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Modeling of Residual Stress and Surface Damage of AISI 4340 using Copper-Tungsten Tool in Die Sinking EDM

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***Abstract:** The present work concentrates on the modeling of the residual stress and cracks induced during the machining of AISI 4340 in die-sinking EDM. Response surface methodology with rotatable central composite design is used with peak current, pulse on duration, voltage and pulse duty factor as process parameters. The relation between these process parameters and induced residual stress and cracks is established. The results of ANOVA elucidates that the present model is significant. Voltage and pulse on time are observed to have major dominance on residual stress. The SEM images reviled that micro-cracks resulted from the thermal stresses developed during machining of the workpiece. At higher levels of pulse on duration, wider cracks are observed due to high thermal gradients.*

***Keywords :** Cracks, EDM, Residual Stress, SEM, XRD.*

I. INTRODUCTION

Electro Discharge Machining (EDM) is among the most widely utilized technique to machine hard to cut, complex contours through generation of intense spark energy in a dielectric medium. It is well known that there is no contact between the tool and the work, hence no mechanical stress is generated. The stress produced in the machined surface is depends on the energy of sparks striking the work surface and the heat produced during sparking. The induced residual stress accounts for development of cracks when the ultimate fracture strength of work is reached.

Until now several researches have been performed on EDM for analyzing the influence of process parameters on induced residual stress and cracks developed on the machined surface. The experts have always seen that discharge energy had great impact on the surface texture and influences the size of craters produced by sparks. Guu (2005) through his research found that lower pulse energy results in better surface. Further he claimed that depth of micro-cracks developed was proportional to the power input. Further he conducted atomic force microscopy (AFM) to yield information about depth of micro-cracks and suggested that the surface must be polished to maximum depth of micro-cracks prior to use. Kumar et al. (2012) elucidated that lower surface damage is achieved when current intensity is low. They also found that the surface damage was directly proportional to discharge current. The study found that the peak current and pulse on duration dominates the variability of residual stress induced in the machined surface.

Tebni et al. (2009) through their study suggested that lower value of EDM parameters will reduce temperature affected layer thickness but raises the surface residual stress. Rizvi and Agarwal (2016) provided an approach to assess the cracks and residual stress and concluded that cracks always appear in the machined surface. Increasing the pulse on duration increases the crack opening. They also concluded that higher residual stresses are result of higher values of peak current and pulse on duration. Younis et al. (2015) through their study found that the micro-cracks occurring on EDMed surface are due to high value of peak current. Higher residual stresses are developed at longer duration of pulse. Mannan et al. (2012) in their research found the abundance of cracks on EDMed surface due to higher value of peak current and pulse on time. They also concluded that cracks are associated with high thermal stresses exceeding fracture strength of the material.

Ekmekci et al. (2005) showed that the maximum value of residual stress will be around the ultimate tensile strength of the machined material and is found in the heat affected zone. They also concluded that residual stress is related to the spark energy. In the light of recent researches, Sidhom et al. (2013) through the investigation have found that the residual stress developed in the machined surface results due to rapid cooling and phase change in white layer that induces surface cracks. They also found that tensile residual stress results due to thermal effect. Mishra et al. (2017) found that cracks are observed on machined surface due to internal stresses caused by heating and sudden cooling of the surface.

Ekmekci et al. (2002) deduce the conclusion that the pulse on duration dominates crack formation on machined surface and the cracks normally concentrate the crater. An inference for relation of density of cracks and pulse on duration was given by Rao et al. (2008) and concluded that increase in pulse on duration increases crack length. Peak current was found to be crucial factor for crack density. Khan et al. (2012) recognized that peak current crucially influences the crack density and increase in current increases micro-cracks. Another research conducted by Hascalik and Caydas (2007) presented the impact of peak current on crack

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density and found that peak current increases the denseness of cracks on machined surface. Gill and Kumar (2014) also observed that peak current increases the crack density.

