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COMPARISON OF CRYO TREATMENT EFFECT ON MACHINING CHARACTERISTICS OF TITANIUM IN ELECTRIC DISCHARGE MACHINING

Rupinder Singh and Bhupinder Singh

Department of Production Engineering
Guru Nanak Dev Engineering College, Ludhiana, 141 006, India
Phone: +91-9872257575, Fax: +91-1612502700
E-mail: rupindersingh78@yahoo.com

ABSTRACT

Earlier studies on cryogenic treatment highlighted that certain metals, after being cryogenically treated, show a significant increase in tool life when used in manufacturing, cutting and shaping processes. The present work deals with experimental investigation of the role of cryogenic treatment on the machining characteristics of titanium in electric discharge machining (EDM). EDM is a potential process to commercially machine tough materials like titanium alloys, due to the properties of non-mechanical contact between the tool and workpiece and the capability to machine intricate shapes. In this research work an effort has been made to compare the machining characteristics of titanium with EDM, before and after cryogenic treatment of the tool and workpiece using a Taguchi design approach. The output parameters for study are material removal rate (MRR), tool wear rate (TWR), surface roughness (SR) and dimensional accuracy (Δd). The results of the study suggest that with cryogenic treatment MRR, TWR, SR and Δd show an improvement of 60.39%, 58.77%, 7.99% and 80.00% respectively.

Keywords: electric discharge machining; material removal rate; tool wear rate; surface roughness; dimensional accuracy.

INTRODUCTION

There are a number of treatment processes used for different metals which cause them to behave differently under different conditions (Dhar et al., 2002). Empirical studies have demonstrated that the life of cutting tools can be increased by cryogenic treatment (Gill et al., 2010). Cryogenic treatment may be oversimplified into a process of chilling a part down to relatively near absolute zero and maintaining that condition until the material has cold-soaked (Gill et al., 2008). The temperature is then allowed to rise until ambient equilibrium is reached (Molinari et al., 2001). The part may then be subjected to a normal tempering reheat, although this step is not always included in the process. The complexity of the process involves determining and achieving the proper duration for the cooling, soaking and warming cycles (Kamody, 1993). Figure 1 shows a schematic of cryogenic equipment.

EDM is a controlled metal removal process that is used to remove metal by means of electric spark erosion (Sarkar et al., 2006). In this process an electric spark is used as the cutting tool to cut (erode) the workpiece to produce the finished part to the desired shape (Liao et al., 1997). The metal removal process is performed by applying a pulsating (ON/OFF) electrical charge of high-frequency current through the electrode to the workpiece. This removes (erodes) very tiny pieces of metal from the workpiece at a controlled rate (Ramakrishnan and Karunamoorthy, 2006). Figure 2 shows a schematic of the EDM process.

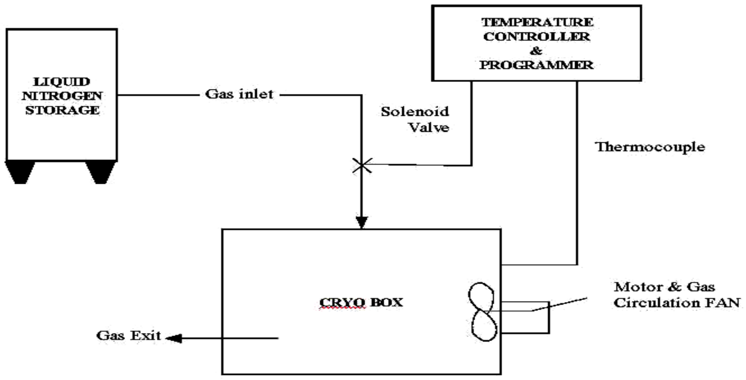


Figure 1. Schematic of cryogenic equipment (Singh & Singh, 2010)

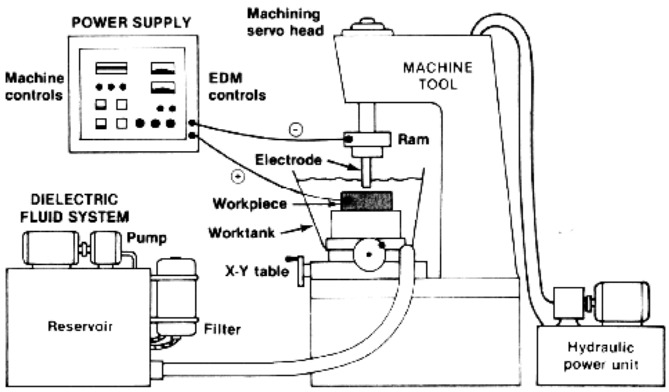


Figure 2. Schematic of EDM process (Singh, 2009)

