. 8 Microstructure of heat affected zone of samples after SEDM in samples (a) 6 A (b) 12 A and (c) 20 A

### 3.2. Fatigue Analysis

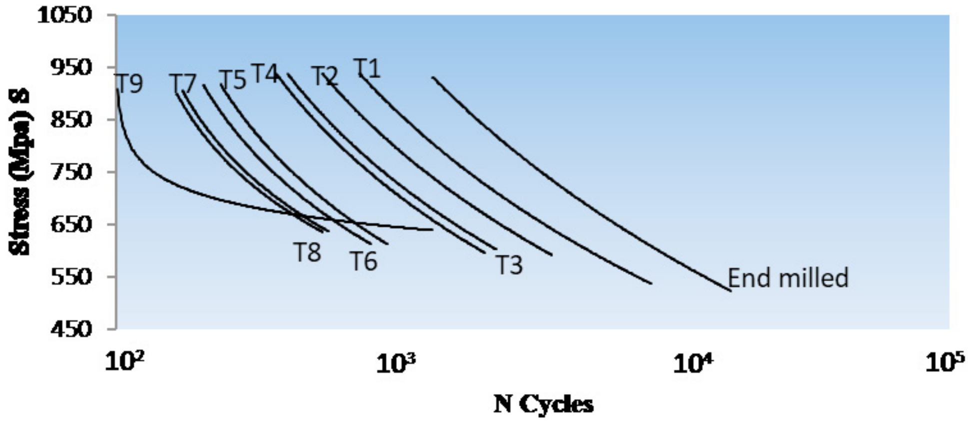



Fig. 9 S-N curve of SEDM samples compared with end milled

Fig 9 indicates the S-N curve generated using the samples produced from 9 different combinations of SEDM experimental trials and the end milled samples. The diagram was produced by plotting the average of five data points at each of the five stress levels. The load applied to each specimen was calculated and reset to maintain the desired stress level. From the S-N curve a stress level range of 900 to 550 MPa was chosen to test the SEDM samples. It can be seen from the S-N graph that the fatigue life of the SEDM samples decreased slightly compared to end milled samples. Fatigue life of 1.76 x $10^5$ was the highest fatigue cycles observed at a load of 160 MPa (8 KN) and 5.02 x 104 at load of 500 MPa (23 KN) closer to yield point. Similarly, the end milled sample at 160 MPa (8 KN) load exhibited 2.71 x $10^5$ cycles, which is 64% more in fatigue life cycle compared to SEDM sample. At load of 500 MPa (23 KN) the end milled sample exhibited 9.07 x $10^4$, which is 54% more than SEDM sample. However, similar fatigue life is observed for all set of peak discharge current with variations in the other parameters such as $T_{on}$, gap voltage and $T_{off}$.

An increase in peak discharge current showed an increase in material removal rate and surface roughness. It is observed that when current pulse duration ($T_{on}$) increases, the material removal rate decreases in proportion to the amount of current and voltage while surface roughness increases which means that increase in pulse on time results in poor surface finish. Quality of surface roughness is also driven by pulse off duration as unsTable spark resulted during shorter pulse off time, which is concurrent with the finding [6][14][15].

Experimental analysis shows that for a constant Peak Current, increase in current pulse duration increases the surface roughness of the work piece for that Peak Current. From Table 2, it can be seen that by keeping the same machining conditions the tensile strength decreases with increase in peak discharge current. This is due to the fact that as current increases, the roughness increases thereby decreasing the tensile strength. More roughness implies lesser surface finish of the workpiece, which will decrease the tensile strength of the workpiece. From Table 2, it can be seen that, as the current increases, the hardness of the samples were decreasing. The decrease of hardness is due to the recast layer formation. This could be due to the reduction of chrome and addition of copper and zinc to the recast layer, which modifies its mechanical properties. The decrease in hardness may be due to the electrolysis happening in the de-ionized water dielectric and this leads to the oxidation on the surface [7, 8, 16] and a decrease in the hardness of the surface.

There is a formation of recast layer in the sample, which was machined at 6A, 12A and 20A as shown in Figs. 10, 11 and 12. As indicated in Table 2, the $R_a$ is better at lower peak current with shallower and flattened crater formation. Due to the formation of recast layer, there is a decrease in hardness and tensile strength in the work piece compared to end-milled sample. Experimental analysis also shows an increase in surface roughness because of recast layer formation. As the peak discharge current increased the recast layer thickness is increased by 35% from sample to sample as shown in Table 2 and Figs. 10, 11 and 12.

From the analysis it was observed that $T_{on}$ is one of the significant factors that can improve $R_a$. Normally for an increase in $T_{on}$ the Ra value will increase because the melting boundary becomes deeper and wider, however, due to longer $T_{on}$, the frequency and intensity of the sparking will reduce. As a consequence, a shallower and flatten crater is produced. Thus, $R_a$ value was not varying too much with increasing $T_{on}$ throughout the trials.