The present paper aims to develop a model in order to assess the relationship between induced residual stress and cracks while machining on EDM using RSM rotatable central composite design..

II. EXPERIMENTAL PROCEDURE

The present study aims to validate the relation between EDM process parameters viz. peak current, pulse on time, voltage and pulse duty factor with the developed residual stress and induced cracks in the machined surface. AISI 4340 was chosen to be the work material while the tool selected was Copper-Tungsten (Cu-W). The RSM rotatable central composite design is used to determine the relation.

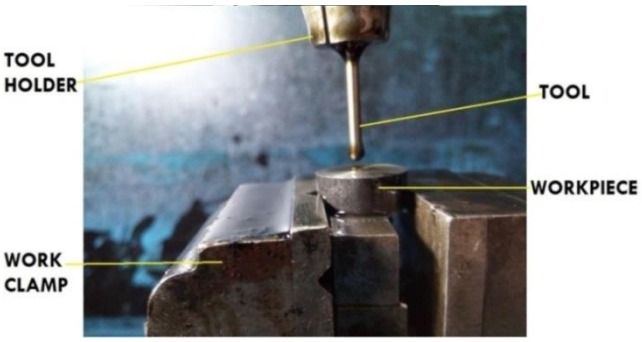


Fig. 1. Arrangement of tool and workpiece on EDM

The experiments were conducted on S-70 ZNC die sinking EDM machine and kerosene was used as the dielectric medium for spark propagation. Fig. 1 shows the arrangement of tool and workpiece on the EDM machine. The machining conditions are described in Table 1 below.

Table – I - Machining conditions

Tool Polarity	Generator	Dielectric	Dielectric Flushing	Flushing Pressure
Negative	3 phase, 380 V 6.5kW	Kerosene	Side flushing with pressure	0.4 MPa Constant

The residual stress developed on the machined surface is measured by means of X-ray diffraction. The XRD was performed on Malvern PANalytical X'Pert[3] Powder Machine.

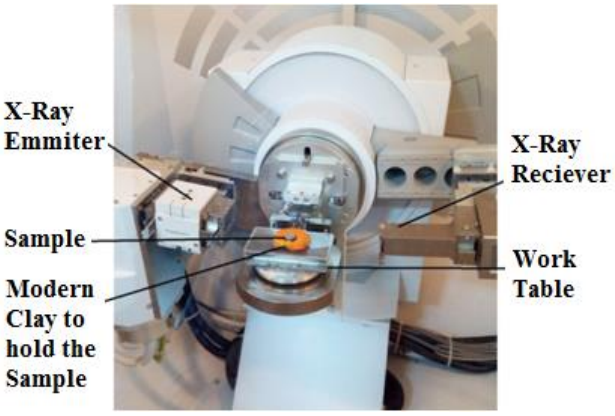


Fig. 2. Setup of Workpiece on Malvern PANalytical XRD Machine

The diffraction of each surface was compared with that of the un-machined surface in order to calculate the strain. Further, after obtaining the value of strain, the level of residual stress generated can be estimated. Scanning electron microscopy (SEM) was employed to characterize the surface and cracks developed on the surface due to machining. Fig. 2 shows the arrangement of the sample on XRD machine for measurement of diffraction.

The strain due to machining is given in the following equation

$$Strain\ (\varepsilon) = \frac{d_{\psi\emptyset} - d_o}{d_0}$$

where d_o is the stress-free lattice spacing and $d_{\psi\emptyset}$ is the stressed lattice spacing.

Further, the residual stress was assessed through the following formulae

$$Residual\ Stress\ (\sigma) = \frac{\varepsilon \times E}{\gamma}$$

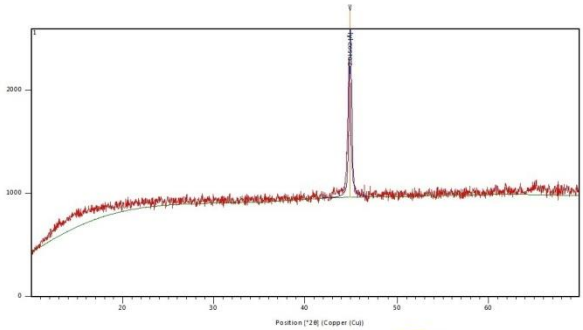
Where E is modulus of elasticity (E = 196 GPa for AISI 4340), γ is the poisons ratio (γ = 0.3 for AISI 4340).

