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Investigation of micro-hardness of H11 die steel using composite material electrodes in EDM

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Electrical Discharge Machining (EDM), a non-traditional material removal process has been well recognized for its ability for precision machining of electrically conducting hard materials. Repetitive heating and cooling of the workpiece surface during the machining make the surface hard. During this process, the transfer of material into workpiece surface due to diffusion of material from the tool electrodes results in the desire surface modifications. This paper investigates the effect of electric discharge machining on H11 die-steel materials with composite material electrodes fabricated by stir casting as well as powder metallurgy process. Copper (85% by weight) has been used as matrix material with tungsten and carbon nanotubes (10%-5% by weight). The performance of fabricated composite electrodes has also been compared with conventional copper electrode. Microhardness achieved has been found to be best when H11 die-steel surface is machined with composite electrodes fabricated by powder metallurgy process. Also, the microhardness has been enhanced by 19.57% with optimal input parameters. Results show that optimum microhardness has been observed at high peak current value when surface is machined with copper conventional electrode while pulse on time has been found to the major contributor when surface is machined by composite material electrode. XRD analysis indicates the formation of tungsten-carbide, iron-carbide, chromium- nickel and copper on the machined surface of the workpiece.

Keywords: Electrical Discharge Machining (EDM), Microhardness, Stir casting, Powder metallurgy, Composite material electrode, H11 die-steel

1 Introduction

The advancement of the new and improved materials presents a challenge to the industry for machining and making complex geometries. Super alloys, composites, and ceramics are commonly known as advanced materials. Machining these advanced hard to machine materials require high precision and excellent surface finish. Due to their hardness, there machining cost is very high when machined with the conventional process. To avoid the cost and save the tool materials, a different class of machining was developed known as advanced machining process. In these machining techniques, no mechanical contact occurs between the workpiece and tool electrode.

EDM is one of the advanced machining processes. It is a non-traditional or non-conventional machining process that machines very hard materials, which otherwise are very difficult or impossible to be machined by traditional method. It is an electro-thermal process that uses the current for eroding the metal from its surface. A small spark occurs in the micro gap intervals between the tool and workpiece which results in local melting and vaporization and unwanted material is removed from the workpiece. Modern day EDMs are capable of machining very complex geometries precisely.

In Electric discharge machining, material of electrode plays a very important role for the desired machining of the workpiece. It is evident from the literature that use of composite material electrodes resulted in improved surface characteristics of the machined workpiece. There are different methods to prepare composite material electrode with different alloying elements. Many researchers have attempted surface alloying from electrodes produced by powder metallurgy process. However, no researcher has yet attempted surface alloying of EDM electrodes made by stir casting process. Stir casting process is useful due to its low cost, simplicity of instrumentation and high production rate and continuous matrix media. In this process, the matrix phase is melted and stirred

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continuously and during this stirring, the reinforcing material is added and then poured into the mould to get the desired shape composite.

Also, Carbon nanotubes have very good mechanical and electrical properties and are composed of the discrete molecular structures linked by the carbon-carbon bonds. The carbon- carbon bond in graphite is one of the strongest structures in nature. But there is hardly any research available comprising the use of carbon nanotube mixed with Aluminium/ Copper/Graphite/Tungsten composite electrode for machining of workpiece on EDM.

In 1943, it was noticed for the first time that when a high gap voltage electric current is passed between two electrodes separated by a short gap, then a spark leads to small amounts of erosion on the electrodes[1]. They also found out that when a dielectric medium is used then the sparking can be controlled to a great extent. Their observations further lead to the development of the electrical discharge machining. The output parameters are highly affected by the dielectric medium used. Soni *et al.*[2] studied the performance of the EDM process and tool wear using the copper as a tool and the die-steel as the workpiece. It was observed that the surface of the workpiece was modified due to migration of the elements from the tool electrodes. It was due to the interaction of the main electrical parameters such as pulse energy, pulse width, discharge current and polarity.

Pellicer *et al.*[3] presented the influence of the important input parameters. A set of designated experiments with input parameters like peak current, open gap voltage and pulse on time were carried out on H13 steel. Statistical methods were used for MRR and SR analysis. Results helped to choose the EDM process depending upon the product selected. Llanes *et al.*[4] studied and evaluated the mechanical behavior of EDM, w.r.t. implementation of the linear elastic fracture mechanics concept, Effectiveness of the thermal annealing for fatigue strength, EDM influence on fatigue limit and post-machining actions for the mitigating strength.

Sidhom *et al.*[5] studied that localized corrosion resistance of austenite stainless steels. Experimental techniques such as SEM, XRD and roughness measurement, revealed micro-structural changes. It was also revealed through SEM characterization that pitting resistance of austenite stainless steel was weakened. Goyal[6] investigated that the high MRR is observed in copper manganese composite electrode when copper to manganese weight ratio is 70:30 rather than using Cu-Mn weight ratio as 80:20. Balasubramanian et.al.[7] used EN8 and D3 steels in their research work and two types of electrodes i.e. cast copper and sintered copper were used for the machining. They used research surface methodology technique for the analysis of the parameters and used ANOVA for checking out the significance of parameters. They concluded that MRR is high and TWR is low for cast copper electrode and surface roughness was comparatively less for sintered copper electrode in case of EN8 steel and similar results were observed for D3 steel.

Vikas *et al.*[8] studied the changes in the surface roughness of EN 41 steel by changing the values of input parameters in EDM. Grey Taguchi method was used for optimization of the output parameters. Input parameters were arranged for the experiments in L27 orthogonal array for the experiments. RSM (Response Surface Methodology) was used for the study of results and observed that surface roughness is mostly influenced by input current.

