ISSN (e): **2250 – 3005** || Volume, 07 || Issue, 10|| October – 2017 ||
International Journal of Computational Engineering Research (IJCER)

Experimental Investigation on Electric Discharge Machining of High Carbon-High Chromium Tool Steel

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ABSTRACT
Electrical Discharge Machining (EDM) is one of themostcommonlyusedprocessestomachinehardenedmaterials which are difficult to process or machine usingconventionalmethods.Thisresearchworkhasbeendonetodeterminetheoptimizedparametersduring Electrical Discharge Machining (EDM) of AISI D3 diesteel.TheexperimentshavebeendesignedusingResponseSurfaceMethodology(RSM)BoxBehnkendesignandtheoptimizationiscarriedoutusingtheVIKORmethodwhichisaMulti-CriteriaDecisionMaking(MCDM)technique.TheInputparametersconsidered in this study are, Peak Current (Ip), Pulse ontime(Ton),GapVoltage(Vgap),andPulseofftime(Toff). The response variables considered in this studyare Material Removal Rate (MRR), Surface Roughness(SR),Overcut(OC),andParallelism.Anelectrolyticcopper flat was used as the electrode and the AISI D3steel was prepared in the form of round blanks. Further,theimpactoftheinputparametersontheresponsevariablesisalsoanalyzed,andalsothepercentageofcontribution of input parameters on each of the responsevariables is also determined. The optimized combinationof the input parameters obtained are Peak current (Ip) =20A, Pulse on time (Ton) = 30µs, Pulse off time (Toff) =9µs, and Gap voltage (Vgap) = 50V. A Scanning ElectronMicroscope(SEM)analysishasalsobeendoneonsamples that were machined at high, medium, low andthe optimized input parameter values to study the effectofmachiningparameterson themachinedsurface.
Keywords—EDM,RSM,VIKOR,AISID3steel,SEManalysis,Toolsteel.

I. INTRODUCTION

ElectricalDischargeMachining(EDM)isoneofthenon-traditionalmachiningprocesseswhichisusedwhentheworkpiece material is electrically conductive and is of highhardnesswhichmakesitdifficulttomachineusingconventional processes. In this process, material removal isachievedbyelectricalsparksproducedinadielectricmedium because of which the base material vaporizes, andthus the material is removed. This process is also adoptedwhentheshape requiredtothemachineis complex andcannot be done or would be very difficult to be done bytraditional processes. The general setup for an EDM processconsistsofaworkpiecematerialplacedinadielectricmediumandthedesiredfinalshaperequiredintheworkpiece materialisformedonthetoolmaterial.AsElectrical Discharge Machining (EDM) is used mostly inmachining components which are critical a large amount ofresearch is done to determine the optimum parameters andthe effect of these parameters on the properties of the finalproduct.

AllaM.Ubaidet.al.Studiedtheeffectofinputparameterson the responses like material removal rate and electrodewearrateduringthemachiningofAISIM2steelwithcopperandbrasselectrodes.Theoptimumcombinationfor maximizing MRR and minimizing EWR was determined.This study also proved that in recent times EDM has beenunder extensive research which makes it a good reason toconduct this study [1]. Ali Kaylon conducted a study on themachiningof caldie tool steel usinggraphite and copperelectrodes.TheoptimumparametersformaximumMRRandminimumEWR,surfaceroughnessweredetermine dforeachelectrode material. Using ANOVA it was further determinedthatamongalltheinputparametersdischargecurrentwasthemostinfluencingparameter.Itwasfurtherfoundthatgraphiteelectrodesproducedabettersurfacefinishthancopperelectrodes[2].VikasK.Shuklaet.al.PerformedEDMon Nimonic-80A alloy and determined the influence of inputparameters discharge current and pulse on time on

MRR andsurface roughness. It was found that an increase in currentandpulseon-timeincreasedtheMRRwhereasitwastheexact opposite for the pulse-off time. Finally, the optimumparameters to attain high MRR and low surface roughnesswere determined [3].Sudhir Kumar et.al.Performed multi-variable optimization of EDM on AISI420 stainless steelusing a combination of Taguchi and GRA. It was observedthat current had the highest influence on MRR and EWRfollowed by voltage and pulse on time. A comparative studybetween Taguchi and RSM methodology was also carriedout and it was determined that RSM had a better ability toaccuratelypredicttheresults[4].

