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Crystalline Characterization and Parametric Optimization of AISI M2 Steel using a Tungsten-Thorium Electrode in EDM process

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Abstract: The work focuses to study the impact of process parameters on the machining performance of electrical discharge machining of AISI M2 steel and improving the machining efficiency by simultaneous optimization of conflicting output responses. Taguchi-based L27 array has been employed for framing the experimental work and to optimize output characteristics individually. Current, pulse on time and spark gap have been selected to understand their impact on material removal rate (MRR) and electrode wear rate (EWR). During XRD analysis, broadening peaks confirmed the changes in mechanical properties due to the homogeneous dispersion of the particles inside the matrix. The reported value of the maximum and minimum value of material removal rate (MRR) through the experimentation was 0.018876 mg/min and 0.001208 mg/min and for electrode wear rate (EWR), it was 0.304761 mg/min and 0.014113 mg/min respectively.

Keywords — EDM, MRR, EWR, AISI M2 Steel, Crystallinity.

I. INTRODUCTION

Machining hard material is a great challenge in the manufacturing sector. A contact point cutting tool with hard coating on the surface provides better machining but leads to the early failure and deterioration of the tool material. For machining, hard work material non-contact type machining processes place a lead role in the manufacturing operations [1]–[4]. Among the non-contact type machining electrical discharge machining process (EDM) plays a unique role in the material removal and generation of complex geometries on the hard material. AISI M2 steel material plays a deterministic role in the development of intricate die and fixtures for different applications. The high-temperature sparks generation during machining leads to the easy removal of material in the case of EDM. In a similar context, Paswan et al. [5] tried the graphene-based nanofluid die-electric medium for the machining of Inconel-718 material under different operating regimes. It was observed that the use of nanofluid in the dielectric significantly reduces the tool wear with improved material outcomes. However, the cost associated with additives-based EDM limits the industrial scalability of the process [5]. On a similar exploration, numerous articles were published on the machining of hard material by the make use of the composite tool. In this process, the processing of composite tooling determines the overall tool wear rate and material removal phenomenon [6], [7]. Cogun et al. [7] prepared the Copper boron carbide (Cu-B_4C) composite tool by the conventional powder metallurgical techniques. It was found that the surface machined with composite tools exhibits higher hardness compared to monolithic tool material. The formation of intermetallic compounds was the main culprit for the higher machined surface hardness [7]. Similar observations were reported by Krishna et al. [8] by the make use of different tooling materials. The machined surface is dependent upon the choice of cutting tool made for cutting purposes [8]–[10]. The vigilant choice of process parameters also affects the outcomes of the machining process [11]. Numerous researchers tried advanced process algorithms for the selection of input conditions for optimized outcomes [12].

The present study aims to study the effect of process conditions on the machining performance of the AISI M2 steel with the help of tungsten thorium electrode material. The choice of hard cutting tool material is based upon the earlier observations made by different researchers in the particular area for machining with EDM. In the present case, the three different levels of input conditions were

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made for the material removal rate and electrode wear rate of the AISI M2 steel. The microstructure, phase transformation studies were made to correlate the metallurgical aspect with the material outcomes.

II. EXPERIMENTAL DETAILS

In the present case, the machining was for the AISI M2 steel with tungsten thorium electrode material. The EDM operation was performed in the die-sinking type EDM machine supplied by Massive Engineering Pvt. Ltd., Model 5030. The photographic representation of the EDM and the machined surface is given in Fig. 3. The commercial-grade EDM oil D30 (specific gravity of 0.763 and freezing point of 940 ^{0}c) was used as dielectric fluid. The side flushing technique was employed with pressure 0.3 kg/cm^2 to extract the debris over the work surface. The tungsten-based alloy is used as a tool material as shown in Fig. 2 (EDX spectrum analysis for chemical composition is also shown in Fig. 2). The tool material is of a cylindrical cross-section of 6 mm diameter and has Brinell hardness (BHN) of 482.29.