III. EXPERIMENTAL RESULTS

A. Residual Stress

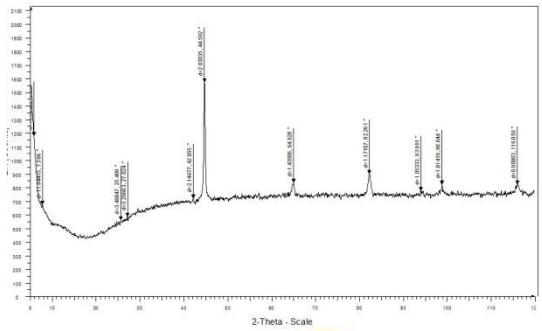
The investigation conducted is to analyze the influence of EDM parameters on residual stress developed in AISI 4340 using copper-tungsten electrode.

The residual stress measured for the present model lies between 4.641 GPa (Tensile) and 0.431 GPa (Tensile). The above Fig. 3a and Fig. 3b shows the d-spacing of machined and un-machined samples respectively. On the basis of graphs obtained, the generated residual stresses of machined surface are studied.



Pos. [°2θ]	Height [cts]	FWHM Left [°2θ]	d-spacing [Å]	Rel. Int. [%]
44.9285	1199.97	0.3120	2.01592	100.00

(a)



Pos. [°2θ]	Height [cts]	d-spacing [Å]	Rel. Int. [%]
44.592	1578	2.03035	100.00

(b)

Fig. 3.a. XRD graphs and details for machined sample1. b. XRD graphs and details for un-machined sample

Table – II – Sequential Model Sum of Square for Residual Stress

Source	Sum of Square	DOF	Mean Square	F-Value	p-value	
Mean vs Total	194.15	1	194.15			
Linear vs Mean	25.01	4	6.25	11.30	<0.0001	
2FI vs Linear	6.55	6	1.09	2.79	0.0389	Suggested
Quadratic vs 2FI	4.20	4	1.05	4.62	0.0113	
Cubic vs Quadratic	3.25	8	0.4067	8.56	0.0032	Aliased
Residual	0.3802	8	0.0475			
Total	233.55	31	7.53			

Table – III – Lack of fit Test for Residual Stress

Source	Sum of Square	DOF	Mean Square	F-value	p-value	
Linear	14.38	20	0.719	543.2	<0.000	
			0	1	1	
2FI	7.83	14	0.5591	422.44	<0.0001	**Suggested**
Quadratic	3.63	10	0.3626	273.96	<0.0001	
Cubic	0.3723	2	0.1861	140.63	<0.0001	Aliased
Pure Error	0.0079	6	0.0013			

From the SMSS and lack of fit test in table II and table III, 2FI model is suggested for residual stress. ANOVA table IV shows the analysis of the results obtained for residual stress of the machined surface. The model F-value of 8.06 implicit that the present model is significant and there is only a 0.01% chance that this F-value could occur due to noise. Thus that present model represents the data within the required 95% confidence interval. From the test, pulse on time (B), voltage (C), pulse on time-voltage (BC), pulse on time-pulse duty factor (BD) and voltage-pulse duty factor (CD) are significant model terms as their p-value less than 0.05.

