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Experimental study to assess the effect of Electrode bottom profiles while machining Inconel 718 through EDM Process

M Manohar[a], T Selvaraj[b], D Sivakumar[a], Shibu Gopinath[a] and Koshy M George[a]

[a]*Scientist/ Engineer, Materials & Mechanical Entity, Vikram Sarabhai Space Centre, ISRO, Trivandrum – 695022 (India)*
[b]*Professor, National Institute of Technology, Tiruchirappalli – 620015 (India)*

Abstract

Electrical Discharge machining (EDM) is a non-conventional machining process, in general adopted to produce components with complex profiles that are difficult to be achieved through conventional manufacturing processes. Since long, EDM is widely used in industries to machine ‘difficult to machine materials’ like HCHC steel (tool and die material). INCONEL 718 is one of the alloys that have relatively poor machinability in the conventional machining processes, due to its work-hardening nature, retention of high strength at high temperature (700 k) and low thermal conductivity. For Inconel alloy, EDM is a preferred material removal process due to its advantages like reduced machining stresses, lesser work-hardening effects and lesser metallurgical damage. While analysing the possible improvements in the EDM process, it was observed that the bottom surface profile of the electrode was contributing towards many aspects like Material Removal Rate (MRR), Electrode Wear Rate (EWR), surface roughness and surface integrity. Certainly such process improvements would contribute a lot in the shop-floor in terms of productivity and product-quality, while machining Inconel 718 alloy. To understand the effect of the electrode bottom profile and also its extent of influence on machining Inconel alloy, experimental study was carried out through EDM. Electrodes of different bottom profiles were used and the machined surfaces were analysed in terms of recast layer, surface topology, form tolerance and MRR. Electrodes having Convex, Concave and Flat profile at their bottom surface were chosen for the experimental study; electrodes were made of copper rod of 12 mm diameter with convex or concave profile at their bottom with three different radii of curvature namely, 6,8 or10 mm. The surface roughness of the machined surface was measured and the nature of recast layer formed was evaluated and characterized using scanning electron microscope (SEM). The observations and results of the above experimental study are discussed and analysed in this paper. Nature of the machined surface obtained using the above mentioned electrodes are compared and discussed. It is concluded that the adverse effects caused due to the erosion of flat profile electrodes on the machined surfaces could be overcome by employing convex profile electrodes; concave profile electrodes almost simulate the condition of eroded flat-profile electrode; convex profile electrodes produce machined surfaces of better quality in terms of higher surface finish, thinner recast-layer and closer geometry, in addition to higher MRR compared to flat profile or concave profile electrodes.

* Corresponding author. Tel.: +91 471 2563806
E-mail address: manohar_isro@yahoo.com

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1. Introduction

Electric discharge machining (EDM) is a non-conventional machining process in the manufacture of complex shaped dies, moulds and critical parts used in automobile, aerospace, surgical and other industrial applications [Ho.K.H et.al (2003)]. The process uses thermal energy of the electric-spark to machine electrically conductive parts regardless of the hardness of the work material. In this process, material is removed from a part by means of repeated electrical discharges between tool (the electrode) and the work piece in the presence of a dielectric fluid [Luis CJ et.al (2005)]. The electrode is moved towards the work-piece until the gap is sufficient for the impressed voltage to ionise the dielectric. Short duration discharges are generated in a liquid dielectric gap, which separate the tool and work piece. The material is removed due to the erosive effect of the electrical discharges from the tool and work piece [Marafona.J et.al (2005)]. This unique feature of EDM has a distinct advantage and application in the manufacture of complex shaped die and mould which are difficult to be machined by conventional machining processes [Guu.Y.H et.al (2001)]. However the EDM process has limitations such as longer cycle-time, lower productivity and relatively higher cost, which restrict its application to specific materials and specialised jobs. Hence, researchers focus their attention on improving the process-capabilities of the EDM process, to make it economically conducive for adoption.