B. Singaravel et.al. conducted a comparative study ofEDMonAISID2steelbyusingconventionalEDMdielectriclikekeroseneagainstvegetableoilslikeCottonseedoil and Jatropha oil. Optimization was done using a hybridapproach comprising of Taguchi and VIKOR methods. Itwas observed that optimization was achieved with far lesscomputation compared to other multi-objective optimizationmethods[5]. Phan Nguyen Huu et.al.Utilised the MOORAtechnique for multiple variable optimizations of vibration-assisted EDM on SKD61 tool steel. The weights for theresponsevariablesweredeterminedusingAnalyticalHierarchy Process (AHP). This study concluded that lowfrequency assisted vibration helped in improving machiningusingEDM.FurtheroptimizedparametersforhighMRRandlow TWR and surface roughness were determined[6]. T.R.Paulet.al.didacomparativestudyofMOORAandMOORA-PCAmethodsforoptimizationofEDMonInconel800. They considered pulse on time, pulse off, and peakcurrent as input parameters and the response variables wereMRR and surface roughness. It was found that the proposedhybrid method was as effective as the original method[7].NishantK.Singhet.al.predictedtheMRRandsurfaceroughnessusingmathematicalmodelsbasedonANN, ANFIS, and RSM. The material considered in this study wasAISI D3 steel, later a comparative study was done betweenthepredictedvaluesandthevaluesobtainedbyexperimentation;itwasfoundthatthepredictionswerealmost the same and the ANFIS method, in particular, hadmoreaccuratepredictions[8].TiagoCzelusniaket.al.reviewed the types of electrode materials used in EDM overtime.Thisstudyalsoincludedadditivelymanufactured EDMelectrodes,theiradvantages,anddisadvantages[9].LuboslavStraka and SlavomiraHasova studied the impact of inputparametersontheMaterialRemovalRate(MRR)andElectrode Wear Rate (EWR) during the machining of ENX210Cr12 with the copper electrode. The main aim was toattain maximum MRR and minimum EWR. It was observedthat as current and pulse on-time increased MRR increased,also with a constant current and increase pulse on time therewas a reduction in EWR[10]. Mohammad JafarHada et.al.inEDMastheshapeofthetoolisproducedontheworkpiece material, a study was conducted on the effect ofsurface roughness of the tool on the machining performanceand the final surface roughness of the machined workpiece.AISI 1050 was selected as the workpiece and copper wasused as the electrode material. It was found that MRR is lesswhen the tool surface roughness is high and TWR increaseswith an increase in tool surface roughness. However, theinitialsurfaceroughnessofthetoolhasaveryminimaleffectonthefinalsurfaceroughnessofthemachinedsurface[11]. UttamKumarMohantyet.al.usedtheVIKORindexMCDMtechniquetodeterminetheoptimizedparametersformachiningofhighcarbonhighchromiumtoolsteel.ANOVA also was done to determine the influence of inputparametersontheresponsevariables.Itwasfoundthatcurrent hadthe highest impact on the response variableswhereasvoltagewastheleastinfluencingfactor[12].

Vinothkumar and Pradeepkumar did a comparative studyonEDMofAISID2steel usingtheconventionalEDMprocess and the cryogenically cooled EDM process. It wasfound that EWR was less in the cryogenically cooled EDMprocessandthesurfaceroughnessofthefinalworkpiecealsois improved [13]. Muhammetgul et.al.conducted a detailedliteraturereviewoftheVIKORmethodanditsfuzzyadaptations in different fields. It was concluded that VIKOThas its major application in Agriculture, material selection,andmechanicalrelateddisciplines[14].ManivananandPradeepKumarmadeuseofTechniqueforOrderedPreference by Similarity to Ideal Solution (TOPSIS) to findouttheoptimizedvaluesformachiningofAISI304Stainlesssteel. It was found that feed rate had the highest influence onthe quality of the hole machined followed by peak current[15]. ShaileshDewangan et.al.made use of grey-fuzzy logictodeterminetheoptimizedparametersformachiningofAISIP20 tool steel. ANOVA results showed that pulse on timehad the highest influence on surface roughness followed bypeak current. It further showed that the grey-fuzzy techniquereduced the complexity of the traditional GRA method formulti-criteriadecision-making [16].

