Comparative Assessment of MRR, TWR and Surface Integrity in Rotary and Stationary Tool EDM for Machining AISI D3 Tool Steel

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Abstract— Electric Discharge Machining (EDM) is a well-established and one of the most primitive unconventional manufacturing processes, that is used world-wide for the machining of geometrically complex or hard and electrically conductive materials which are extremely difficult to cut by any other conventional machining process. One of the major flaws, over all its advantages, is its very slow Material Removal Rate (MRR). In order to eradicate this slow machining rate, various researchers have proposed various methods like; providing rotational motion to the tool or work-piece or to both, mixing of conducting additives (such as SiC, Cr, Al, graphite etc) powders in the dielectric, providing vibrations to the tool or work-piece or to both etc.

Present work is a comparative study of Rotational and Stationary Tool EDM, which deals with providing rotational motion to the copper tool for the machining of AISI D3 Tool Steel and the results have been compared with stationary tool EDM. It has been found that the tool rotation substantially increases the MRR up to 28%. The average surface finish increases around 9-10% by using the rotational tool EDM. The average tool wear increment is observed to be around 19% due to the tool rotation. Apart from this, the present work also focusses on the recast layer analysis, which are being re-deposited on the work-piece surface during the operation. The recast layer thickness is less in case of Rotational EDM and more for Stationary Tool EDM. Moreover, the cracking on the re-casted surface is also more for stationary tool EDM as compared with the rotational EDM.

***Keywords*—**EDM, MRR, Ra, TWR.

I. Introduction

ELECTRIC DISCHARGE MACHINING (EDM) process originated around 1770, when English Scientist Joseph Priestly discovered the erosive effect of the electric discharges (sparks). In 1930, first attempts were made to machine metals and diamonds using electric discharges, and the process was referred to as "arc machining or spark machining" [1].

In 1943, two Russian Scientists, B.R. Lazarenko and N.I. Lazarenko at the Moscow University did pioneering work on EDM [2]. The destructive effect of an electric discharge was channelized and a controlled process for the machining of materials was developed. The relaxation-capacitance (RC) circuit was introduced in 1950s, which provided the first consistent dependable control of pulse time and a simple servo system control circuit to automatically sense the required inter-electrode gap between the tool and the work-piece. In 1980s, the introduction of Computer Numerical Control (CNC) in EDM, brought tremendous advancement in improvising the efficiency of the machining process. Modern EDM machines are so stable these days that these can be operated round the clock under adaptive control system monitoring [3].

A. Working Principle

EDM is an electro-thermal non-traditional controlled metal removal process, where electrical energy is utilized to generate electric spark and due to the thermal energy of the spark, most of the material removal takes place. Here, the spark behaves like a cutting tool to cut the work-piece, in order to produce the finished job to the desired shape. The material removal process is accomplished by the application of a pulsating (on/off) electric charge carrying high frequency current through the electrode to the work-piece. This causes material removal in the form of tiny particles from the work-piece at a controlled rate. Schematic diagram of EDM process is shown in Figure 1.

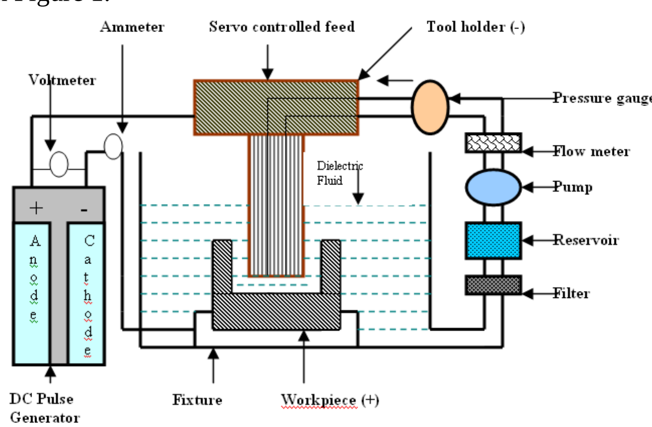

Figure 1: Schematic diagram of EDM process

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B. Process Mechanism

The material erosion mechanism primarily utilizes the electrical energy and converts it into thermal energy, through a series of discontinuous electrical discharges occurring between the tool and the work-piece, submerged in the dielectric fluid [4]. The thermal energy generates a virtual plasma channel between the two electrodes [5] at a temperature in the range of 8000-12000^{0}C [6], this temperature can go as high as 20000^{0}C [7]. This temperature range causes the material of any hardness to melt at the surface of each pole. When the pulsed DC power supply of around 20,000-30,000 Hz [8] is turned off, the plasma channel breaks down. This causes an abrupt reduction in temperature at the tool work-piece interface, which allows the circulating dielectric to flush away the molten material from the melt cavity, in the form of microscopic debris [1]. The arc description during the EDM process is shown clearly in Figure 2.