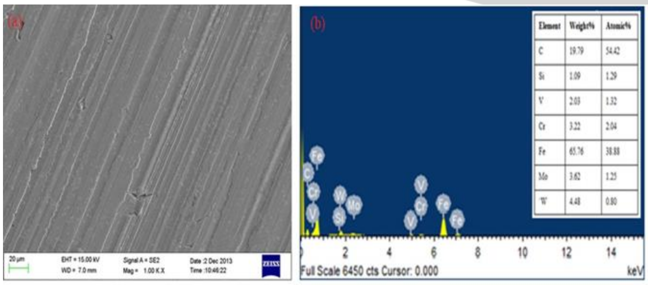

Fig. 1 Surface morphology and EDAX spectrum of the selected workpiece for machining

The workpiece material used in this study is AISI M2 steel of cross-section 50 x 50 mm and a thickness of 6 mm. the surface morphology and EDX spectrum analysis for the workpiece is shown in Fig. 1. Composition are C is weight 19.79%, and atomic 54.42%, Si is weight 1.09% and atomic 1.29%, V is weight 2.03% and atomic 1.32%, Cr is weight is 3.03% and atomic 1.32%, Fe is weight 65.76% and atomic 38.88%, Mo is weight 3.62% and atomic 1.25% and W is weight 4.48% and atomic 0.80% respectively. In the graph of Fig. 1 also percentage composition.

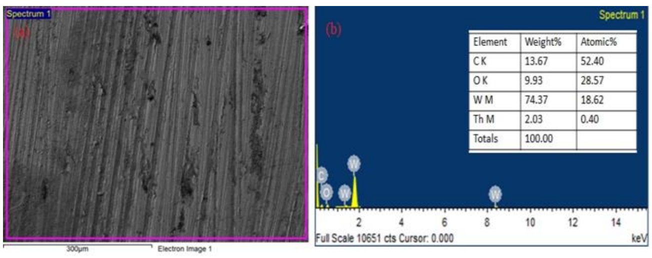

Fig. 2 Surface morphology and EDAX spectrum of the selected EDM tungsten thorium electrode material for machining (The SEM were taken at the tool surface)

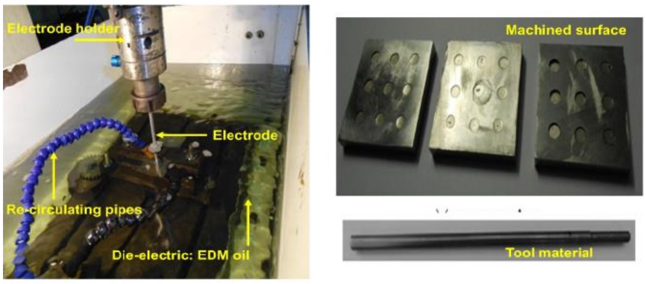

Fig. 3 Schematic representation of machining operation and machined surface with tool material

The electrode was shaped cylindrical with the help of lathe machine processing inbuilt with portable grinder attachment having a diameter of 6 mm. the workpiece was positioned at the desired place and clamped in the collet and its alignment was checked with the help of try square. The depth of cut was automatically adjusted by the servo head attached to EDM with input parameters. The workpieces and electrodes were weighed before and after machining operation by a digital precision scale. MRR and EWR for both workpiece and tool material were calculated for each experiment. Then the experiments were carried out for three variable input process parameters i.e. current (I_p), pulse on time (T_{on}), and spark gap control (Sg), while other input parameters were kept constant for obtaining MRR and EWR (see details in Table 1).

Table 1 Input parameters for experimentation

S.No.	Input Parameter	Parametric Values
1.	Current (I_p)	2, 5, and 7 A
2.	Pulse on time (T_{on})	45, 60, and 90 μs
3.	Spark gap (Sg)	4, 5 and 6
4.	Sparking voltage	50 V
5.	Servo system	electro-hydraulic
6.	Polarity	reverse polarity
7.	Dielectric fluid used	commercial grade EDM oil
8.	Fluid flushing technique	side flushing with pressure (0.3 kg/cm2)

III. TESTING AND CHARACTERIZATION

Surface Topography: Surface topography is the three-dimensional representation of geometric surface irregularities. A surface can be curvy, wavy, rough, or smooth depending on the magnitude and spacing of the peaks and valleys and how the surface is produced. Waviness is the component of texture upon which roughness is superimposed. The surface texture is a key factor affecting the functionality and reliability of components.

Scanning Electron Microscopy (SEM): SEM micrographs of the un-machined and machined surfaces obtained with SEM LEO 435 VP, in the resolution of 4 nm in HV and 6 nm in VP at various magnification ranges from 500 x to 6.00 Kx. Total five numbers of micrographs have been taken for each sample and the lowest surface roughness micrographs have been presented in the results.