Studies show that selection of process variables and fixing the appropriate range of parameters to machine every product decides the quality of the product and in turn the design requirements [Norliana Mohd Abbas et.al (2007) and Shankar Singh et.al (2004)]. Hence, it is essential to understand the process intricacies, the factors influencing the output parameters (responses) and the role of the process variables. For increasing the flexibility of the process and improving its efficiency, efforts are needed by which a component could be machined with higher order quality and increased productivity. Though EDM technology has been established to be effective in machining out complex shapes and also to machine hard materials, there are several problems associated with this machining process. The success of tuning EDM to wide applications in machine shop depends on understanding the material removal mechanisms, the contributing factors to the material removal mechanisms, the relationship between the process parameters and the formation of surface and sub-surface damages on the product. Investigating the nature and extent of surface and sub-surface damages on the machined job is important as they provide vital information on the mechanisms of material removal.

Electrode material, geometry of the electrode, dielectric fluid, work material are the process variables in EDM and the process parameters like current, gap voltage, spark on-time, spark off-time, duty cycle, work piece polarity are the influencing attributes, to decide the outcome of the process [Ahsan Ali Khan et.al (2009),Lee H.T et.al (2004), Ahmet Hascalyk et.al (2004) and Haddada M.J et.al (2008)]. Process parameters like discharge current and pulse-on time have considerable effect on the surface roughness and surface integrity of the machined surface while machining ceramic-composites and play dominant role in causing surface and sub-surface damages [Patel K,M et.al (2009)].

The performance of EDM is usually evaluated by the output parameters namely material removal rate (MRR), electrode wear rate (EWR), wear ratio (WR), machined surface roughness (Ra) etc., It is desirable to obtain higher MRR with lower EWR, WR and Ra values. Electrode profile has a definite effect on the machining performance of any work material. MRR was the maximum for the electrodes having bottom profile round shaped, followed by the square, triangular and the diamond shaped electrodes [Ahsan Ali Khan et.al (2009)].

Crack formation on the machined work piece could be attributed to the presence of the residual stresses induced during the machining processes. Studies were conducted to investigate the relationship between machining conditions and surface cracking with an objective of establishing machining conditions which prevent the occurrence of such cracks. Relationship of crack critical line (CCL) between work material and electrode diameter was deduced, mapping crack zone and no crack zone [Lee H.T et.al (2004)].

Machining parameters do have an effect on the formation of recast layer and white layer, surface roughness of the machined surface, density of cracks while machining AISI D5 tool steel [Ahmet Hascalyk (2004)].

The nature and characteristics of the recast layer formed at the machined surface of the work piece has strong relationship with the type of dielectric used during EDM. Formation of micro-cracks and micro-voids within the recast layer, formation of oxides and carbides in the recast layer and the roughness of the machined surface are attributed to the type of dielectric used in EDM [Yanzhen Zhang et.al (2011)].

Efficiency of the EDM process is increased considerably by the addition of surfactant to the dielectric (kerosene), in terms of higher MRR without affecting the present range of surface roughness and thin recast layer formed [Kun Ling Wu (2009)]. In an experimental study of EDM, selecting the process variables, fixing their levels and assessing their influence in the output parameter(s) is essential [Bhattacharyya.B et.al (1999)]. Scanning Electron Micrographs are used for the analysis of the recast layers formed. Subsequent material removal is retarded due to the formation of recast/ transfer layer [Manoj Kumar B.V et.al (2007)]. Process parameters, concentration of electrolyte and the tool tip geometry greatly influence the MRR while machining ceramic materials by ECDM process [Ramasawmy.H et.al (2004)]. Direct current is the most dominant process parameter in modifying the surface texture of the EDM surface, specifically while removing the recast layer formed. The interaction between the process variables, namely the current and the distance between electrodes is more important than the individual effect of the latter [Ramasawmy.H et.al (2002)].

Considering the research work done by others on different work-materials and taking into account of the machining characteristics of Inconel 718 alloy, EDM experiments were carried out with copper electrode and analysed for their adaptability to this material.