Titanium (Ti) and its alloys exhibit excellent corrosion resistance and have high strength to weight ratio, which makes them ideal for use primarily in two areas of application: corrosion-resistant service and specific strength for efficient structures. Normally, low strength, unalloyed, commercially pure (CP) Ti is used in the fabrication of tanks, heat exchangers and reactor vessels for chemical processing and power generation plants. High strength Ti alloys are used in high performance applications such as aerospace (Sarkar et al., 2006). The conventional method in machining of Ti alloys is not suitable (Singh, 2009). Research on machining of pure Ti using conventional machines highlights chipping, stresses, cutting tool wear and thermal problems during machining which are caused by mechanical energy. Instead of conventional machining, the EDM process is a potential machining method to eliminate such problems (Puri and Bhattacharya, 2003). This is because there is no mechanical contact between the tool and workpiece in the EDM system (Saha, 2008). Furthermore, machining with EDM is burr-less, highly accurate and has the capability to produce intricate cavities in one operation. However, not much work has been reported hitherto on EDM of pure Ti (Singh, 2009).

The objective of the present work is to compare the machining characteristics of Ti with EDM, before and after cryogenic treatment of the tool and workpiece using the Taguchi design approach. In the present study cryo-treatment was done at -80°C (Reitz and Pendray, 2001; Molinari et al., 2002). Figures 3 and 4 show cryogenic and tempering cycles for the present study. The output parameters for study are material removal rate (MRR), tool wear rate (TWR), surface roughness (SR) and dimensional accuracy (Δd).

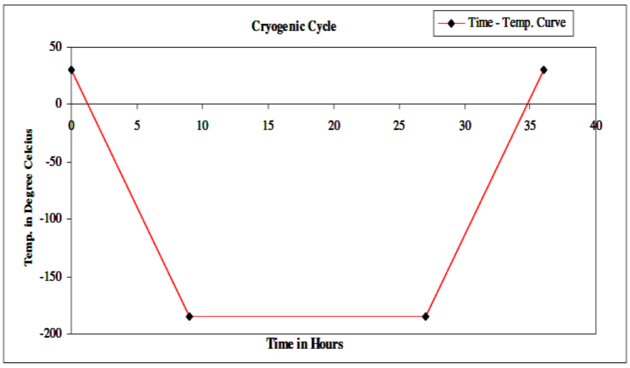


Figure 3. Cryogenic cycle

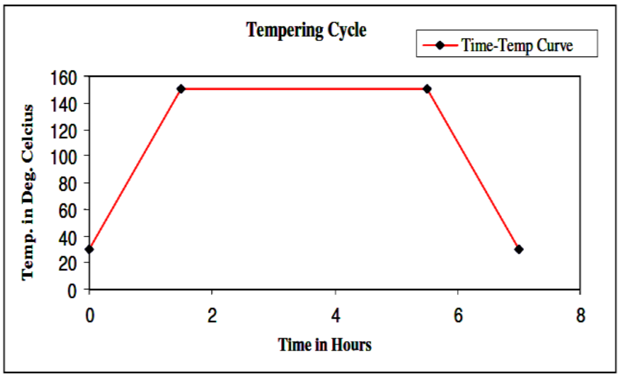


Figure 4. Tempering cycle

EXPERIMENTAL DETAILS

The material selected for the study was CP Ti (Titan 15) ASTM Gr.2 as the workpiece and Ti, copper (Cu) and copper chromium (CuCr) as electrode/tool materials. Table 1 shows the chemical composition of the workpiece. The workpiece samples were cut into 20 mm × 12 mm × 12 mm and electrodes were of 6mm diameter and 100 mm length for the experimentation. Table 2 shows a list of input parameters for the present study. The experimentation was conducted on a CNC EDM machine. Table 3 summarizes the results of pilot experiments with different combinations of electrode, workpiece and current.

Table 1. Chemical analysis (%) TITAN 15 (UTS 491 MPa)

C	H	N	O	Fe	Ti
0.006	0.0007	0.014	0.140	0.05	Balance

Table 2. Input parameters

Work material CP Ti	**Non-cryo treated/plain**		**Cryogenically treated**
Tool Materials	CuCr (Non-cryo treated) Copper (Non-cryo treated) Ti (Non-cryo treated)		CuCr (Cryogenically treated) Cu (Cryogenically treated) Ti (Cryogenically treated)
Current Ampere	2	4	6