Table – IV – ANOVA results for Residual Stress

Source	Sum of Squares	Df	Mean Square	F-value	p-value
Model	31.57	10	3.16	8.06	<0.0001
A-Peak Current	1.20	1	1.20	3.07	0.0951
B-Pulse on Time	5.40	1	5.40	13.79	0.0014
C-Voltage	18.39	1	18.39	46.94	<0.0001
D-Pulse duty Factor	0.0200	1	0.0200	0.0509	0.8237
AB	0.2285	1	0.2285	0.5832	0.4540
AC	0.0355	1	0.0355	0.0907	0.7664
AD	0.1159	1	0.1159	0.2959	0.5925
BC	1.81	1	1.81	4.63	0.0438
BD	.51	1	.51	6.40	0.0199
CD	1.85	1	1.85	4.72	0.0421
Residual	7.84	20	0.5918		
Lack of Fit	7.83	14	0.5591	422.44	<0.0001
Pure Error	0.0079	6	0.0013		
Cor Total	39.40	30			

Voltage (p-value < 0.0001) is the most dominating factor for residual stress for the present model followed by pulse on time. Earlier researchers have only focused on thermal aspects of machining. Pulse on time too had influence on residual stress which is in good agreement with earlier researches. Pulse duty factor was least influencing among the selected set of parameters for residual stress.

Fig. 4 shows the main effect for various parameters. It is observed that value of residual stress is almost near its mean value for peak current and pulse duty factor. Thus these two parameters are least influencing for residual stress. With pulse on time, the residual stress initially decreases upto 25µsec and then start to increase at a slow pace. With voltage, the residual stress tends to increase. It is observed that residual stress is majorly dominated by voltage and pulse on time as suggested by ANOVA. Unlike previous researches, peak current does not show much effect on residual stress and shows a decreasing trend for the present model.

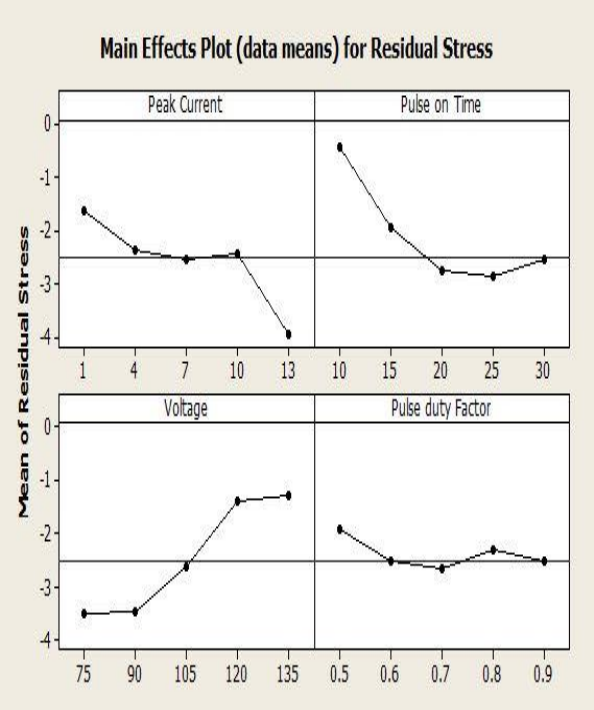


Fig. 4. Main Effect Plot for EDM parameters

The major cause of residual stress in the machined surface is gradual heating during machining and cooling after the spark discontinues. The discharge energy produced by the spark induces heat in the machined surface. On cooling, the stresses are induced on to the machined surface. When the level of this internal stress exceeds the value of tensile strength of the material, the surface will develop cracks.

B. Development of Cracks due to residual stress

During machining on EDM, the spark produces an intense heat (above 10000K) in the plasma channel that affects the microstructure of the base metal.