Machining of material like Inconel through EDM process is complex in nature. Inconel 718 is a precipitation-hardened nickel-chromium alloy. It contains substantial levels of iron, molybdenum, and niobium and trace amounts of titanium and aluminium, possessing high strength and temperature-resistance combined together. Establishing the process capabilities of EDM for machining Inconel 718 and optimising the process is important, since it has wide specialised engineering applications, like components of nuclear reactor, spacecraft, steam turbine and propulsion systems.

Normally, electrodes of flat bottom profile are chosen during rough machining for bulk material removal. It is observed that erosion of this electrode will be in the concave form starting at the bottom centre of the electrode. To account for this erosion effect, it was proposed to use electrodes of convex bottom profile and study the effect of this profile on other aspects of machining. As a flat bottom profile electrode gets eroded and reaches a stage of concave profile over a period, it is necessary to understand the machining behaviour and hence it was proposed to include electrodes of concave bottom profile itself.

In this work, influence of process parameters and effect of three different bottom surface profiles of the electrode on the machined surface including topology, recast layer, formability and the MRR were studied, analysed and discussed.

2.0 Experimental Details

2.1 Optimal parameters

For proper selection of the process parameters that will yield the desired product quality (output), a good knowledge of the input parameters determining the output performance and its prediction is very important [Ross PJ (1996) and Montgomery D.C (1991)]. The essential steps in the study include identification of factors that are to be included in the experiments and determining their levels for varying. Accordingly, the process parameters namely, Peak Current (A), Pulse 'on' Time (µs) and Pulse 'off' Time (µs), Applied voltage, and Flushing pressure were considered for the study. Output parameters chosen for assessing the process performance were machining time, Electrode wear rate, Recast layer, surface topography etc.,

Optimal input parameter values were obtained by conducting experiments on Inconel 718 material using copper as electrode by L18 orthogonal array. Table 1shows the three factors (input parameters) and the three levels considered for the experiments.

Table 1
Process variables and their levels

Input Parameter	Unit	Level 1	Level 2	Level 3
Peak Current	A	4	8	**12**
Pulse ON Time	µs	200	400	**600**
Pulse OFF Time	**µs**	**10**	**20**	**40**

The other process parameters - voltage and flushing pressure of the electrolyte were kept constant throughout the experiments.

Based on the surface roughness measured on the machined surface, optimum set of process parameters was arrived as

Current =12 A
On time =400 µs
Off time =40 µs

2.2 Work piece material

The work material chosen for the study was Inconel 718 in the annealed condition, in the form of a circular disc of 65 mm diameter and thickness of 10 mm and 3mm.

Hardness of work piece was measured using a portable Hardness Tester HT-7, and the values are given in Table 2.

Table 2
Hardness values

Scale	Trial 1	Trial 2	Trial 3	Average
Rockwell (B)	81	79	81	**80.33**
Vickers	**145**	**145**	**144**	**144.33**

2.3 Electrodes

Electrodes used were of copper rods of 12mm diameter. Three electrodes having convex bottom profile as shown in Fig-1, three electrodes having concave bottom profiles as shown in Fig. 2 and one flat bottom profile electrode were chosen for the experimental study.

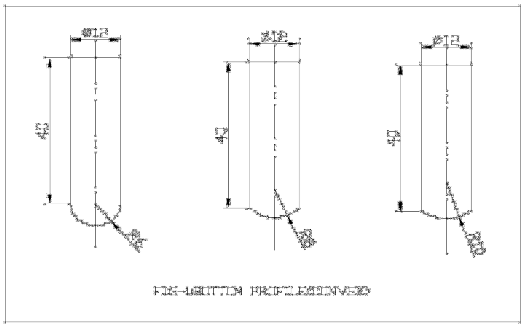


Fig-1 Bottom profile

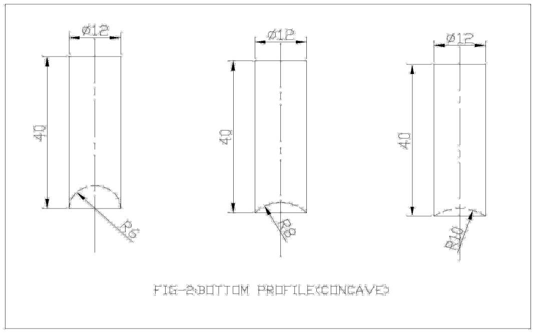


Fig-2 Bottom profile

Cylindicity of the above mentioned electrodes were measured using Co-ordinate measuring machine (CMM) to ensure that they maintain geometry of high order. Cylindricity measurements of all the 7 electrodes carried out are given in Table 3.