Table 3. Experimental Observations

Input parameters											Output Parameters			
Tool/ Electrode		Work Piece	Current (Amp)		Initial weight (gm)		Final weight (gm)		Time Taken (min)	TWR (gm/min)	MRR (gm/min)	SR (µm)	Δd (mm)
					Tool	Work piece	Tool	Work piece					
Cryogenically treated	Ti	Non-cryo treated Ti	A1	2	11.697	16.789	10.516	15.614	108	0.0109352	0.0108796	0.595	0.06
Cryogenically treated	Ti	Non-cryo treated Ti	A2	4	10.516	15.614	9.387	14.476	99	0.011404	0.0114949	0.609	0.07
Cryogenically treated	Ti	Non-cryo treated Ti	A3	6	9.387	14.476	8.338	13.325	92	0.0114022	0.0125109	0.628	0.07
Cryogenically treated	Cu	Non-cryo treated Ti	A1	2	23.69	14.578	22.173	13.416	82	0.0185	0.0141707	0.603	0.06
Cryogenically treated	Cu	Non-cryo treated Ti	A2	4	22.173	13.416	20.603	12.296	73	0.0215068	0.0153425	0.613	0.06
Cryogenically treated	Cu	Non-cryo treated Ti	A3	6	20.603	12.296	19.396	11.139	62	0.0194677	0.0186613	0.632	0.07
Cryogenically treated	CuCr	Non-cryo treated Ti	A1	2	22.896	16.409	21.316	15.287	86	0.0183721	0.0130465	0.599	0.06
Cryogenically treated	CuCr	Non-cryo treated Ti	A2	4	21.316	15.287	19.667	14.109	76	0.0216974	0.0155	0.612	0.07
Cryogenically treated	CuCr	Non-cryo treated Ti	A3	6	19.667	14.109	18.464	12.921	65	0.0185077	0.0182769	0.631	0.07
Non-cryo treated	Ti	Non-cryo treated Ti	A1	2	14.89	20.513	13.671	19.287	117	0.0104188	0.0104786	0.591	0.1
Non-cryo treated	Ti	Non-cryo treated Ti	A2	4	13.671	19.287	12.443	17.896	109	0.0112661	0.0127615	0.606	0.1
Non-cryo treated	Ti	Non-cryo treated Ti	A3	6	12.443	17.896	11.414	16.589	98	0.0105	0.0133367	0.622	0.09
Non-cryo treated	Cu	Non-cryo treated Ti	A1	2	28.143	17.918	26.491	16.176	83	0.0199036	0.020988	0.597	0.09
Non-cryo treated	Cu	Non-cryo treated Ti	A2	4	26.491	16.176	24.729	14.319	77	0.0228831	0.0241169	0.612	0.1
Non-cryo treated	Cu	Non-cryo treated Ti	A3	6	24.729	14.319	23.287	12.573	66	0.0218485	0.0264545	0.629	0.09
Non-cryo treated	CuCr	Non-cryo treated Ti	A1	2	27.674	19.981	26.149	18.546	88	0.0173295	0.0163068	0.594	0.1
Non-cryo treated	CuCr	Non-cryo treated Ti	A2	4	26.149	18.546	24.604	16.906	79	0.019557	0.0207595	0.609	0.09
Non-cryo treated	CuCr	Non-cryo treated Ti	A3	6	24.604	16.906	23.317	15.409	68	0.0189265	0.0220147	0.627	0.09
Cryogenically treated	Ti	Cryogenically treated Ti	A1	2	14.97	20.015	13.819	18.685	122	0.0094344	0.0109016	0.587	0.02
Cryogenically treated	Ti	Cryogenically treated Ti	A2	4	13.819	18.685	12.695	17.165	109	0.0103119	0.013945	0.599	0.04
Cryogenically treated	Ti	Cryogenically treated Ti	A3	6	12.695	17.165	11.697	15.623	102	0.0097843	0.0151176	0.618	0.04
Cryogenically treated	Cu	Cryogenically treated Ti	A1	2	28.14	17.876	26.473	16.413	89	0.0187303	0.0164382	0.593	0.03
Cryogenically treated	Cu	Cryogenically treated Ti	A2	4	26.473	16.413	24.816	15.109	76	0.0218026	0.0171579	0.605	0.03
Cryogenically treated	Cu	Cryogenically treated Ti	A3	6	24.816	15.109	23.69	13.853	67	0.016806	0.0187463	0.628	0.04
Cryogenically treated	CuCr	Cryogenically treated Ti	A1	2	26.945	17.503	25.597	16.024	93	0.0144946	0.0159032	0.591	0.03
Cryogenically treated	CuCr	Cryogenically treated Ti	A2	4	25.597	16.024	24.076	14.637	81	0.0187778	0.0171235	0.603	0.04
Cryogenically treated	CuCr	Cryogenically treated Ti	A3	6	24.076	14.637	22.896	13.296	73	0.0161644	0.0183699	0.624	0.04