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Energy Dispersive X-ray Spectroscopy (EDX): EDX is an investigative technique used for the elemental analysis or chemical characterization of a sample. It relies on the investigation of an interaction of some source of X-ray excitation and a sample. The chemical composition of the tool and work materials were investigated through EDX coupled with SEM.

IV. RESULTS AND DISCUSSIONS

According to the experimental procedure total of 27 sets of experiments are performed and repeated with variation in input parameters. The average values of material removal rate for tool steel are summarized in Table 2. The highest and lowest value of MRR is 0.018876 mg/min. and 0.001208 mg/min, respectively obtained for the experiment 21 and 14 having the input parameters as I_p 7A, T_{on} 45 µs, S_g 6 and I_p 5A, T_{on} 60 µs, S_g 5, accordingly. The highest value of MRR through electrical discharge machining for AISI M2 high-speed tool steel with copper electrode reported earlier was 0.015276 mg/min having the input process parameters as current 7A, pulse on-time 45 µs and spark gap of 5 and the minimum value of MRR was 0.000840 mg/min with the input process parameters as current 5A, pulse on-time 90 µs and spark gap of 6 [13].

Table 2 The Experimental layout using Taguchi Orthogonal Array Design L_{27} (3^3) with the result

S. N.	I_p (A)	T_{on} (µs)	Spark Gap	MRR (mg/min)	EWR (mg/min)
1	2	45	4	0.004484	0.303211
2	2	45	5	0.004680	0.019914
3	2	45	6	0.004684	0.071733
4	2	60	4	0.003712	0.049353
5	2	60	5	0.002844	0.109142
6	2	60	6	0.003200	0.010000
7	2	90	4	0.002220	0.250450
8	2	90	5	0.002120	0.684810
9	2	90	6	0.001900	0.048631
10	5	45	4	0.002148	0.043891
11	5	45	5	0.001672	0.039784
12	5	45	6	0.001224	0.040196
13	5	60	4	0.001264	0.165506
14	5	60	5	0.001000	0.063600
15	5	60	6	0.001276	0.037304
16	5	90	4	0.001208	0.184768
17	5	90	5	0.001136	0.126056
18	5	90	6	0.000876	0.192694
19	7	45	4	0.003956	0.073508
20	7	45	5	0.011152	0.010616
21	7	45	6	0.018876	0.013986
22	7	60	4	0.003792	0.036286
23	7	60	5	0.007884	0.027295
24	7	60	6	0.006088	0.035611
25	7	90	4	0.002092	0.157361
26	7	90	5	0.002880	0.067361
27	7	90	6	0.002820	0.119290

Finally, the maximum and minimum value of material removal rate is significantly improved while machining AISI M2 tool steel with the tungsten-thorium electrode. The 3D surface plots for MRR against input parameters are shown in Fig. 4.

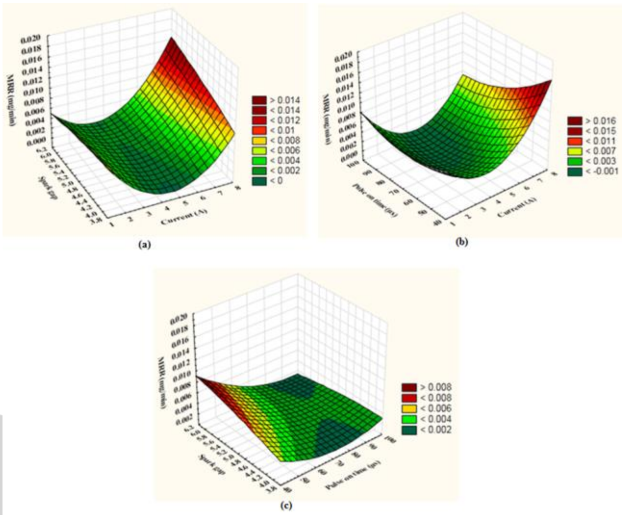

Fig. 4 Response surface graphs of MRR for work material in (a)-(c)

The electrode wear rate has been calculated by the formula given elsewhere [14]. The founded higher and lower values of EWR with tungsten-thorium electrode are 0.684810 and 0.010000 mg/min, obtained for experiments 8 and 6 having the input parameters I_p 2A, T_{on} 90 µs, S_g 4 and I_p 2A, T_{on} 60 µs, S_g 6 respectively which extremely improved values. The three-dimensional surface plot for EWR against different input parameters is depicted in Fig. 5 (a)-(c).