S. Dewangan et.al. carried out EDM on AISI P20 toolsteeltodeterminetheoptimalparametersandbasedonMCDM technique of TOPSIS determine the robustness ofthedecisionmakers'preference.RSMwasusedtodesigntheexperiments, from the study itwas determinedthat peakcurrentandpulseon-timeinfluencedthewhitelayerthickness,andasthepeakcurrentincreasedthesurfacecrackdensity also increased. It was also found that higher peakcurrent and on time had a negative effect on the amount ofovercut[17]. T. Muthuramalingam and B. Mohan conductedan extensive review on the effect of modeling and influenceofinputprocessparametersontheresponseprocessparameters like material removal rate, Surface roughness,and electrode wear rate in the EDM process. It was foundthatpeakcurrentandpulseontimehadthehighestimpactontheperformanceoftheEDMprocess.Lessattentionhasbeengiven to modifying the electrical process parameters relatedto the pulse characteristics[18]. Md. AshikurRahman Khanet.al.studiedtheeffectofvariousinputparameterslikepulseon time, pulse off time, peak current, gap voltage, and eventhetypeofelectrodematerialonthesurfaceroughnessofthemachinedTi-5Al-2.5Sn.Threeelectrodematerialswereconsideredcopper,coppertungsten,andgraphite;itwasfoundthatatlowdischarge energycopper-tungstenelectrodeproduces the best surface finish whereas graphite electrodeproducestheworstsurfacefinish[19].

L.TangandY.F.Guomadetheuseofgreyrelationanalysis and orthogonal design of experiments to optimizethe machining parameters for EDM of novel S03 stainlesssteel.Themostinfluencingparameterwaspeakcurrentfollowedbypulseontimeandthengapvoltage[20]. MehrdadHosseiniKalajahi et.al.did a comparative studybetween the finite element analysis and experimental studyofEDMonAISIH13toolsteel.Itwasfoundthatanincreasein current, voltage, and duty cycle had a positive effect onthematerialremovalrate.Whereaswhenthepulseon-timeisincreased the Material removal rate increases up to a certainpointandthendecreases[21].S.P.Sivapirakasamet.al.proposedahybridapproachformulti-criteriadecisionmakingforEDMwhichconsistedof TaguchiandfuzzyTOPSIS. A high carbon high chromium tool steel materialwas machined using a copper electrode. It was determinedthattheproposedmethodtooptimizeforgreenmanufacturingwaslesscomplexandoptimizationwasachieved with very little effort [22]. SerafimOpricovic andGwo-HshiungTzeng did a comparative study between twomulti-criteria decision making (MCDM) techniques namelyVIKOR and TOPSIS. In the TOPSIS method, ideal solutionis considered as two points but the method does not considerthe relative distance of the solution from these two pointswhereas in VIKOR the closeness to the ideal condition isconsideredtoranktheoutcomes [23].

II. WORKPIECE AND TOOL PREPARATION

AISI D3 tool steel has been used as the workpiece materialand the tool selected for this work is electrolytic copper. TheAISID3wasprocuredintheformofhotrolledroundbarsofdiameter 25mm and a total length of 1500mm. The roundbarswere cuttoa thicknessof20mmand a totalof54pieceswere made. The electrolytic copper electrode was procuredin the form of flats of thickness 10mm and length 50mm.The workpiece was turned and faced using a manual lathe tothedimensionsof24mmdiameterand20mmthickness.Thecopperelectrodewasmachinedusingaverticalmillingmachine to the dimensions of 9.7 mm thickness and 50 mmlength. The machined workpiece and electrode are presentedinFig1,

Fig1:Workpieceandcopperelectrodebeforemachining

After the workpiece was machined one sample was taken tocheckthehardnessofthematerial.Vickershardnesstestwasused, since this is hardened steel a diamond indenter wasused and a load of 150kg was applied on the sample. TheVickershardnesstestgaveahardnessvalueof54HRCwhichconfirmsthatthiswashardenedAISID3steel.