Muthuramalingam *et al.*[9] discussed the importance of electric process parameters for efficient EDM process. It was suggested that the optimal combination of the input parameters such as pulse on time and peak current play a more important role during EDM. The electrical conductivity of electrode is responsible for making EDM more efficient. Shao *et al.*[10] presented an electro-thermal model of micro EDM to show the crater formation. The realistic boundary and physical conditions were used for solving the problem by FEM. Muthuramalingam *et al.*[11] used the modeling of process parameters and studied the influence of process parameters on the efficacy of the machining process. Marashi *et al.*[12] reviewed different types of techniques for the betterment of EDM capabilities. It was observed that surface morphology and surface roughness characteristics of AISI D2 steel surface were enhanced by adding titanium nano powder to the dielectric medium. J.W. Murray *et al.*[13] studied the role of debris between two electrodes silicon and titanium carbide with the help of imaging through scanning electron microscopy and transmission electron microscopy. This paper is useful for determining the prediction and control of discharge gap size.

Selvarajan *et al.*[14] carried out experimental work on Si3N4-TiN ceramics by using composite copper electrodes on EDM. They used L25 orthogonal array for designing experiment while taking pulse on time, dielectric pressure, current, pulse off time and gap voltage as the input parameter. ANOVA wasused and it was observed that current, gap voltage and pulse on time play a key role in machining. K K Saxena *et al.*[15] used Taguchi's L9 method on hardest ceramics SiC and improvement in machined surface was observed when characterized by scanning electron microscopy, white light interferometry, energy dispersive x-ray spectroscopy, atomic force microscopy and X-ray diffraction.

C. Prakash *et al.*[16] observed a significant decrease in surface crack density on the machined surface with 4 g/l Si powder concentration in powder mixed EDM. The machining performance was also enhanced. C.P. Mohanty *et al.*[17] compared the efficiency of brass, copper and graphite electrodes by machining Inconel 718 super alloy through L27 orthogonal array with the different parameters on performance measures. They used quantum behaved particle swarm optimization algorithms for comparing the best levels of input parameters.

W. D. Wong-Angel *et al.*[18] used powder metallurgy to investigate the mechanical properties of alloys. Images by SEM revealed that alloy with the copper was pores free and had more density whereas alloy without copper was not that dense and had pores in it. Experiments showed that during sintering process copper forms liquid which fills the voids between other metals. Hence there are less pores and more density.

H. Guo *et al.*[19] studied the set of samples where imaging was performed with a scanning electron microscope to examine the microstructures produced. The effect of composite materials including nanocomosites has also been explored by the researchers[20-24]. Varol *et al.*[25] studied copper based nano composites using nano-graphite, graphene nano-sheets and carbon nano-tubes that were created by using flake powder metallurgy technique. The chief objective of using separate reinforcement contents was to access their distinct microstructure, density, electrical conductivity and hardness of copper based nano-composite. The results in this study showed that the particle size of the copper based nano-composite powders reinforced with 5% CNT nano-composites are 97.8, 94.9, 49.5 mm respectively and the lowest density value is obtained to be 6.73 g/cm^3. The highest density values were obtained to be 8.78 g/cm^3 for sintered Cu- 0.5% nano-graphite. For all the nano composite groups, increasing the reinforcement content from 0.5% to 5% resulted in decrease in hardness values. Good surface alloying having thin recast layer was achieved using multi walled carbon nano tubes in EDM[26,27].

2 Materials and Methods

The work materials chosen for this experimental work is H11 hot die-steel as this is widely used die-steel material. The chemical composition of the die-steel material H11 is given in Table 1 below:

The die-steel material workpiece has been hardened before experimentation. FESEM and XRD tests have been performed for the workpiece surfaces before the experimentations.

Clear grain boundaries are visible in the original microstructure of the workpiece. All fabricated composite material tool electrodes as well as conventional copper electrodes have been characterized using WDXRF tests showing graphs of intensity counts vs energy, at SAIF, Panjab University Chandigarh.

The characteristic peaks are the most important feature in a WDXRF spectrum. The intensity counts for an element's characteristic peaks show the chemical concentration of that element. The FESEM results are shown in the Fig. 1 for H11 die-steel.

Table 1 — Chemical composition of the die-steel material H-11

Elements	Material Content (%)
Carbon	0.33-043
Manganese	0.20-0.50
Silicon	0.80-1.20
Chromium	4.75-5.50
Nickel	0.3
Molybdenum	1.10-1.60
Vanadium	0.30-0.60
Copper	0.25
Phosphorus	0.03
Sulphur	0.03
Iron	rest

Fig. 1 — FESEM image of H-11die-steel workpiece.

The XRD test for the H11 die-steel workpiece has been performed and is shown in Fig. 2.

The experiments have been conducted using L18 orthogonal array. This orthogonal array consists of four input parameters with two levels for one input parameter and three levels for other three input parameters as described in Table 2. After completing the experiments, the response variable as microhardness (MH) has been studied. Vickers Hardness tester at UIET, Panjab University has been used to measure the hardness value in HV. The microhardness tester was used to measure the hardness value in HV.

The parameters were then optimized using the ANOVA technique based on the Taguchi method. The composite tool electrodes are manufactured by powder metallurgy process and stir casting process using copper powder having tungsten and carbon nanotubes as alloying elements. The following compositions (wt %) of powder metallurgy electrodes and stir casted electrodes have been fabricated as shown in Table 3.

Electrodes of different composition as mentioned in Table 3 were fabricated using powder metallurgy process and stir casting methods. Both fabricated composite material tool electrodes as well as conventional copper electrodes have been characterized using WDXRF tests showing graphs of intensity counts vs energy. As evident from the WDXRF test of fabricated Cu-W-CNT electrode that copper and tungsten intensities are more in case of electrode fabricated by powder metallurgy as compared to the electrode fabricated by stir casting. This may be due to higher oxidation effect during the stir casting process. The detailed composition and intensity graphs are shown in Figs 3 and 4 for the Cu-W-CNT electrode fabricated by powder metallurgy and stir casting processes respectively.