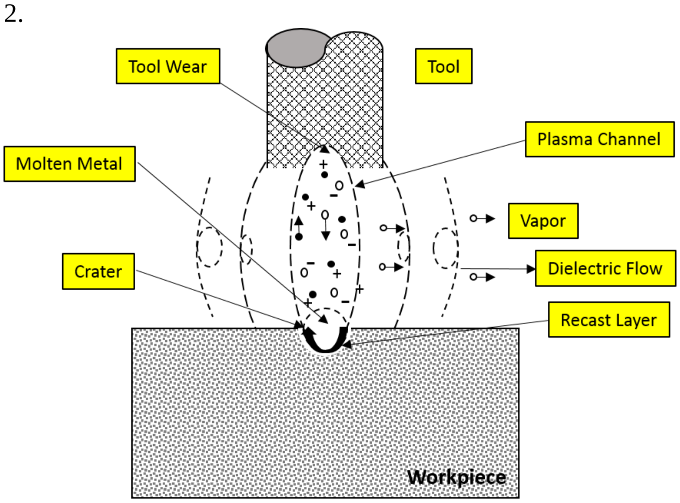

Figure 2: Arc description in EDM process

The volume of material removed per discharge is approximately in the range of 10^{-6}-10^{-4} mm^3 and the material removal rate (MRR) is typically between 2-400 mm^3/min [1] based on specific application. As, the shaped electrode defines the area wherein the spark erosion would occur, the accuracy of the part produced by EDM is fairly good. After all, electric discharge machining is a reproductive shaping process, in which the form of the tool electrode is mirrored in the work-piece [9].

C. Process Characteristics

(a). The process can be used to machine any electrically conductive material, irrespective of its hardness.

(b). The rate of material removal depends mainly on the thermal properties of the work-piece, rather than its hardness or strength.

(c). The work-piece and the tool are not in physical contact with each other at any point of time during the machining.

(d). The tool also needs to be electrically conducting in nature and the tool wear also depends on the thermal properties of the tool material.

(e). The heat affected zone (HAZ) is limited to 2-4 μm of the spark crater and also, the process is burr free.

(f). However there is a possibility of overcut and taper cut in EDM, that can be compensated and controlled.

II. Experimental Set-up

In order to rotate the tool electrode, a motorized set-up was made and mounted on the Electronica Z-axis Numerical Control (NC) Electric Discharge Machine (Model: ELEKTRA 5535-EZNC). Figure 3 shows the rotating set-up mounted on the EDM.

Figure 3: EDM with rotary tool set-up

Table 1: Technical features of rotary EDM set-up

Motor	PMDC
Voltage	120 V
Current	2 Amperes
Poles	4
Power	240 Watts
Speed	0-3000 RPM

Electrode rotation helps to solve the flushing difficulty encountered while machining small holes with EDM. In addition to the increase in MRR, the quality of the hole produced is superior to that obtained using a stationary electrode. It produces cavities having the shape of the electrode. It improves flushing by creating a pumping effect of the dielectric liquid through the gap. [10, 14].

Table 2: Experimental Parameters

Current	10, 15, 20, 25 Amperes
Voltage	75 Volts
T_{on}	150 μm
T_{off}	58.33 μm
Polarity	Positive
Tool Rotational Speed	0-1000 rpm

Technical features of rotary EDM setup are mentioned in Table 1 and Table 2 shows the experimental parameters of the rotary EDM set-up.

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Figure 4: AISI D3 Tool Steel work-pieces after machining

Experiments were done on AISI D3 Tool Steel flats, of thickness 5 mm with copper rod as tool material having 10 mm diameter. Figure 4 above shows the results from four different sets of experiments (a, b, c and d), each set contains two experiments, the first one was carried out using the stationary EDM and the later one using the rotary EDM. All the experiments done using the rotary EDM process, a uniform rotational speed of 1000 RPM. Experiments in set (a) were carried out on uniform current of 10 amperes, similarly for set (b), (c) and (d), 15, 20 and 25 amperes of uniform current respectively, had been used. Further in this work, a detailed comparative analysis has been made.