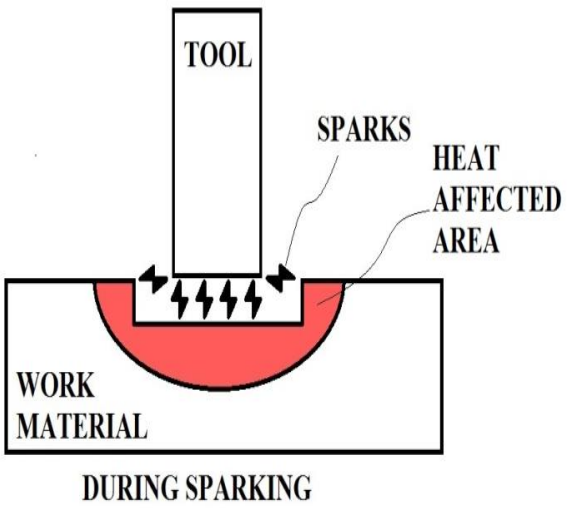


Fig 5. Heat affected area during machining on EDM

The material is removed due to melting and vaporization while the area adjacent to the removed layer is prone to the heat induced and thus affected. During sparking, this area is continuously subjected to the spark heat. Figure 5 illustrates the influence of heat dissipated during sparking in the work.

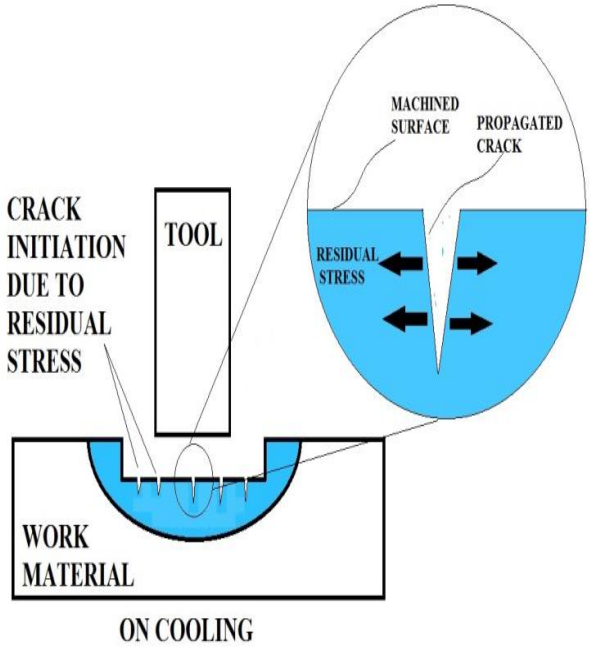


Fig 6. Crack initiation due to residual stress developed during EDM

The above figure 6 shows the post effect of machining on the surface of the EDMed material. As soon as the machining is discontinued and the workpiece is allowed to cool down, the internal residual stresses developed near the machined surface during machining due to thermal gradients causes material shrinkage. During this process, the machined surface develops cracks and the openings are spread over the surface. This will depend on the intensity of residual stresses produced during machining.

C. Micro-Cracks

In order to assess the micro-cracks developed on the EDMed surface, scanning electron microscopy (SEM) was conducted. The major cause of crack development is the development of internal stresses created at the time of machining. The appearance of cracks depends upon the machining condition and EDM parameter. Moreover, the discharge energy of the spark also had great emphasis on crack initiation.

The micro-cracks results from the thermal stresses developed during machining of the workpiece. The uneven temperature distribution results in evolution of residual stress that results in opening of the machined surface. At higher levels of pulse on duration, wider cracks are observed due to high thermal gradients. Crack formation initiates when the developed internal residual stress due to machining exceeds the maximum value of tensile strength of the material.

As it can be seen from the SEM images in figure 7 that when the developed stress is high as in the case of sample 1 (4.541GPa tensile) shown in Fig. 7a, the machined surface experiences cracking. The cracks are dispersed all over the machined surface due to induced thermal gradient.