3 Results and Discussion

3.1 Microhardness Optimization

Composite material electrodes fabricated by stir casting and powder metallurgy processes have been used for the machining of H11 die-steel workpieces.

Table 2 — Machining parameters and their levels

Factors	Units	Level 1	Level 2	Level 3
Fabrication Process		Stir Casting	Powder Metallurgy	-
Peak Current	(Amp)	6	8	10
Pulse on time	(µs)	50	100	150
Voltage	(V)	30	40	50

Table 3 — Electrodes of different composition (wt %) to be used for EDM

Fabrication Process	Composition (wt%)		
	Cu	W	CNT
Powder metallurgy	85	10	5
Stir casting	85	10	5
Conventional Copper electrode			
Extruded Cu Electrode	100	0	0

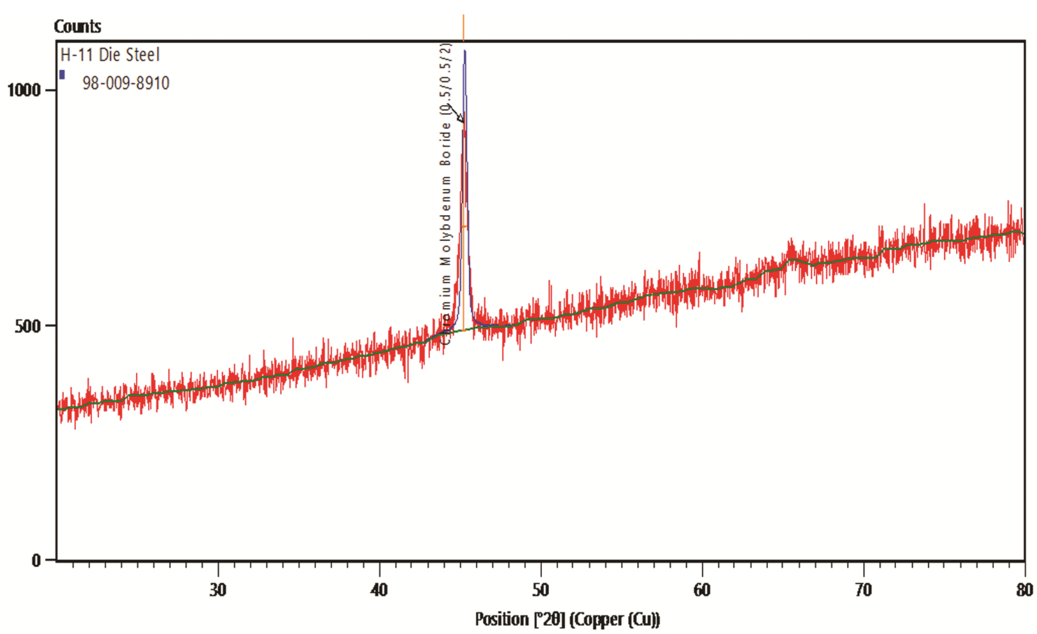

Fig. 2 — XRD results for H11 die-steel workpiece.

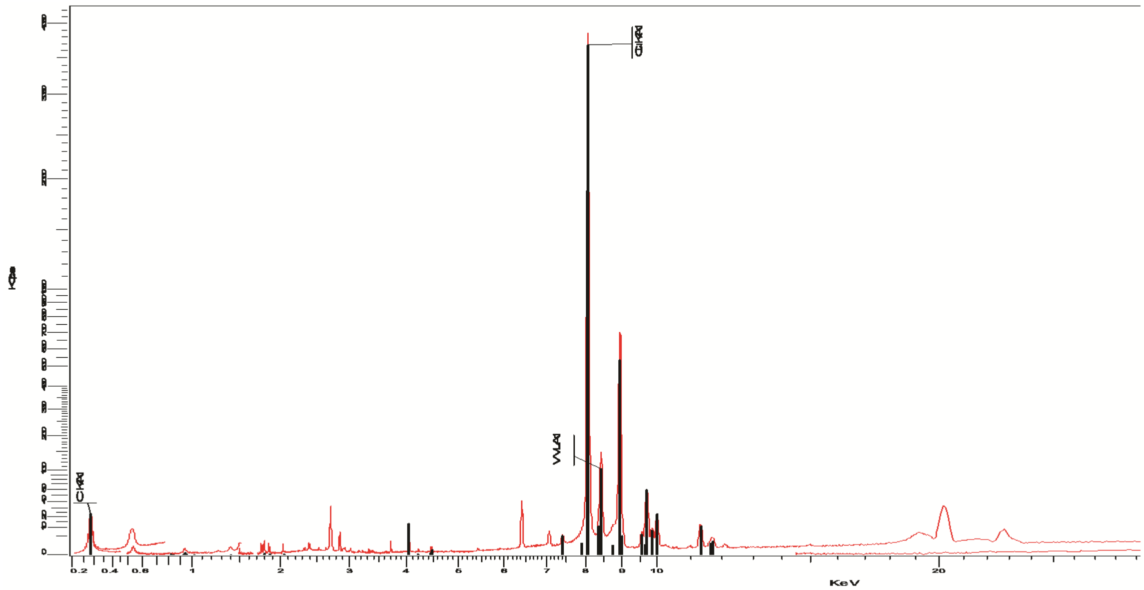

Fig. 3 — WDXRF test of Cu-W-CNT (wt%: 85 - 10 - 05) tool fabricated by Powder Metallurgy process.