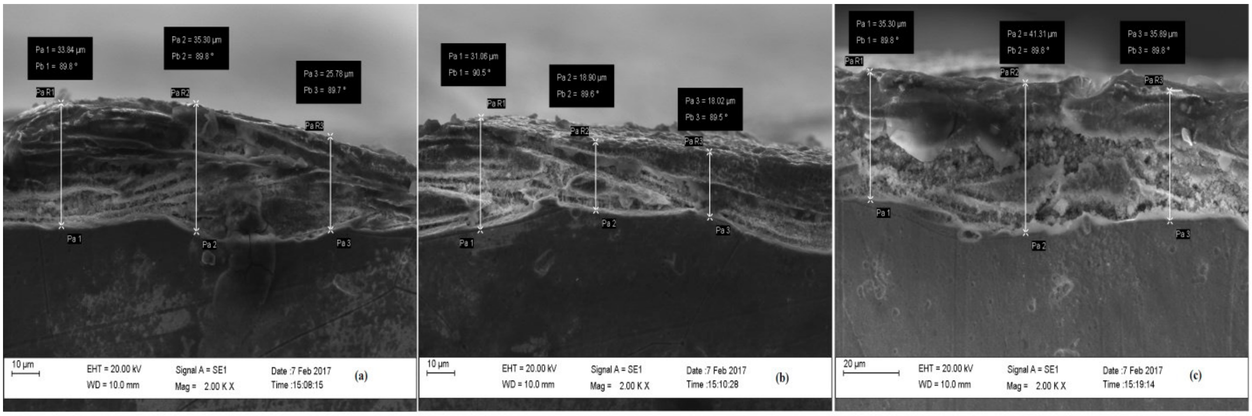


Fig 10 Recast layer formation on 6A sample of (a) 200µs (b) 400µs (c) 810µs variation

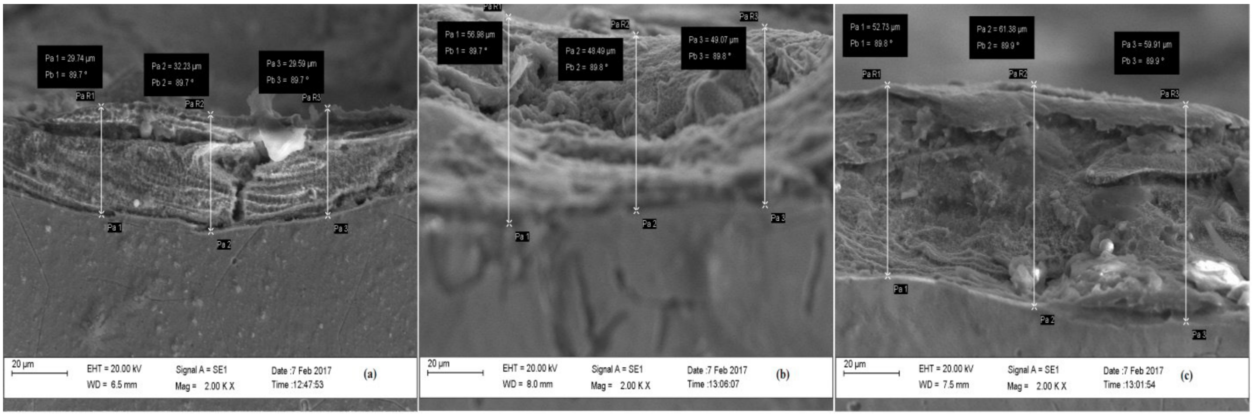


Fig. 11 Recast layer formation on 12A sample of (a) 200µs (b) 400µs (c) 810µs variation

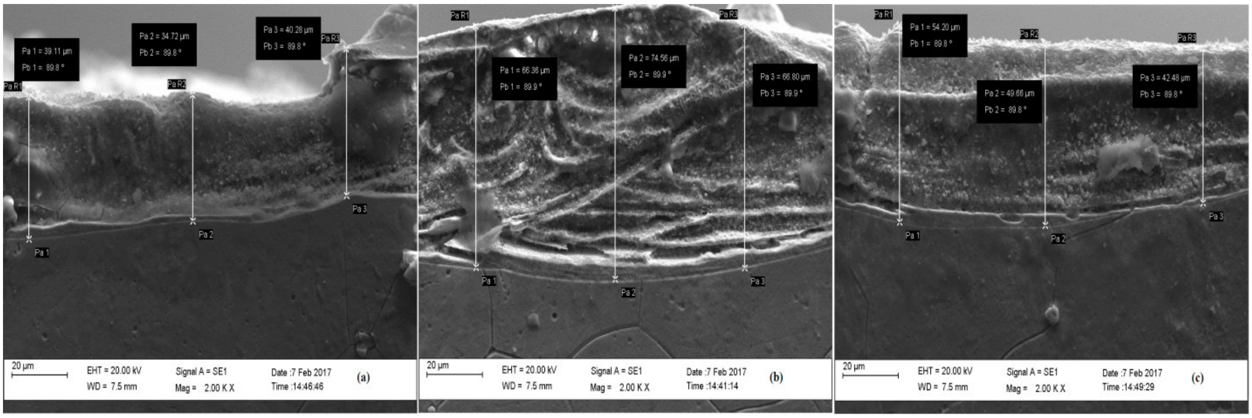


Fig. 12 Recast layer formation on 20A sample of (a) 200µs (b) 400µs (c) 810µs variation

## 4. Conclusions

Experimental investigation on the influence of the recast layer formed during SEDM of Inconel 718 is being reported in this paper. It is being concluded that when the peak discharge current is increased the average recast layer thickness observed to be in the range of 20 to 70 µm. Due to the formation of recast layer there is a significant change in the mechanical and fatigue characteristics of Inconel 718. The formation of recast layer makes the material surface quality poor which acts as a potential crack initiation zones which indeed decreases the tensile strength and the fatigue strength of the material compared to end milling process. As the current increases the material removal rate also increases thereby increasing the surface roughness of the material.

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