Table 3
Cylindricity of electrodes

Sl. No.	Bottom Profile of the electrode	Cylindricity (mm)
1	R6 (convex)	0.12
2	R8 (convex)	0.124
3	R10 (convex)	0.09
4	R6 (concave)	0.08
5	R8 (concave)	0.072
6	R10 (concave)	0.063
7	Flat	0.114

3. Machining Performance

3.1 Material Removal

Machining was carried out by EDM process on Inconel 718 material using the copper electrodes of the same diameter having flat, concave and convex bottom profiles. Experiments were carried out using electrodes of different bottom profiles (i) to machine the flat surface of 10 mm thick circular discs over a region of 30 mm square to 3 mm depth; the roughness (Ra) of the machined surface was measured; machined surface was observed by SEM to assess its topology and the nature of recast layer formed (ii) to generate 12 mm Dia. holes on the 3mm thick work piece (through the material thickness); time taken to drill the hole was recorded and the cylindricity of the holes was measured.

Surface roughness of the machined region was measured and the values are tabulated in Table 4.

Table 4
Surface roughness of the machined surface

Electrode Type	Surface roughness (Ra) µm
Convex profile - R6	3.2
Convex profile -R8	3.5
Convex profile -R10	4.1
Concave profile -R6	4.4
Concave profile -R8	5.1
Concave profile -R10	5.6
Flat profile	4.6

3.2 Assessing Recast Layer and Topology

EDM was carried out using each electrode on the flat surface of circular discs to remove material in a region of 30 mm square to a depth of 3 mm. Using the 7 electrodes described above, in a similar manner 7 such regions were machined; nature and condition of the machined surface was assessed in terms of the extent of possible damage by observing surface topography using a Scanning Electron Microscope (SEM).

3.2.1 Recast Layer

The recast layer (RCL) is the result of the re-solidification of the melted material which was not swept away from the component's surface by the dielectric during the EDM process. RCL is known to exhibit high hardness, high surface roughness, and good adherence to the bulk metal and fair resistance to corrosion [Haddada M.J et.al (2008)]. It makes the surface hard and brittle and decreases the fatigue strength due to the presence of micro-cracks and micro-voids [Liao Y.S et.al (2004)]. In general, the surface generated by EDM is characterized by an uneven fused structure, globules of debris, shallow craters and micro pores. During EDM, the work-piece surface undergoes melting and vapourisation followed by rapid cooling/quenching by the dielectric fluid. This produces a characteristic heat-affected zone (HAZ), generally with an upper region comprising redeposited / recast material [Lee H.G et.al (2004) and Che-Chung Wang et.al (2009)]. The depth of recast layer depends upon the volume of debris which is left on the work-material surface during machining.

Figure 3(a) and 3(b) show the SEM photograph depicting the recast layer of work piece that was formed during machining with R6 – convex electrode; Figure 3(c) that of R8 - convex electrode; 3(d) that of R10 – convex electrode and Figure 3(e) that of flat profile electrode.

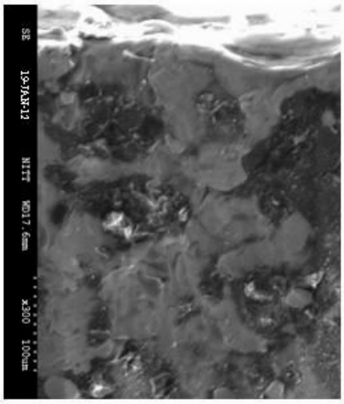
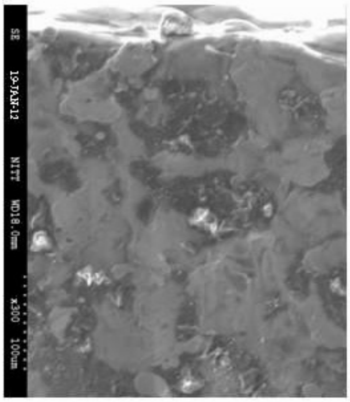