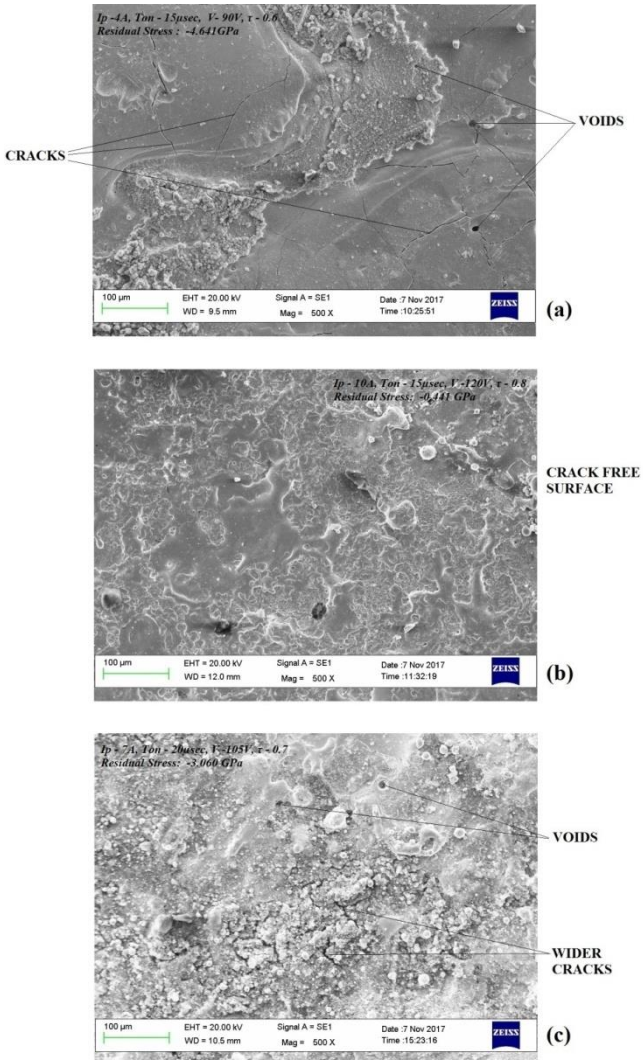


Fig. 7. a. SEM image of machined surface of Sample 1. b. SEM image of machined surface of Sample 14. c. SEM image of machined surface of Sample 31

When the developed residual stress is low as in the case of sample 14 (0.441GPa tensile), the surface is crack free as shown in Fig. 7b. The induced heat in this case is not sufficient to create such level of stress that causes surface cracks. Moreover in Fig. 7c, when the residual stress ranges to 3.060GPa (tensile), wider and concentrated cracks appear on the machined surface.

IV. CONCLUSION

The present experimental modeling for residual stress and surface damage of EDM of AISI 4340 using Cu-W tools for obtaining low stressed and better machined surface has following conclusions:

- The XRD technique revealed the development of residual stress in the machined AISI 4340 samples up to 4.641GPa. The most crucial factors for residual stress are voltage and pulse on time. Peak current, though less effective, but have significance towards the development of residual stress. Pulse duty factor is the insignificant factor for the present model.
- From the analysis, higher value of peak current, pulse on time and pulse duty factor while lower value of voltage is suggested for achieving lower value of residual stress. To develop least level of residual stress in AISI4340 using Cu-W as tool, it is suggested to set $7A \le Ip \le 13A, 20\mu sec \le Ton \le 30\mu sec, 75V \le V \le 105V, 0.6 \le \tau \le 0.9$ for the present model.
- Residual stress in the machined surface results from gradual heating and cooling during machining. Heat is induced in the machined surface by the sparks. On cooling, the stresses are induced on to the machined surface. When the level of this internal stress exceeds the value of tensile strength of the material, the surface will develop cracks.
- The major cause of crack development is the development of internal stresses created at the time of machining. The appearance of cracks depends upon the machining condition and EDM parameter. Moreover, the discharge energy of the spark also has great emphasis on crack initiation.
- The micro-cracks resulted from the thermal stresses developed during machining of the workpiece. The uneven temperature distribution results in evolution of residual stress that results in opening of the machined surface.
- At higher levels of pulse on duration, wider cracks are observed due to high thermal gradients. Crack formation initiates when the developed internal residual stress due to machining exceeds the maximum value of tensile strength of the material.