III. EXPERIMENTATION

ThemachiningwascarriedoutonRatnaparkhiENCseries–EDM5530die-sinkingEDMmachine.Thespecificationofthemachineisgiven inTable1.

Table1:EDMmachinespecification

Rangeofpulseontime	1to99µs
Rangeofpulseofftime	1to9µs
Length	2175mm
Breadth	2150mm
Height	1650mm

The AISI D3 blanks were purchased in an already hardenedstate. Based on literature four input parameters were taken toperform the machining, these parameters are Peak current(I_p), Gap voltage (V_{gap}), Pulse on time (T_{on}), and Pulse offtime (T_{off}). In each parameter, three levels of values wereconsideredasshowninTable2,

Table2:Inputparameters

S.No	Parameters	Levels		
		Low	**Medium**	**High**
1.	Peak current (I_p)(A)	10	20	30
2.	Gap Voltage (V_{gap})(V)	25	50	75
3.	PulseonTime (T_{on})(μs)	30	60	90
4.	PulseoffTime (T_{off})(μs)	3	6	9

The Design of Experiments (DoE) was done using ResponseSurface Methodology (RSM) Box Behnken design. As thereare four factors and three levels a response surface design of27trialswaschosen[25,26].Eachexperimentaltrialisdonetwicetoensurestabilityintheresults.

Table3:DoEdesignmatrix

Maximumworkingcurrent	35A
Maximumworkingvoltage	220V

S.No	I_P (A)	T_{on}(μs)	T_{off}(μs)	V_{gap}(V)
1	20	60	6	50
2	20	60	6	50
3	10	60	6	75
4	10	60	9	50
5	10	30	6	50
6	20	90	6	75
7	20	60	6	50
8	30	30	6	50
9	20	60	3	75
10	30	90	6	50
11	20	30	6	75
12	20	90	9	50
13	20	90	3	50
14	20	30	9	50
15	30	60	9	50
16	30	60	6	25
17	20	60	9	25

18	10	60	6	25
19	10	60	3	50
20	10	90	6	50
21	20	60	3	25
22	20	30	6	25
23	20	60	9	75
24	30	60	6	75
25	30	60	3	50
26	20	90	6	25
27	20	30	3	50

The four responses considered are Material Removal Rate(MRR),Surfaceroughness(Ra),Overcut(OC),andParallelism.TheMRRiscalculatedbythebelowformula,

$$MRR = \frac{\text{Weight before machining} - \text{Weight after machnining}}{\text{Time taken to perform machining}} \quad (g/min)$$

For this purpose, each of the 54 samples is weighed beforemachiningandaftermachiningasshowninFig2.TheSurface roughness is measured using the Mitutoyo SJ-201surfaceroughnesstester.Overcutisnothingbutthedifference between the width of the tool used for machiningandthewidthoftheslotmachinedontheworkpiece.

Overcut (OC) = Width of Slot machined – Width of thecoppertool.

The parallelism of the slot is measured using the MitutoyoCrystaApex-SCoordinateMeasuringMachine(CMM).Thiswas done by creating two reference planes one for the topsurfaceofthesampleandoneplaneforthemachinedsurfaceandthedifferencebetweentheparallelismofthesetwoplanesismeasured.

Fig2:Weighingofsamplesbeforeandaftermachining

Fig3:EDMmachineandmachining

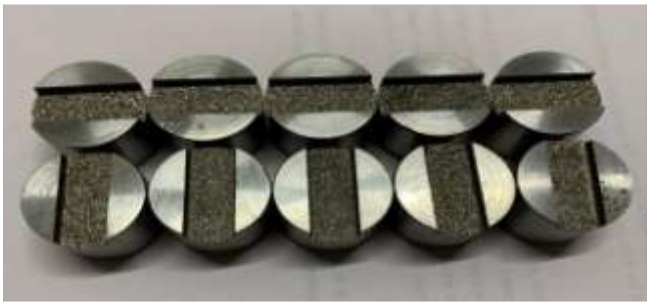

Fig4:Sampleofmachinedworkpieces

IV. RESULTS AND DISCUSSION

After the experiments were done the surface roughness,overcut and parallelism weremeasuredusing the surfaceroughnesstesterandtheCMM.TheMRRwasalsocalculated using the formula given above. The results of theresponsevariablesaregivenintheTable4,