A. Tool details

Copper rods of 10 mm diameter have been used as tool.

Advantages of using copper as tool are:
(a). High thermal and Electrical Conductivity
(b). Higher wear resistance
(c). Ease of machinability
(d). Ease of availability
(e). Economical

B. Work-piece details

AISI D3 Tool Steel flat plates of thickness 5 mm have been used as Work-piece.

Applications of AISI D3 Tool steel:
(a). Blanking, stamping and cold forming dies and punches for long runs;
(b). Lamination dies
(c). Bending, forming, and seaming rolls
(d). Cold trimmer dies or rolls
(e). Burnishing dies or rolls
(f). Plug gages
(g). Drawing dies for bars or wire
(h). Slitting cutters
(i). Lathe centres that subject to severe wear

C. MRR Analysis

In EDM, the metal is removed from both work-piece and tool electrode. MRR depends on the work-piece material, tool material and the machining variables such as pulse conditions, electrode polarity, and the machining medium. A material of low melting point has a high metal removal rate and hence a rougher surface. Typical removal rates ranges from 0.1 to 400 mm^3 /min.

Experimentally obtained values of material removal rate for the rotational and stationary tool EDM process are shown in Table 3 and 4 respectively.

Table 3: MRR for Rotating Tool EDM

S.No.	Current (A)	Tool Rotation Speed (RPM)	MRR (g/min)
1	10	1000	0.0795
2	15	1000	0.1429
3	20	1000	0.2067
4	25	1000	0.2730

Table 4: MRR for Stationary Tool EDM

S.No.	Current (A)	MRR (g/min)
1	10	0.0401
2	15	0.1029
3	20	0.1837
4	25	0.2436

Experimental results as shown in Figure 5, indicates that the MRR during the rotary EDM process is always greater than that in the stationary process. This is due to the fact that with the electrode rotation the molten material from the melt pool is cleared more frequently, as a result of which fresh work-piece surface is exposed to the tool every time the debris is being cleared away. Since the work-piece surface now exposed to the tool surface is fresh and almost free from the left over molten material, the spark intensity is more, which causes more surrounding material to melt and in this way the material in the vicinity of the spark gets melted and flushed away by the flow of the dielectric and electrode rotation, resulting in improved MRR.

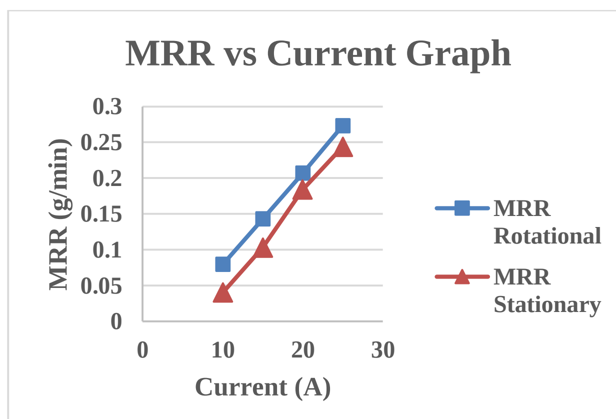

Figure 5: MRR Vs Current curve

D. TWR Analysis

Experimentally obtained values of tool wear rate for the rotary and stationary tool EDM process are depicted in Table 5 and 6 respectively.

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Table 5: TWR for Rotating Tool EDM

S.No.	Current (A)	Tool Rotation Speed (RPM)	TWR (g/min)
1	10	1000	0.0009
2	15	1000	0.0038
3	20	1000	0.0089
4	25	1000	0.0200

Table 6: TWR for Stationary Tool EDM

S.No.	Current (A)	TWR (g/min)
1	10	0.0007
2	15	0.0029
3	20	0.0075
4	25	0.0162

Below is the graph (Figure 6), in which the experimental results have been plotted in graphical form. It is very evident from both, the tables and the graph that the TWR during the rotational process is always greater than that in the stationary process. With the tool rotation, the molten material from the melt pool is cleared easily and effectively, so fresh materials are exposed after the melt pool is cleared, this causes greater spark intensity which increases the melting of more material in the vicinity of the spark, so the work-piece and the tool material both gets incremental sparks which increases both the MRR as well as the TWR. Since the flow of electron is always directed from the negative towards the positive terminal, therefore more of the work-piece material gets eroded as compared to the tool material. As, a result of which the MRR gets substantially increased by increasing the current and the TWR increases very less as compared to the MRR, with the increment in current.