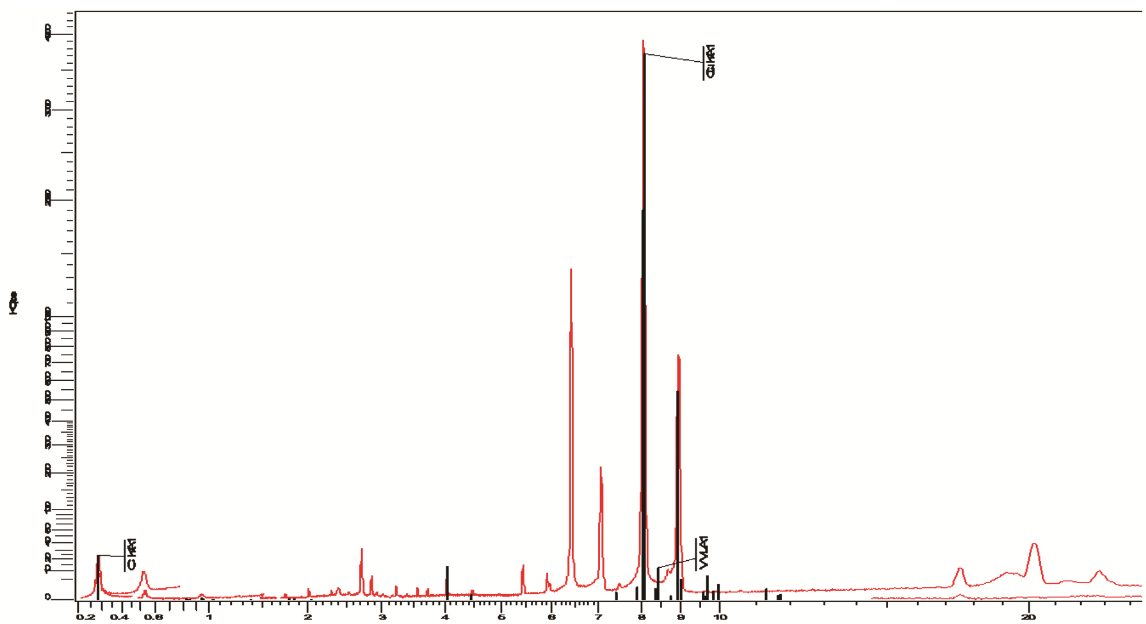

Fig. 4 — WDXRF test of Cu-W-CNT (wt %: 85 - 10 - 05) tool fabricated by Stir casting process.

The set of eighteen experiments have been conducted using L18 orthogonal array. Depth for each machining cut was fixed as 1.5 mm. L9 orthogonal array was used to compare the performance of fabricated composite material electrodes with conventional Cu electrode. For calculating S/N ratios, the "higher the better" criteria has been used as given in equation 1. Therefore, higher values of microhardness are considered to be optimal.

$$S/N = -10*\log(\Sigma(1/Y^2)/n) \quad \dots (1)$$

L18 orthogonal array has been selected to conduct the experiments as shown in Table 4.

The observed values of microhardness after machining H11 die-steel workpiece with Cu-W- CNT electrodes fabricated by powder metallurgy and stir casting process alongwith the corresponding calculated S/N ratios are given in Table 5.

From this data, the average values by factor levels of microhardness and the corresponding S/N ratios for the two/three levels of input process parameters have been calculated and are given in Table 6.

The effects of input process parameters on performance output are shown in Fig. 5(a - d).

It can be observed from the factor effect plots that the electrode fabricated with powder metallurgy process provides better hardness to machined surface as compared to the electrode fabricated with stir casting process. The movement of tungsten and carbon ions in the workpiece surface during machining increases the microhardness of the surface.

The microhardness of the machined surface first increases and then decreases with the increase in peak current. Also, microhardness is best achieved for third level of pulse on time and third level of voltage. It can be seen that the second level of electrode fabrication process (A2), second level of peak current (B2), third level of pulse on time (C3) and the third level of voltage (D3) give the highest values of MH. Hence, the sequence of input process parameters for optimum microhardness is A2, B2, C3, D3. After putting the corresponding values of means ηopt comes out to be 55.922 and after putting the corresponding values of ηopt, yopt has been calculated as 625.336 HV.

Since the obtained optimum input parameters combination is not present in the orthogonal array, therefore three confirmation experiments corresponding to this optimal sequence were performed. The average value of microhardness achieved corresponding to this optimal sequence of process parameters was 626.264 HV which is very near to the optimum value given by Taguchi analysis.

To obtain percentage contribution of the input factors and their significance, ANOVA of the S/N data was performed. It is presented in Table 7, which shows that all the four factors are significant for the response characteristic of microhardness. Pulse on time is found to be the major contributor 43.589% followed by Voltage at 17.714%.

3.2 EDM of H11 die-steel workpiece with conventional copper electrode

The observed values of microhardness after machining H11 die-steel workpiece with Conventional Copper electrode and the corresponding S/N ratios calculated are given in Table 8. From this data, the average values by factor levels of microhardness and the corresponding S/N ratios for the three levels of input process parameters have been calculated and are given in Table 9.