Table4:Responseparameters

S.No	MRR (g/min)	R_a(μ)	Overcut (mm)	Parallelism (mm)
1	0.4373	24.185	0.3745	0.0825
2	0.4642	21.985	0.3885	0.084
3	0.1876	19.145	0.3315	0.1255
4	0.3066	19.595	0.3155	0.083
5	0.3224	14.61	0.268	0.0425
6	0.2889	25.365	0.411	0.1355
7	0.4651	24.555	0.3695	0.0855
8	0.6550	17.87	0.2815	0.2605
9	0.3095	25.02	0.335	0.2375
10	0.5044	27.3	0.5025	0.1225
11	0.3985	16.79	0.2895	0.168
12	0.4508	26.24	0.4125	0.1535
13	0.3696	24.08	0.406	0.132
14	0.7507	17.605	0.295	0.0735
15	0.6893	25.675	0.3925	0.076
16	0.6191	31.74	0.357	0.05
17	0.6376	21.335	0.339	0.1025
18	0.4450	20.1	0.289	0.113
19	0.2503	21.18	0.315	0.075
20	0.8156	21.045	0.342	0.0805
21	0.5661	25.24	0.3315	0.1015

22	0.6942	19.54	0.257	0.048
23	0.3653	24.56	0.384	0.05
24	0.4524	27.605	0.3955	0.07
25	0.5685	28.13	0.382	0.0785
26	0.4924	30.15	0.4055	0.0715
27	0.4344	15.865	0.255	0.069

VIKORmethod:
Thismethodisoneamongthemulti-criteriadecision-makingtechniquesusedtofindtheoptimizedsetofparameters [27]. The steps for this method are given below.**Step1:**Assigntheweightsdenotingtheimportanceoftheresponsevariables.
Step2: Identifybeneficialandnon-beneficialcriteria,i.e.thecriteria for which lower values are desired are called non-beneficial criteria’s and those whose higher value is desiredarecalledbeneficialcriteria.
Step 3: Find best and worst values for beneficial and non-beneficialcriteria.Bestisthemaxvalueforbeneficialcriteria and min value for non-beneficial criteria.The worstisminvalueforbeneficialcriteriaandthemaxvaluefornon-beneficialcriteria.
Step4: Calculateunitymeasure(Si).

$$S_i = \sum_{j=1}^{n} w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)}; \quad i = 1, \ldots, m$$

Step5: Calculateindividualregret(Ri).

$$R_i = \max_j \left[w_j \frac{\left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \right]; \quad i = 1, \ldots, m,\ j = 1, \ldots, n$$

Step 6: Find,S* = min Si ; S^- = max Si ; R* = min Ri ; R^- =maxRi.CalculateQiforeachrowinwhichʊ=0.5.

$Q_i=\upsilon[(S_i-S^*)/(S^--S^*)]+(1-\upsilon)[(R_i-R^*)/(R^--R^*)]$

Step 7: Based on the values of Qi ranking is done the lowestvalueisgiventhefirstrank.
Step8: Tofinalizetheoptimizedvaluetwochecksneedtobedone,
C1=Acceptableadvantage andC2=Acceptablestabilityindecisionmaking.
ForC1thebelowconditionneedstobesatisfied,$Q(A^2)-Q(A^1)\geq DQ$
Where DQ = 1/(j-1), j is given by the number of trials. ForC2 the condition is the trial that ranks first according to theQivalueneedstorankfirsteitheraccordingtothecorrespondingSiorRivalues.
If any of the above conditions fail the C2 check is done forthe lower-ranked values starting from rank 2 and ranks 3trials and is repeated till it satisfies the condition. At thatpoint, the pair of values is taken as the optimized solution.TheranksofthecorrespondingtrialsaregiveninTable5.