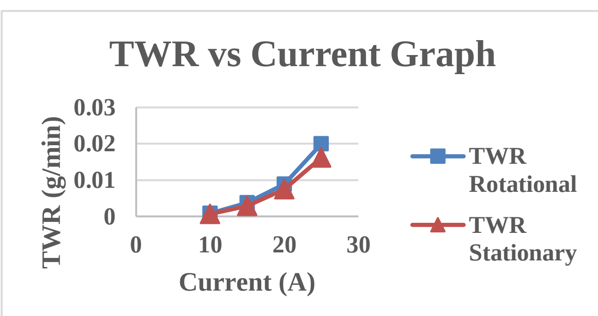

Figure 6: TWR Vs Current Curve

E. Surface Roughness Analysis

Average surface roughness is expressed as the 'Ra' value of the material.

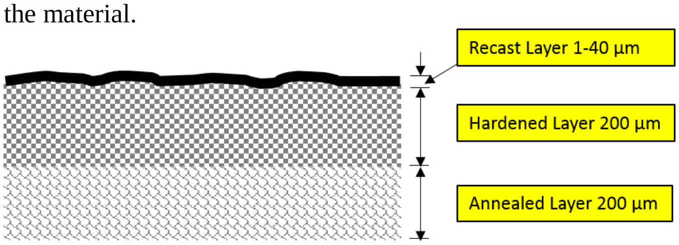

Figure 7: Various layers on work-piece after EDM process

Surface texture after EDM process is shown in Figure 7. Surface roughness analysis was carried out on the work-pieces using Bruker GT-KO non-contact type optical profilometer (Figure 8):

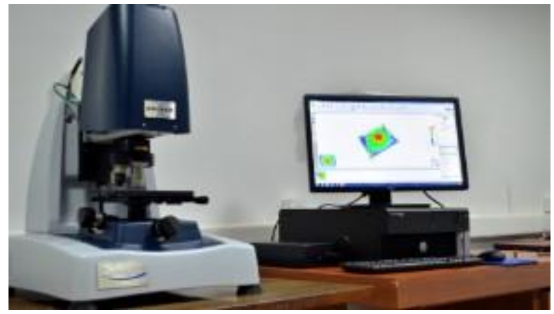

Figure 8: Optical Profilometer

Tables 7 and 8 show the surface roughness (Ra) values, for the rotary and stationary tool EDM process:

Table 7: Ra for Rotary Tool EDM

S.No.	Current (A)	Tool Rotation Speed (RPM)	Ra (µm)
1	10	1000	5.59
2	15	1000	6.195
3	20	1000	7.02
4	25	1000	7.264

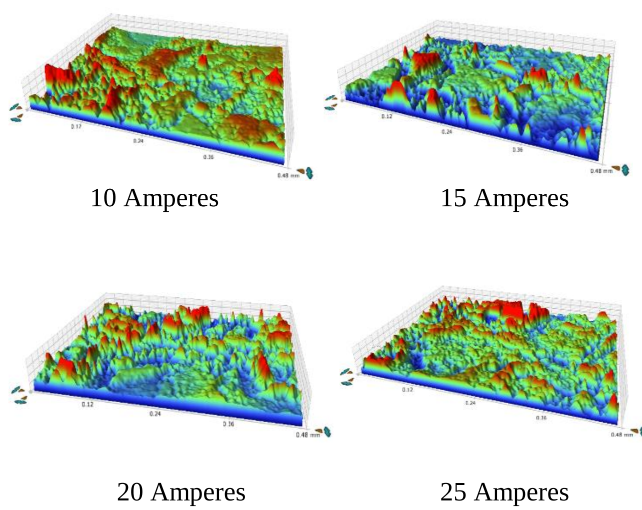

Figure 9: Surface profiles obtained from 3D optical profilometer for machining AISI D3 Tool Steel using rotary EDM at different values of current.