Fig 3 (a) RCL formed by R6 (30μm)



3 (b) RCL formed by R6 (25μm)

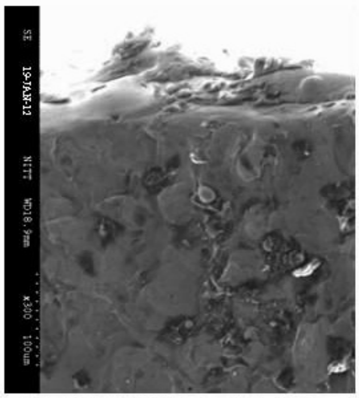


Fig 3 (c) RCL formed by R8

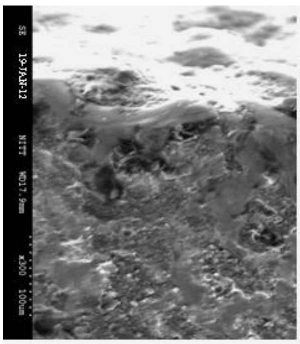


Fig 3 (d) RCL formed by R10

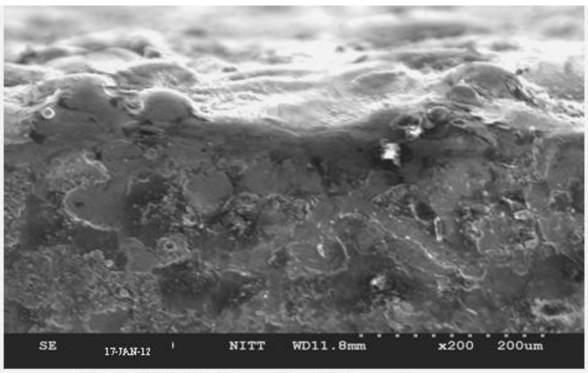


Fig 3 (e) RCL formed by Flat profile

Table 5 gives the details of thickness of the Recast layers formed over the machined surface of the work-piece, using different radii of convex profile electrodes and the flat profile electrode.

Table 5

Thickness of the RCL

Electrode used in the experiment	**Thickness measurements of the Recast layer formed (μm)**	**Average thickness (μm)**
R6 (convex)	30, 25, 38	31
R8 (convex)	33, 48, 41	41
R10 (convex)	45, 38, 54	46
Flat	62, 68, 73	68

Thickness was measured at different locations to ensure that the entire range covering minimum and maximum conditions was included. However, average values were taken for comparison of performance of electrodes.

3.2.2 Topology

The topology of the (EDM) machined plain-surfaces by using electrodes of convex R6, R8, R10 profiles and flat profile are shown in Figures - 4(a), 4(b), 4(c) and 4(d) respectively. The profile of the bottom surface of the electrode has influence in generating the surface while machining, in terms of melting the material in contact and facilitating its removal before it gets solidified. Topology of the machined surface is very well understood and is explained through the micrographs of SEM .

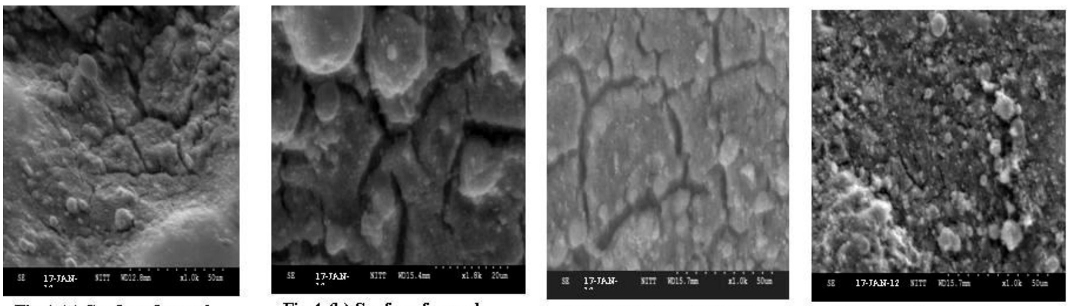


Fig 4 (a) Surface formed by R6 Convex **Fig 4 (b) Surface formed by R8 Convex** **Fig 4 (c) Surface formed by R10 Convex** **Fig 4 (d) Surface formed by Flat profile electrode**