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REFERENCES

1. Ekmekci, B., Elkoca, O., Koltuk, F., Tekkaya, A.E., Erden, A., 2002. Metallurgical Properties of Electric Discharge Machined Surfaces. 6th Biennial Conference on Engineering Systems Design and Analysis.
2. Ekmekci, B., Elkoca, O., Tekkaya, A.E., Erden, A., 2005. Residual Stress State And Hardness Depth In Electric discharge Machining: De-Ionized Water As Dielectric Liquid. Machine Science and Technology, 39-61, https://doi.org/10.1081/MST-200051244.
3. Gill, A.S., Kumar, S., 2014. Surface Roughness Evaluation for EDM of EN31 with Cu-Cr-Ni Powder Metallurgy Tool. International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 1308-1313, doi.org/10.5281/zenodo.1094209.
4. Guu,Y.H., 2005. AFM surface imaging of AISI D2 tool steel machined by the EDM process. Applied Surface Science, 245–250. doi:10.1016/j.apsusc.2004.08.028.
5. Hascalık, A., Caydas, U., 2007. Electrical discharge machining of titanium alloy (Ti–6Al–4V). Applied Surface Science, 9007-9016, https://doi.org/10.1016/j.apsusc.2007.05.031.
6. Khan, A.A., Ndaliman, M.B., Zain, Z.M., Jamaludin, M.F., Patthi, U., 2012. Surface Modification using Electric Discharge Machining (EDM) with Powder Addition. Applied Mechanics and Materials, 725-733, https://doi.org/10.4028/www.scientific.net/AMM.110-116.725.
7. Kumar, R., Roy, S., Gunjan, P., Sahoo, A., Sarkar, D.D., Das, R.K., 2018.

8. Analysis of MRR and Surface Roughness in Machining Ti-6Al-4V ELI Titanium Alloy Using EDM Process. 2nd International Conference on Materials Manufacturing and Design Engineering Procedia Manufacturing, 358-364, https://doi.org/10.1016/j.promfg.2018.02.052.
9. Mannan, K.T., Krishnaiah, A., Arikatla, S.P., 2012. Surface Characterization of Electric Discharge Machined Surface of High Speed Steel. Advanced Materials Manufacturing & Characterization, 161-168, http://dx.doi.org/10.11127/ijammc.2013.02.028.
10. Mishra, D., Rizvi, S.A.H., Ziaulhaq, M., 2017. Experimental Investigation of EDM of AISI 4340 for Surface Integrity. International Journal of Innovative Research in Science, Engineering and Technology, 133-136.
11. Rao, G.K.M., Satyanarayana, S., Praveen, M., 2008. Influence of Machining Parameters on Electric Discharge Machining of Maraging Steels – An Experimental Investigation. Proceedings of the World Congress on Engineering, 1536-1541.
12. Rizvi, S.A.H., Agarwal, S., 2016. An investigation on surface integrity in EDM process with a copper tungsten electrode. 18th CIRP Conference on Electro Physical and Chemical Machining Procedia CIRP, 612-627, doi: 10.1016/j.procir.2016.02.254.
13. Sidhom, H., Ghanem, F., Amadou, T., Gonzalez, G., Braham, C., 2013. Effect of electro discharge machining (EDM) on the AISI316L SS white layer microstructure and corrosion resistance. International Journal of Advanced Manufacturing Technology, 141-153, doi 10.1007/s00170-012-4156-6.
14. Tebni, W., Boujelbene, M., Bayraktar, E., Salem, S. Ben, 2009. Parametric approach model for determining Electrical Discharge Machining (EDM) conditions: effect of cutting parameters on the surface integrity. The Arabian Journal for Science and Engineering, 725-737, https://doi.org/10.4028/www.scientific.net/AMR.83-86.725.
15. Younis, M.A., Abbas, M.S., Gouda, M.A., Mahmoud, F.H., Abd Allah, S.A., 2015. Effect of electrode material on electrical discharge machining of tool steel surface. Ain Shams Engineering Journal, 977-986, https://doi.org/10.1016/j.asej.2015.02.001.

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