The effects of input process parameters on performance output are shown in Fig. 6 (a-c). It can be observed from the factor effect plots that

Table 4 — L_{18} orthogonal array design

Trial	A Method	B Current (Amp)	C Pulse on time (μs)	D Voltage (V)
1	Stir	6	50	30
2	Stir	6	100	40
3	Stir	6	150	50
4	Stir	8	50	30
5	Stir	8	100	40
6	Stir	8	150	50
7	Stir	10	50	40
8	Stir	10	100	50
9	Stir	10	150	30
10	PM	6	50	50
11	PM	6	100	30
12	PM	6	150	40
13	PM	8	50	40
14	PM	8	100	50
15	PM	8	150	30
16	PM	10	50	50
17	PM	10	100	30
18	PM	10	150	40

Table 5 — Observed microhardness (HV) and calculated S/N ratios (dB) of H11 die- steel surface machined with Cu-W-CNT electrode

Expt. No.	Microhardness (HV) R1	R2	R3	S/N Ratio (dB)
1	409	487	523	53.357
2	487	430	468	53.252
3	599	557	519	54.889
4	564	467	503	54.097
5	479	477	555	53.979
6	522	588	598	55.059
7	451	455	465	53.196
8	558	486	483	54.081
9	510	544	555	54.572
10	525	505	510	54.207
11	510	478	557	54.190
12	506	553	533	54.477
13	512	508	497	54.075
14	582	594	598	55.437
15	637	640	550	55.628
16	563	478	534	54.347
17	539	487	519	54.215
18	597	565	520	54.933
Total	9550	9300	9489	977.992
Overall mean of MH = 524.798				Mean, m= 54.333

R1, R2 and R3 represent the readings of three repetitions.

microhardness of the machined surface first decreases and then increases with increase in peak current. Also, microhardness is best achieved for third level of pulse on time and first level of voltage.

It can be observed that the third level of peak current (B3), third level of pulse on time (C3) and the first level of voltage (D1) give the highest values of MH. Hence, the sequence of input process parameters for optimum microhardness is B3, C3, D1.

After putting the corresponding values of means ηopt comes out to be 55.602 and after putting the corresponding values of ηopt, yopt has been calculated as 602.734 HV. Since the obtained optimum input parameters combination is not present in the orthogonal array, therefore three confirmation experiments corresponding to this optimal sequence were performed. The average value of microhardness achieved corresponding to this optimal sequence of process parameters was 603.264 HV which is very near to the optimum value given by Taguchi analysis.

To obtain percentage contribution of the three factors and their significance, ANOVA of the S/N data was performed. It is presented in Table 10, which

Table 6 — Average values by factor levels of Microhardness when surface machined with Cu-W-CNT electrode

Para-meters	Fabrica-tion Process (Stir /PM)		Peak Current (Ampere)		Pulse on time (µs)		Voltage (V)	
Levels	Raw Data	S/N data	Raw Data	S/N data	Raw Data	S/N data	Raw Data	S/N data
L1	508.870	54.054	508.714	54.062	497.647	53.880	526.697	54.343
L2	540.725	54.612	548.411	54.712	516.073	54.192	503.222	53.985
L3			517.268	54.224	560.673	54.926	544.474	54.670

Table 7 — ANOVA table of S/N data for Microhardness (95% confidence level)

	DOF	Sum (sq.)	Ve	F (Cal)	F (Tab)	% P	Remarks
Fabrication Process	1	1.404	1.404	47.617	4.965	17.673	SF
Current	2	1.375	0.688	23.320	4.103	17.311	SF
Pulse on time	2	3.462	1.731	58.720	4.103	43.589	SF
Voltage	2	1.407	0.704	23.863	4.103	17.714	SF
Error	10	0.295	0.029			3.712	
Total	17	7.943					

DOF : Degree of freedom, S/N : Signal to Noise, SF:Significance

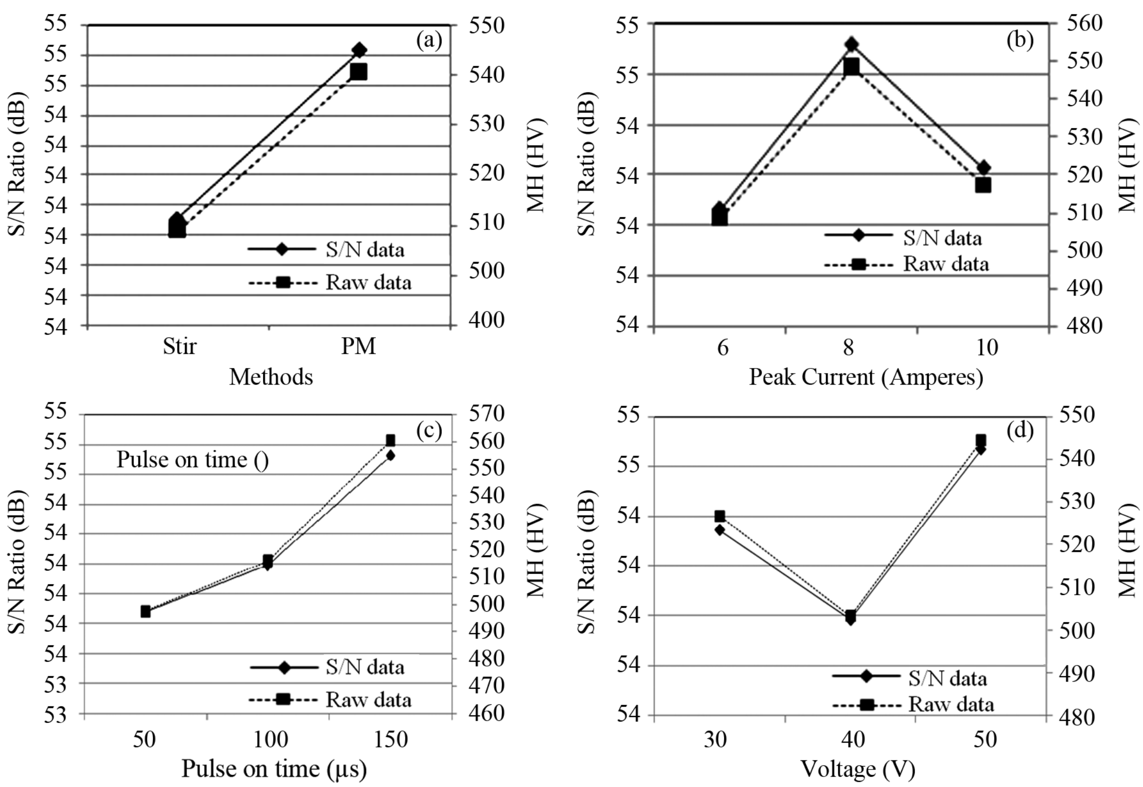

Fig. 5 — Effect on microhardness due to (a) electrode fabrication processes, (b) peak current, (c) pulse on time, and (d) voltage.