Table5:VIKORranking

S.No	Rank(Based onQi)	Rank(Based onRi)	Rank(Based onSi)
1	17	17	16
2	12	13	14
3	27	27	25
4	22	24	17
5	16	22	8
6	26	25	27
7	13	12	15
8	4	4	4
9	25	23	26
10	19	10	24
11	14	19	12
12	20	15	22
13	23	20	23
14	1	1	1

15	6	5	7
16	8	9	11
17	5	6	5
18	11	16	10
19	24	26	21
20	2	2	3
21	7	8	9
22	3	3	2
23	21	21	20
24	18	14	18
25	10	7	13
26	15	11	19
27	9	18	6

SEManalysis:
FurtherinthisstudySEManalysis[24]wasdoneondifferent input parameter samples, the images of which aregiveninFigs5,6,7&8.Machiningdefectssuchasridge-richsurfaces,micro-voids,andmicro-cracksarepartofthesurfacemicrogeometrycharacteristics.Materialmeltedduring EDM generated the ridge-rich surface, which wasthenblastedoutofthesurfacebythedischargepressure.Thesurface,ontheotherhand,quicklyachievedthesolidification temperature when the working fluid-cooled it.Gasbubblesejectedfromthemoltenmaterialduring solidificationareresponsibleforthemicro-voids.Thermalstrains causedmicro-cracks toform. The rapidheating andcoolingrate,aswellasthenon-uniformtemperaturedistribution,werethemaincausesofresidualstressinthemachinedsurface.Furthermore,theEDMsurface'sshapewasinfluencedbythedischargeenergyused.Thesurfacecharacteristicdisplayschanginghillocksandtroughswhenvaryingpulsedcurrentandpulse-ondurationareused.Deepercracksorvoids,aswellasmoreprominentflaws,arevisible in the pulsed current and pulse-on duration variation.Fig5.showstheSEMimagesofthesurfacemachinedusingalowerparametersetting.Theparametersusedarepeakcurrent10amps,pulseonduration30µsandpulseoffduration 3µs and,gapvoltage25v. Itcanbeinferredthat thesurfaceconsistsofshallowvoidsandcrestssparkedduringmachining.

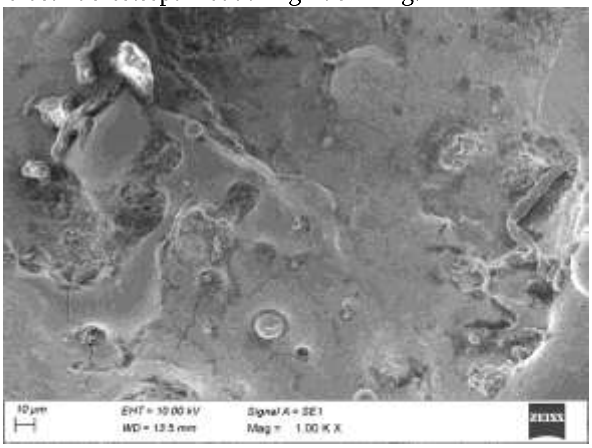

Fig5:SEMimageofmachinedsurfaceatlowparametersetting

Fig 6.shows the SEM images of the surface machined usinga medium parameter setting. The parameters used are peakcurrent20amps,pulseonduration60µsandpulseoffduration 6µs and, gap voltage 50v. The surface consists ofdensevoidsandcrestssparkedduringmachiningwhencompared with the surface obtained using minimum levelprocessparameters.

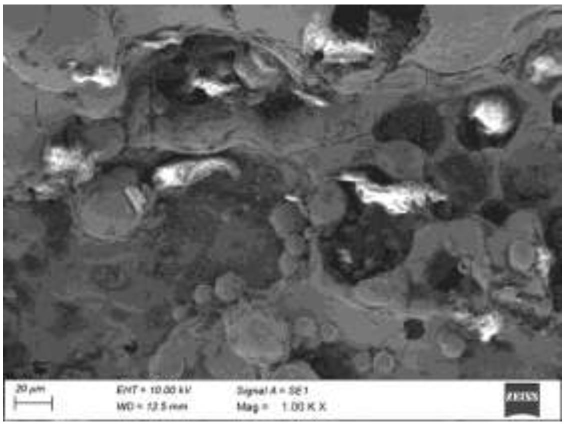

Fig 7.shows the SEM images of the surface machined usinga higher level parameter setting. The parameters used arepeak current 30amps, pulse on duration 90µs and pulse offduration 9µs and, gap voltage 75v. The surface consists ofcoursevoidsandcrestssparkedduringmachining.The topography reveals the presence of grey areas which showsheavyburningofthesurfaceirrespectiveoftherapidcoolingbythedielectricmedium.