Table 8: Ra for Stationary Tool EDM

S.No.	Current (A)	Ra (µm)
1	10	5.889
2	15	6.946
3	20	7.079
4	25	8.394

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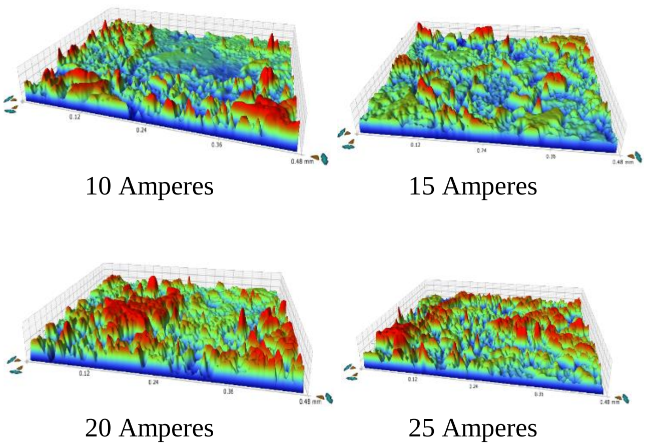


Figure 10: Surface profiles obtained from 3D optical profilometer for machining AISI D3 Tool Steel using Stationary EDM at different values of current.

Below is the graph in which the experimental results have been plotted in graphical form. It is very evident from both, the tables and the graph that the surface finish during the rotary EDM process is better than that in the stationary EDM process (as Ra for stationary tool EDM is greater than the Ra for rotary tool EDM). This is so, because due to the rotation of the electrode the molten metal does not easily gets deposited on the work-piece surface. With the motion of the electrode it gets easily flushed away with the dielectric flow. As a result, the surface produced is more uniform and crack free as compared with the stationary tool EDM. Figure 11 shows clearly that at every point the Ra value of rotary EDM is less than that of the stationary EDM, i.e., the surface finish of rotary EDM process is better than that of the stationary tool EDM.

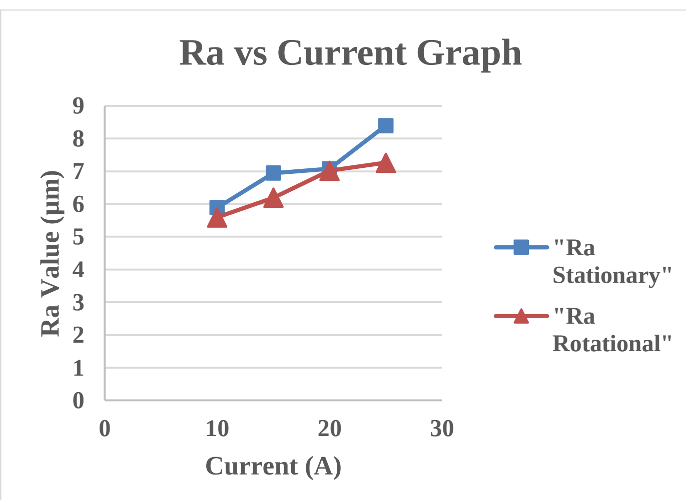


Figure 11: Ra Vs Current curve

F. Recast Layer Analysis

Recast layer analysis for the AISI D3 Tool Steel has been carried out by using JEOL JSM-6010LA Scanning Electron Microscope (Figure 12):

Figure 12: Scanning Electron Microscope

For Rotary EDM

The images obtained by the SEM process shows that the recast layer thickness on the AISI D3 Tool Steel is not uniform, it varies from 2-25 µm. Moreover, there are less micro-cracks observed on the work-piece surface, while the tool is rotating, as due to the tool rotation almost all the molten material gets flushed away with the dielectric flow which in case of stationary EDM remains on the surface and after hardening forms a recast layer with micro-cracks on the work-piece surface.

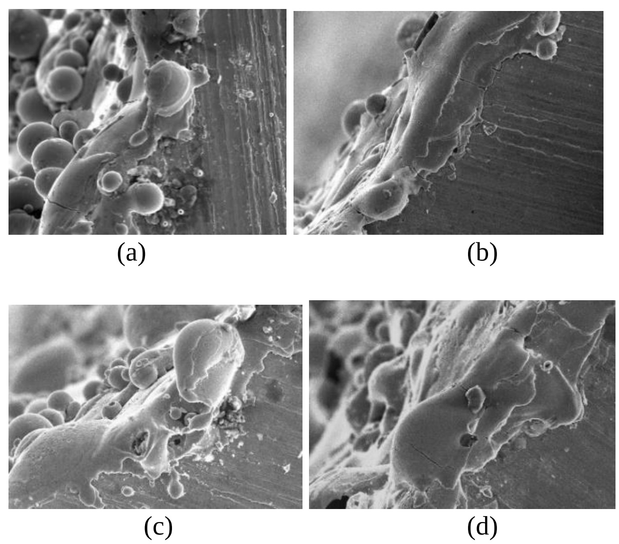
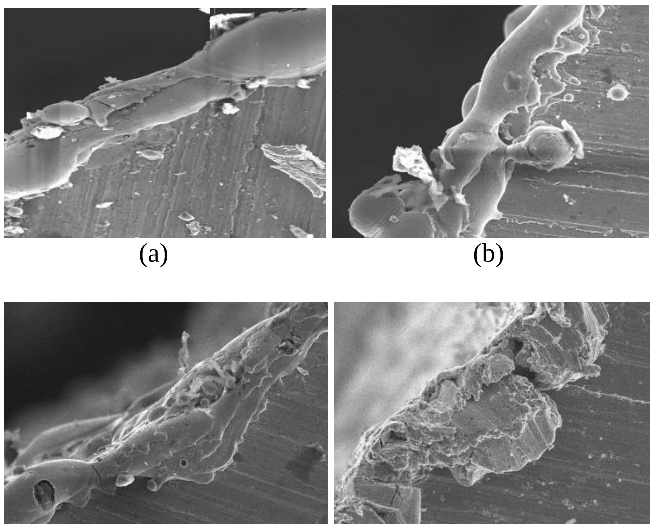