3.3 Formability

Circular disc of 65 mm diameter and 3 mm thickness were used for drilling holes of 12 mm diameter by EDM process. Such machined holes on the disk were subjected to geometric check using CMM. The cyclindricity of the holes was measured and the values are given in Table 6.

Table 6

Role of the electrode in the cylindricity of hole generated

Electrode used	Time min:sec	Cylindricity of the hole generated mm
R6(convex)	12:05	0.058
R8(convex)	12:36	0.074
R10(convex)	12:57	0.091
R6(concave)	18:55	0.112
R8(concave)	17:03	0.151
R10(concave)	15:48	0.249
Flat	13:58	0.127

4.0 Analysis of experimental data:

It was observed that all the chosen electrodes having convex, concave and flat bottom profile exhibited good performance in machining Inconel 718 material with an objective of achieving higher MRR and improved surface roughness. Among the chosen profiles of the electrodes, convex profile electrodes perform better than concave and flat profile electrodes in terms of MRR, surface roughness and also thickness of RCL formed. After completing the machining experiments, all the electrodes were subjected to visual inspection (magnification of 10X) to assess the extent of wear and it was noticed that flat profile electrodes had worn the maximum followed by the electrodes of convex profile and concave profile.

4.1 Recast layer

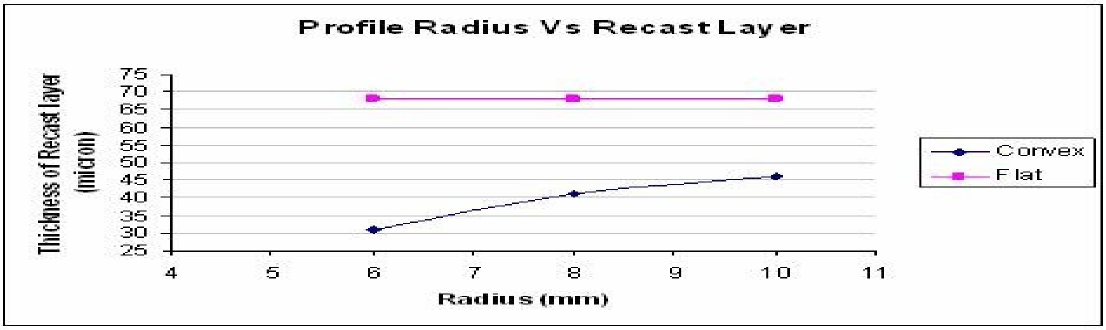


Figure - 5

Variation of the thickness of RCL with respect to the profile radius of the electrode is shown in figure 5. It is observed that the thickness of recast layer is lesser while using convex bottom profile electrode compared to that of flat bottom profile electrode; This is due to the reason that for the same diameter electrode and same machining parameters, active surface area is initially lesser resulting in generation of lesser heat energy and progressively increases as the electrode advances towards work-piece metal resulting in increased heat energy and consequent higher material removal. Further in the case of convex profile electrode, access to the electrolyte is better compared to flat or concave profile electrodes, for flushing the molten metal thereby reducing the formation of RCL. This reason is substantiated by the experimental data that as the radius of curvature of the electrode profile increases thickness of the recast layer also gradually increases. However, thickness of the recast layer built in the case of convex profile electrode is much lesser (almost half) than that of flat profile electrode. It may be noted that in the case of flat profile electrode, contact surface area is more, heat energy density is uniform throughout the bottom surface and the electrolyte has relatively poorer access to flush away the molten metal as compared with the convex profile electrode.