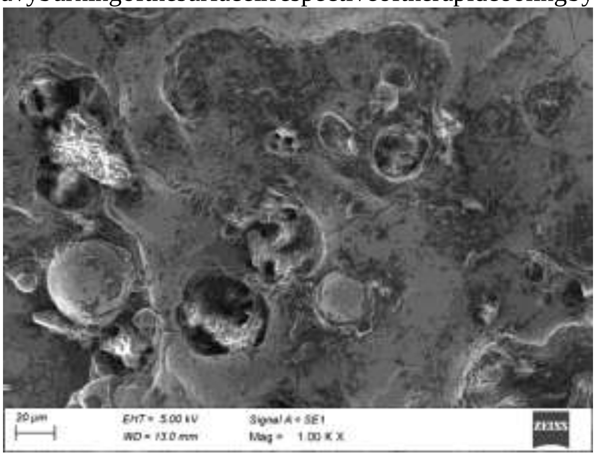

Fig8:SEMimageofmachinedsurfaceathighparametersetting

Fig 8.shows the SEM images of the surface machined usingan optimum parameter setting. The parameters used are peakcurrent20amps,pulseonduration30µsandpulseoffduration 9µs and, gap voltage 50v. The surface consists of afew shallow voids and crests when compared with surfacemachined using other parameter settings. The surface wasfoundtobesmoothwithbettertopography.

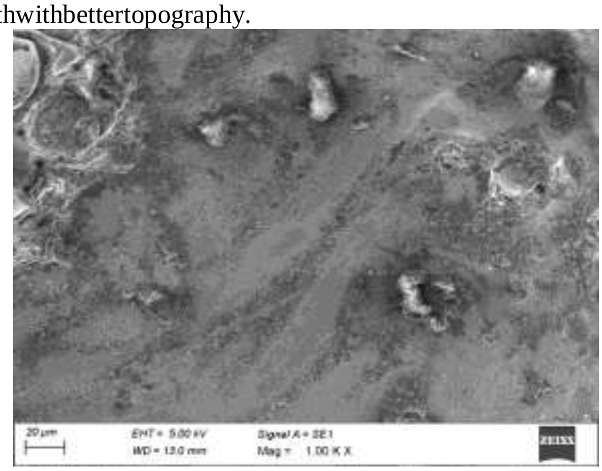

Fig8:SEMimageofmachinedsurfaceatoptimizedparametersetting

Higher pulsed current and longer pulse-on duration cause apoorersurfacefinish.Thisisbecauseagreaterpulsedcurrentand longer pulse-on duration may generate more frequentdielectricfluidcracking,aswellasmorefrequentmeltexpulsion,resultingindeeperandwidercratersonthework piece's surface**.** In comparison to the SEM results, it isevident that excellent surface topography was obtained onthe machined surface using the identified optimal parametersetting.Theeffectofoptimumparametercombinationisalsowell-establishedusingconfirmationtrials.

V. CONCLUSION

BasedontheexperimentsandtheoptimizationdoneusingtheVIKORmethodtheconclusionisthat,theoptimized parameterfoundareI_p=20A,V_{gap}=50V,T_{on}=30µs,andT_{off}=9µs. The SEM images also prove that the surface machinedusingthesesetofparametershadbettersurfacecharacteristics with no cracks and very little recast. It wasalsofoundthattheVIKORmethodgivesanoptimizedsolutionwithveryfewcalculationscomparedtootherMCDM techniques. For the responses, MRR, Overcut, andSurface roughness Peak current, and Pulse on timewerefound to be the most influencing parameters whereas forparallelism Peak current and gap voltage were found to bethemostinfluencingparameters.

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