Table 8 — Observed microhardness (HV) and calculated S/N ratios (dB) of machined workpiece with conventional copper electrode

Expt. No.	Microhardness(HV) R1	R2	R3	S/N Ratio (dB)
1	558	552	571	54.967
2	537	558	603	55.029
3	583	553	578	55.130
4	536	506	589	54.654
5	522	593	554	54.868
6	550	552	573	54.932
7	555	580	575	55.116
8	610	597	608	55.629
9	604	610	578	55.517
Total	5055	5100	5229	495.844
Overall mean of MH = 569.784				Mean, m= 55.094

R1, R2 and R3 represent the readings of three repetitions.

Table 9 — Average values by factor levels for Microhardness when surface machined with conventional copper electrode

Para-meters	Peak Current (Ampere)		Pulse on time (μs)		Voltage (V)	
Levels	Raw Data	S/N data	Raw Data	S/N data	Raw Data	S/N data
L1	565. 944	55. 042	558. 091	54. 913	574. 433	55. 176
L2	552. 677	54. 818	575. 642	55. 175	569. 027	55. 067
L3	590. 732	55. 421	575. 619	55. 193	565. 892	55. 038

shows that two factors are significant for the response characteristic of microhardness. Peak Current is found to be the major contributor 73.463% followed by Pulse on time at 19.539 %.

It can be observed from Table 10 that peak current is the major contributor when the H11 workpiece surface has been machined with conventional Cu electrode. This is due to the fact that increase in microhardness here is due to the quenching effect only. While Pulse on time has been found to be the major contributor when H11 surface has been machined with composite Cu-W-CNT electrode which is due to the surface alloying effect.

The Optimal parametric conditions for the machining of die-steel material workpiece on EDM have been determined for different composite material electrodes combinations. The best combinations of the input process parameters for high microhardness while machining H11 die-steel material by fabricated composite electrode and conventional Cu electrode has been summarized in Table 11. The improvement in the microhardness values have been determined w.r.t. the initial microhardness values.

Table 10 — ANOVA table of S/N data for Microhardness (95% confidence level)

	DOF	Sum (sq.)	Ve	F (Cal)	F (Tab)	% P	Re
Current	2	0.556	0.278	26.200	4.103	73.463	SF
Pulse on time	2	0.148	0.074	6.968	4.103	19.539	SF
Voltage	2	0.032	0.016	1.496	4.103	4.195	ISF
Error	2	0.021	0.011			2.804	
Total	8	0.757					

DOF : Degree of freedom, S/N : Signal to Noise, Re :Remarks, SF:Significant, ISF:Insignificant

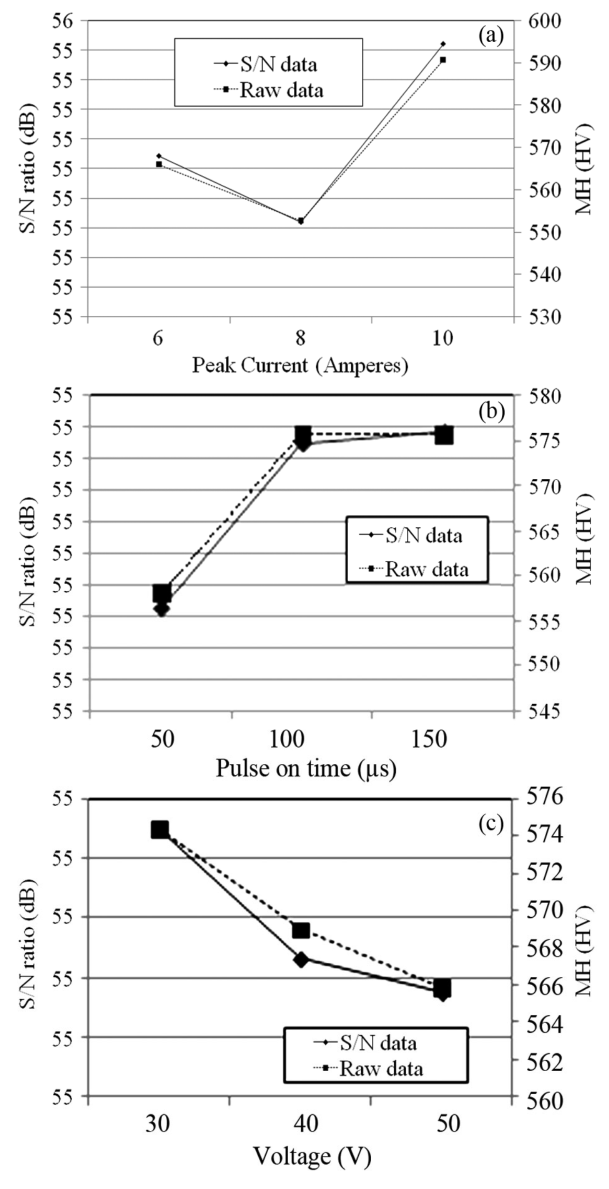

Fig. 6 — Effect on microhardness due to (a) peak current, (b) pulse on time, and (c) voltage.