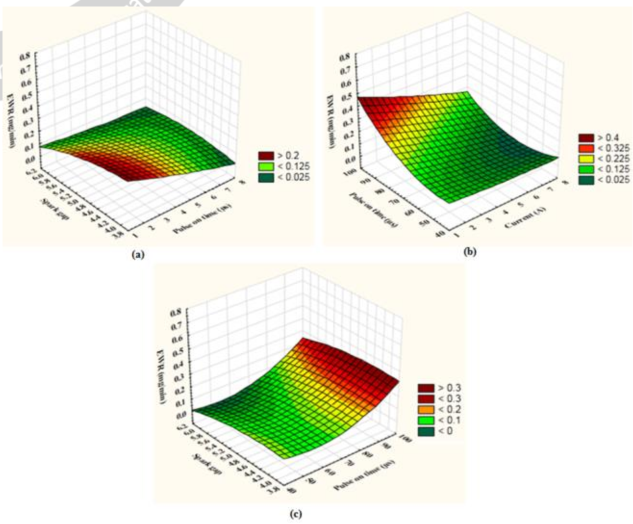

Fig. 5: Response surface graphs of EWR for work material in (a)-(c)

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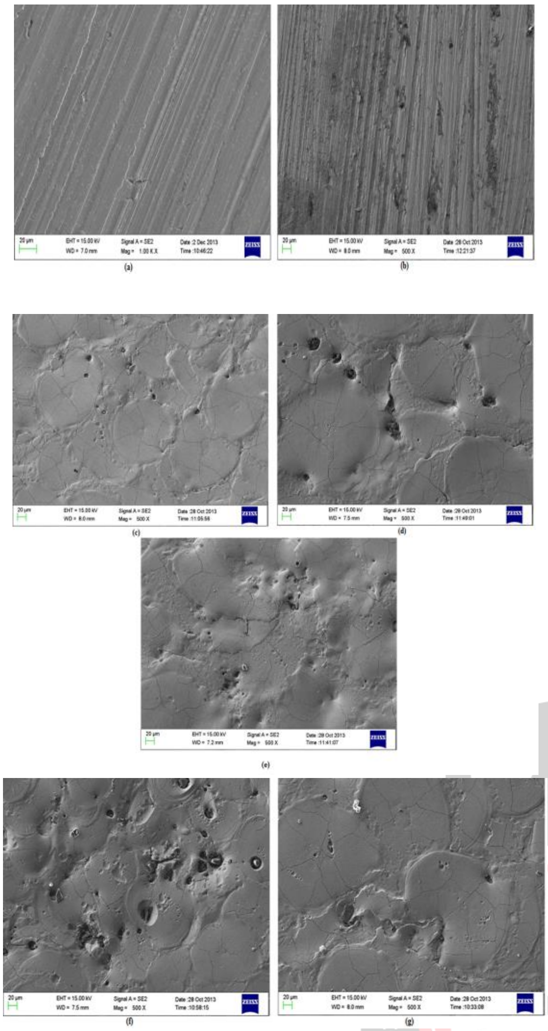

Fig. 6 (a)-(g) SEM micrographs of (a) un-machined workpiece and (b) Tungsten-thorium electrode, surface image before machining, (c) Sample no. 15, (d) Sample no. 22, (e) Sample no. 10 for SR, (f) Sample no. 21 for max. MRR and (g) Sample no. 6 for min. EWR