Crack formation could be attributed to the presence of residual stresses induced during the machining process. Bombarding the work piece with successive electrical discharges causes considerable increase in the surface temperature of the work-piece, which then induces thermal stresses within the work-piece. The molten work-piece material which is not flushed by the

electrolyte subsequently re-solidifies as a white layer upon the surface of the work-piece. Due to the rapid cooling effect, residual stresses are induced within the white layer, and when these stresses exceed the material's ultimate tensile strength, cracking of the surface takes place; thermal sapling effect is related to the formation of cracks and normally this phenomenon is observed at high energy EDM. It is observed that crack formation in the RCL formed during machining with convex profile electrode is widely spread and also severe in nature. In the case of RCL formed by flat profile electrodes, size of the cracks is relatively smaller and lesser in number.

4.2 Machining time

Machining time for completing the hole drilling operation indicates the MRR and this indicates the performance of the electrode with regard to the work-material and also the role of the process parameters. In general, during plain-surface machining flat profile electrodes exhibit higher MRR as compared to convex profile or concave profile electrodes. In the case of hole-drilling, convex profile electrodes exhibit better MRR due to the reason that initial contact surface area approaching the work-piece is smaller and the electric discharge density is highly focussed towards the centre of the hole. As the electrode advances towards the work-piece, volume of metal to be removed is lesser at every instant and hence convex profile electrode takes relatively lesser machining time. For hole drilling, convex profile electrodes of smaller radius produce higher MRR. As the radius of curvature increases, MRR is reduced.

Concave profile electrodes take more time than flat profile electrode due to the reason that the exposed electrode surface with the work-piece has a line contact (in the form of a circle), producing lesser electric

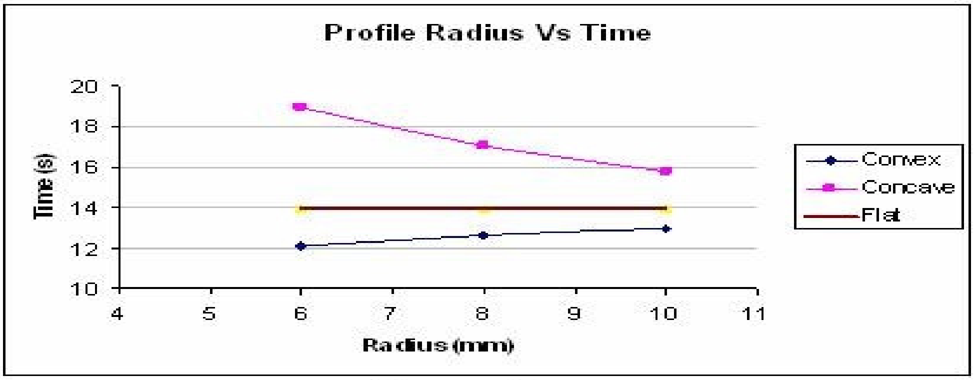


Figure - 6

discharges and as the electrode advances towards the work-piece, the surface area gets enlarged with consequent increase in electric discharges and resulting higher volume material removal. Higher volume of material removal is seen later as Effect of profile radius on MRR ctrode advances inside the work-piece.

Variation of machining time for a specific operation with respect to electrode profile and its radius is shown in

Figure 6. It is noted that machining time of the convex electrode is the least among the chosen profiles. In the case of convex profile electrode, as the radius of curvature increases it progresses towards the flat profile and hence the machining time increases as the radius increases. In the case of concave profile electrode, as the radius of curvature increases, MRR is higher. For smaller radius of concave profile maximum time is taken.