Table 11 — Microhardness analysis of H11 die-steel with PM/Stir casted Composite material electrode & conventional copper material electrode

Electrode	optimal condition parameters	Micro hardness with optimal conditions (HV)	Micro Hardness of un-machined surface (HV)	%age Impro-vement
Cu + W + CNT	A2B2C3D3	625.336	523	19.57
Con-ventional Cu	B3C3D1	602.734	523	15.25

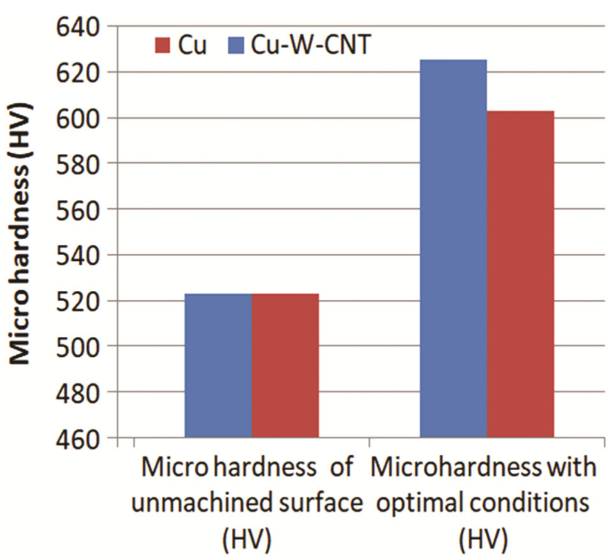

Fig. 7 — Optimal microhardness comparison of the machined surface.

The overall performance of the composite material electrodes fabricated by powder metallurgy and stir casting processes, while machining H11 die-steels have been presented in Fig. 7.

It can be observed from the Fig. 7 that the microhardenss of the surface machined with Cu-W-CNT electrode enhanced by 19.57%.

3.3 Characterization of machined surface with Cu-W- CNT Electrode

The surface analysis has been performed for H11 die-steel workpiece machined by Cu-W-CNT electrodes fabricated by powder metallurgy and stir casting processes with input parameters that gives the best microhardness. Fig. 8 shows the FESEM micrograph of the machined H11 die-steel workpiece. It shows the presence of carbon nano tubes having width around 350 nm and length around 2.8µm.

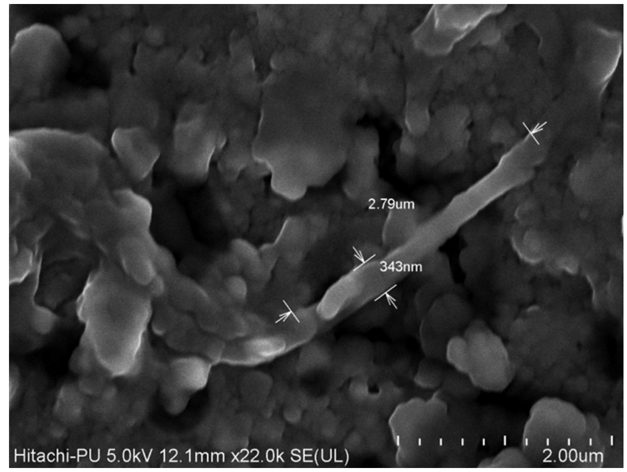

Fig. 8 — FESEM micrograph of the H11 workpiece machined with Cu-W-CNT electrode.

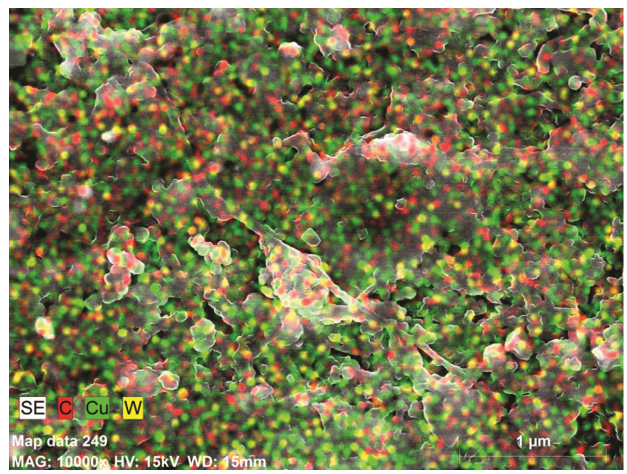

Fig. 9 — Mapping micrograph of the H-11 workpiece.

The mapped micrograph of the H11 die-steel workpiece machined with Cu-W-CNT electrode is shown in Fig. 9. The presence of Cu, W is and C is clearly visible in this micrograph.

The EDS spectra of the machined H11 die-steel workpiece has been shown in Fig. 10. These EDS spectra show the presence of Iron, copper, tungsten and carbon in the machined surface.

Figure 11 presents the XRD pattern of the resolidified layer on the surface of H11 die-steel workpiece. The pattern shows the presence of copper oxide, tungsten carbide, copper iron nickel and iron tungsten in the machined surface.

The trapping of tungsten and carbon ions in the workpiece surface resulted in the increased hardness of the workpiece. The FESEM, XRD and EDS analysis of the machined workpiece surface confirms the change in the micro structure and chemical