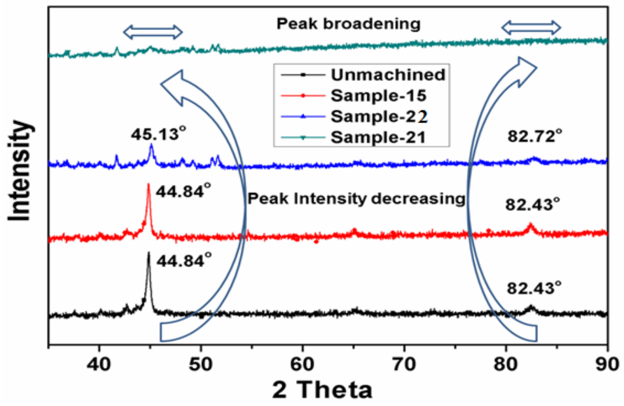

Fig. 7 XRD spectra for un-machined and machined surface

Scanning electron micrographs for the un-machined and machined surface of work material, AISI M2 with different input process parameters, are shown in Fig. 6 (a)-(g). During EDM, processing, high temperature generated by the sparks rapidly vaporizes the dielectric fluid and creates pressure impulses around the tool electrode. The impact pressure and high thermal stresses generated by the discharge produce the craters and micro-cracks in the machining surface. From surface topography micrograph in Fig. 6 (c) for sample no. 10, the finest surface finish of the machined surface among 27 nos. of samples are obtained with process parameter as I_p 5 A, T_{on} 45 µs, and S_g 4 and also found some irregularities in the machined surface, i.e. recasting of debris due to rapid cooling, micro-voids and micro-cracks on the machined surface. The micro-cracks were arisen due to the result of differential thermal gradient on the surface; the value of MRR is 0.001276 mg/min. and the value of EWR is 0.037304 mg/min. The SEM micrograph in Fig. 6 (d) of sample no. 22, shows large valley depth in the surface, more micro-voids, micro-cracks, and some recasting of debris. More heat is developed during the EDM process at a higher current generating high temperature at the work surface followed by rapid cooling; as a result, more cracks were produced on the surface. Also at higher t_{on}, due to higher discharge energy, more micro-voids and micro-cracks are observed and the MRR is obtained at a value of 0.003792 mg/min. and the EWR is obtained at a value of 0.036286 mg/min. Sample no 10, having the process parameter as I_p 5 A, T_{on} 45 µs and S_g 4 and their SEM microscopic structure in Fig. 6 (e) presents fewer micro-voids and fewer micro-cracks as compare to sample no. 22 having the process parameter as I_p 7 A, T_{on} 60 µs and S_g **4.** From the observation, it has been found that for the same current if the pulse on-time is reduced, the micro-cracks would be less. The recast layer is observed on machined surface in nm size and this could be seen from the SEM micrographs that the finest surface finish quality is observed in Fig. 6 (c).

Fig. 7 presents the XRD spectra for both un-machined and machined surfaces. Based on the XRD results it has been concluded that the crystallographic structure of the work surface has changed. In un-machined surface, it has been found that peaks are so sharp and intensity is too high. But as the current is increasing the peaks are broadened so that the crystallographic structure inside the material is changing and it is going to the exfoliation stage which means the machined surface properties are increasing due to the homogeneous dispersion of the particles inside the matrix. The presence of Cr_2O_3 was also found, which rise the hardness, tensile strength, and thermal shock resistance of the HSS after machining. A smaller amount increase in the hardenability and toughness, giving higher final density due to a large capillary force formed in the rearrangement stage of the machining process. Observation from the SEM micrograph in Fig.6 shows that the smaller amount of Si, Mo, Cr, V, and W particles were distributed uniformly in the matrix. These smaller size particles provide the possibility of small particles filling in the voids within the large W grain aggregate (which formed the skeletal structure of the electrode) to reduce the porosity and cracks after machining.

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V. CONCLUSIONS

In this research, the experiments have been planned and conducted to investigate the effects of cutting parameters on material removal rate, electrode wear rate, in the EDM process. Following conclusions could be drawn from this investigation:

- The finest surface finish (sample no. 10) of the machined surface among 27 nos. of samples are obtained with process parameter as Ip 5 A, Ton 45 µs, and Sg 4 and also found some irregularities in the machined surface, i.e. recasting of debris due to rapid cooling, micro-voids and micro-cracks on the machined surface.
- The maximum and minimum value of MRR is obtained for sample no. 21 and sample no. 14 having the input parameters as current 7 A, pulse on-time 45 µs and spark gap of 6 and current 5 A, pulse on-time 60 µs and spark gap of 5 respectively.
- The minimum and maximum value of EWR is obtained for sample no. 6 and sample no. 8 having the input parameters as current 2 A, pulse on-time 60 µs and spark gap of 6 and current 2 A, pulse on-time 90 µs and spark gap of 5 respectively.
- The predicted values match the experimental values reasonably well with MRR and EWR. The current and pulse on time have arithmetical significance on both MRR and EWR the higher current offers more MRR and lower EWR.
- In the XRD study, it has been observed that the peak has been broadened with the increasing current which gives better material properties due to the homogeneous dispersion of the particles inside the matrix.
- The recast layer is observed on machined surface in nm size and this could be seen from the SEM micrographs that the finest surface finish quality is observed.

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