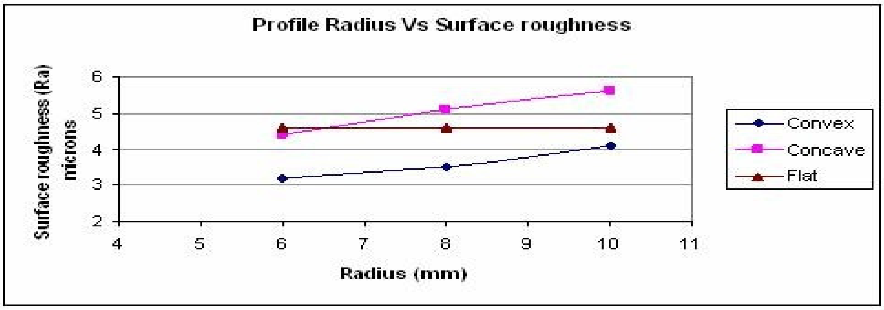


Figure - 7

4.3 Surface roughness

Surface roughness of the (EDM) machined plain surface was measured and given in Table 4. Roughness Values have been plotted in Figure – 7, with respect to profile radius of the electrodes for easy comparison purposes. Electrodes of convex bottom profile exhibit better surface finish due to the reason that smaller surface area is in electric contact with the work-piece and for the same machining parameters, density of the electric discharges is high; faster separation of the metal from the work-piece and effective flushing of the molten metal takes place thereby yielding better surface finish.

4.4 Formability

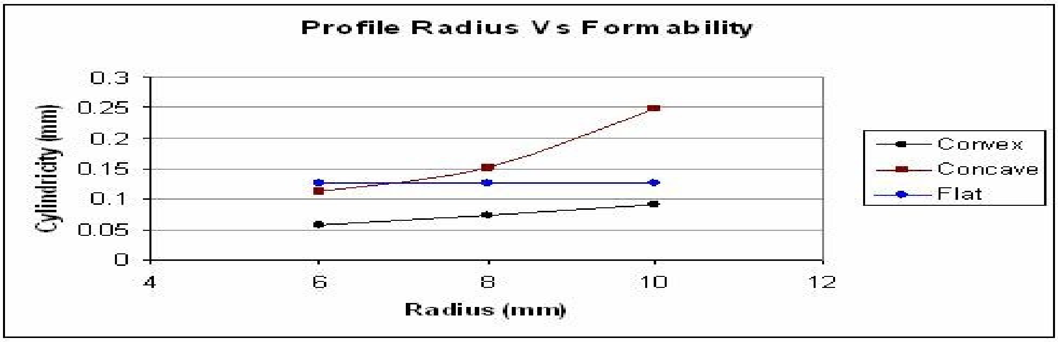


Figure - 8

Effect of profile radius on formability

Formability of the geometry of the EDM generated holes is related to the cylindricity measurement of the hole. For comparison purposes, cylindricity of the holes machined using different electrodes is plotted with respect to the radius of curvature of the profile of the electrode and is shown in Figure 8. Geometry of the drilled hole is very much influenced by the bottom profile of the electrode and its radius of curvature.

Cylindricity of the hole generated gets worsened as the radius of curvature of electrode increases. This shows that electrode of convex profile electrodes have good formability. Very specifically, smaller radius of curvature of concave and convex electrodes has good formability and as the radius of curvature increases, the formability of the generated hole is poor.

Conclusion

Experimental study was carried out to demonstrate that electrodes of convex and concave bottom profile can be used effectively for EDM of Inconel 718 material. Study was meant to find optimal electrode profile for electrical discharge machining of Inconel 718 work material, considering certain output parameters. The conclusions of the experimental work could be summarized as follows

- Electrodes of convex bottom profile perform better than flat or concave profiled electrodes in terms of lesser recast-layer, better surface finish for plain surface machining and closer geometry and MRR for hole drilling.
- Smaller radius of the profile performs better in terms of surface finish and formability, due to the reason that it has smaller contact surface.
- Smaller radius profile always perform better irrespective of its contour (convex or concave)
- Flat profile electrodes perform better than the concave profile electrodes.
- EWR is the least in the case of concave profile electrodes, preceded by convex profile electrodes and the flat profile electrode has the highest EWR.
- It is experimentally demonstrated that the effects of erosion of the flat profile electrode could be overcome by replacing it with the convex profile electrode; also that the performance of concave profile electrodes simulates the machined surface generated by the eroded flat profile electrode, over a period of time.

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