Figure 13: SEM images of AISI D3 Tool Steel using Rotary EDM Process at different values of current.

The above Figure 13 shows the recast layer deposited over the AISI D3 tool steel after its machining by rotary EDM process. Figure 13 (a), (b), (c) and (d) have been carried out at an input current of 10A, 15A, 20A and 25A respectively. These layers are formed due to the deposition of molten metal in the machining cavity. This left over material has the constituents of work-piece material, tool material and the decomposed carbon of the dielectric (hydrocarbon oil). When this layer gets hardened, it solidifies over the work-piece surface and it gets some micro-cracks after solidification. As seen in this figure these layers have a thickness in the range of 2-25 µm when observed from the scanning electron microscope, at a magnification level of 500 times the original size at different values of current.

For Stationary EDM

The images obtained by the SEM process shows us that the recast layer thickness on the AISI D3 Tool Steel is not uniform, it varies from 2-40 µm. Moreover, there are more micro-cracks observed on the work-piece surface, while the tool is stationary as compared to the rotary tool.



(a) (b) (c) (d)

Figure 14: SEM images of AISI D3 Tool Steel using Stationary EDM Process at different values of current.

The above Figure 14 shows the recast layer deposited over the AISI D3 tool steel after its machining by stationary EDM process. Figure 14 (a), (b), (c) and (d) have been carried out at an input current of 10A, 15A, 20A and 25A respectively. As seen in this figure these layers have a thickness in the range of 2-40 µm when observed with the help of a scanning electron microscope, at a magnification level of 500 times the original size at different values of current.

III. Results

The experiments and analysis of AISI D3 Tool Steel machining using the EDM (Rotary tool and Stationary Tool) Process gives us the following inferences:

(a). By using the rotary tool EDM, the MRR increases by 28% as compared to the stationary tool EDM, due to better debris clearance and increased spark intensity.
(b). The surface finish also increases by 9-10% using the rotary EDM over stationary tool EDM, as the tool rotation enables uniform machining on the work-piece.
(c). There is a slight increase in the TWR of around 19% while using the rotary tool EDM over stationary Tool EDM, since due to increased spark intensity in case of rotating tool, both the tool and work-piece experience more erosive action.
(d). The average recast layer during the rotary EDM process is in the range of 2-25 µm, while it is 2-40 µm for the stationary tool EDM process. Also, the micro-cracks visible on the machined surface of the work-piece are less in case of rotary EDM process as compared to the stationary EDM process. In case of rotary tool the cooling of the recast layer is more uniform in comparison to stationary tool. This happens because when the tool rotates it provides better passage for the debris to get out of the machined cavity and in this way very less molten material gets deposited on the work-piece surface and as a result the hardened layer after solidification is almost half of that in the stationary tool EDM. Since the thickness is reduced to half, the layer after solidification is does not cracks much and hence, the micro-cracks on the machined surface are less as compared with that of stationary tool EDM process.

IV. Conclusion

From the above research work we can conclude that the Rotary tool EDM gives a better MRR and surface finish, at the cost of a slightly higher tool wear. Also, the rotary EDM reduces the recast layer and surface micro-cracks. The average recast layer thickness increases with the increase in discharge current. Thicker recast layers have more cracking tendency than that of thinner ones. The recast layer thickness increases with the increase in the drilled hole depth.

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