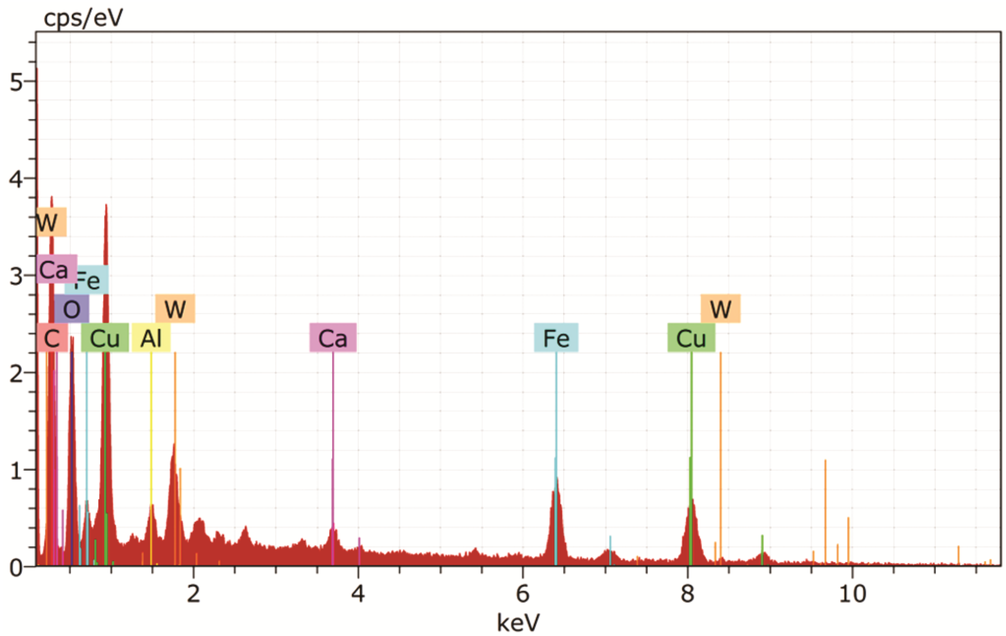

Fig. 10 — EDS spectra of the H11 workpiece machined with Cu-W-CNT electrode.

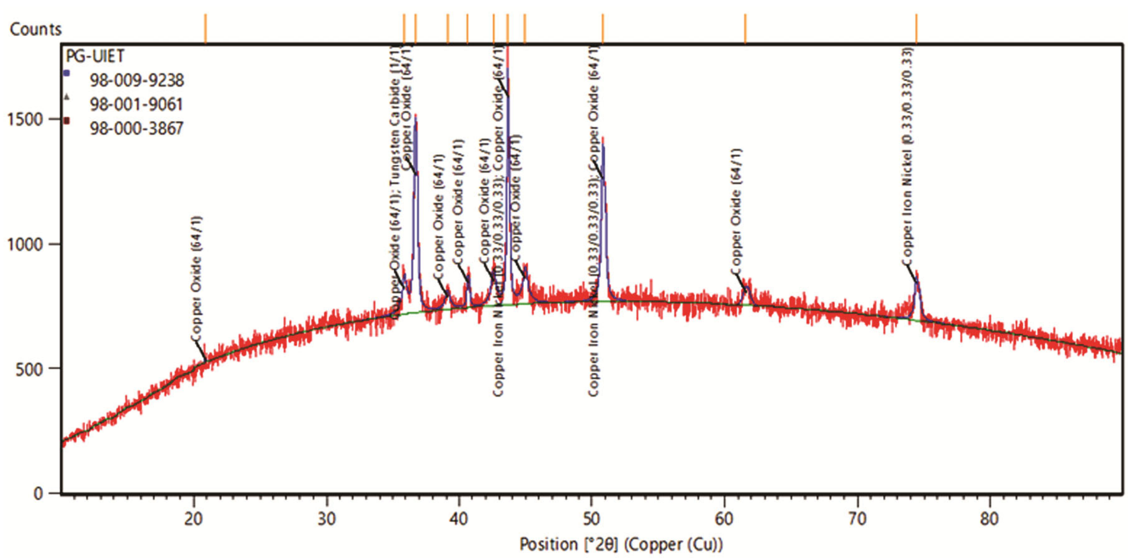

Fig. 11 — XRD pattern of the H11 workpiece machined with Cu-W-CNT electrode.

composition and therefore change in the surface properties. XRD analysis indicated the formation of tungsten-carbide, iron-carbide, chromium-nickel and copper on the machined surface of the workpieces. Therefore a protective layer of these compounds is responsible for high temperature hardness and resistance against hot corrosion.

4 Conclusion

Efforts have been made to investigate the effect of electric discharge machining on the H11 die-steel material with composite material electrodes fabricated by stir casting as well as powder metallurgy processes.

Copper has been used as matrix material with different weight percentages of tungsten and carbon nanotubes. The following conclusions are drawn from this research work :

- Microhardness of the H11 die-steel workpiece has been observed to be best when machined with Cu-W-CNT composite material electrode fabricated by powder metallurgy process. While maximum improvement in microhardness of 19.57% has been obtained. Therefore it has been observed that the addition of CNT and W in the electrode material resulted in increased microhardness of the workpiece surfaces.

- It has been possible to achieve surface alloying of H11 die-steel material by electrical discharge machining using composite material electrodes fabricated by powder metallurgy as well as stir casting processes.
- The presence of tungsten is seen in its free form and also as intermetallic compounds nickel-tungsten and iron-tungsten. This has resulted in significant increase in the micro-hardness of the machined surface.
- Increased percentage of carbon and traces of copper are seen in the machined surfaces. Carbon has been contributed by the breakdown of the hydrocarbon dielectric and copper has migrated from the body of the electrode.
- The presence of inter-metallic compound copper-nickel is expected to have a positive impact on the toughness of the die-steel materials.
- In addition to the desired surface alloying, some samples also show the presence of chromium-iron-carbide, copper-silicon, iron-tungsten-carbide and chromium-nickel which indicates that significant surface modifications take place by this method of machining. High temperature conditions produced during EDM diffuses carbon atoms into the workpiece surface from tool electrode thereby increasing the hardness of surface.
- XRD analysis indicated the formation of tungsten carbide on the machined surface of the die-steel and are responsible for providing resistance against hot corrosion and high temperature.
- Future research may be carried out to investigate the effect of other input process parameters such as duty cycle, pulse off time, type of dielectric. Further, interaction plots can also be studied more in-depth analysis.

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