Table 3. (continued)

	Input parameters								Output Parameters			
	Tool/ Electrode	Work Piece	Current (Amp)	Initial weight (gm)		Final weight (gm)		Time Taken (min)	TWR (gm/min)	MRR (gm/min)	SR (μm)	Δd (mm)
				Tool	Work piece	Tool	Work piece					
Non-cryo treated	Ti		A1 2	11.414	16.923	10.293	15.784	104	0.0107788	0.0109519	0.601	0.05
			A2 4	10.293	15.784	9.046	14.629	96	0.0129896	0.0120313	0.617	0.05
			A3 6	9.046	14.629	8.103	13.486	77	0.0122468	0.0148442	0.633	0.05
	Cu		A1 2	22.719	14.453	21.343	13.311	77	0.0178701	0.0148312	0.607	0.04
			A2 4	21.343	13.311	19.856	12.19	71	0.0209437	0.0157887	0.623	0.05
			A3 6	19.856	12.19	18.493	11.035	66	0.0206515	0.0175	0.638	0.05
	CuCr		A1 2	23.317	13.96	21.783	12.809	81	0.0189383	0.0142099	0.605	0.05
			A2 4	21.783	12.809	20.109	11.651	72	0.02325	0.0160833	0.618	0.06
			A3 6	20.109	11.651	18.676	10.463	64	0.0223906	0.0185625	0.635	0.06

MRR is defined as the difference between the initial weight of the workpiece (before machining) and the final weight of the workpiece (after machining with EDM). TWR is defined as the difference between the initial weight of the tool (before machining) and the final weight of the tool (after machining with EDM).

Mathematically MRR = $(W_1 - W_2)/t$

where W_1 is the initial weight of work-piece in gm (before machining)
W_2 is the final weight of work-piece in gm (after machining)
t is the machining time in minutes for '01mm' fixed depth of cut in workpiece, measured with a stopwatch.

Mathematically TWR = $(V_1 - V_2)/t$

where V_1 is the initial weight of the tool in gm (before machining)
V_2 is the final weight of the tool in gm (after machining)
t is machining time in minutes for '01mm' fixed depth of cut in workpiece measured with a stopwatch.
SR was measured as 'R_a value' expressed in microns by using a surface roughness measuring instrument (Talysurf).

RESULTS AND DISCUSSION

Based upon pilot experimental data (Table 3), a Taguchi L9 orthogonal array was used to optimize MRR, TWR, SR and Δd. Final experimentation was conducted in four sets. In the first set, a cryogenically treated electrode and cryogenically treated workpiece were machined using EDM. In the second setup, a non-cryo treated electrode and non-cryo treated workpiece were selected. In third setup, a non-cryo treated workpiece was machined with a cryogenically treated electrode. In the final setup, a non-cryo treated electrode and cryogenically treated workpiece combination was selected. Table 4 shows the factors description for the cryogenically treated/non-treated electrode and workpiece.

With the help of MINITAB 15 software, the ANOVA was performed to attain the plots and conditions where MRR, TWR SR and Δd have optimized value. The results are valid for 95% accuracy. The ANOVA result shows the value of degree of freedom (DOF), sum of squares (Seq. SS), adjustable mean squares (Adj. MS) and value of F and P test. Figure 5 shows machining parameters versus current for the cryogenically treated electrode and cryogenically treated workpiece and Figure 6 shows the main effects plots by ANOVA analysis from the average value for (a) Δd (b) SR (c) MRR (d) TWR. The following ANOVA results were obtained for the cryogenically treated electrode and cryogenically treated workpiece:

Workpiece: Cryogenic Ti

General Linear Model: TWR, MRR, SR, Δd versus Current, Tool

Factor	Type	Levels	Values
Current	fixed	3	2, 4, 6
Tool	fixed	3	Cryogenic Ti, Cryogenic Cu, Cryogenic CuCr

Analysis of Variance for TWR, using Adjusted SS for Tests

Source	DF	Seq SS	Adj MS	F	P
Current	2	0.0000149	0.0000074	3.96	0.113
Tool	2	0.0001369	0.0000684	36.39	0.003
Error	4	0.0000075	0.0000019		
Total	8	0.0001593			

S = 0.00137150

Analysis of Variance for MRR, using Adjusted SS for Tests

Source	DF	Seq SS	Adj MS	F	P
Current	2	0.0000135	0.0000068	15.22	0.013
Tool	2	0.0000316	0.0000158	35.61	0.003
Error	4	0.0000018	0.0000004		
Total	8	0.0000469			

S = 0.000666547

Analysis of Variance for SR, using Adjusted SS for Tests

Source	DF	Seq SS	Adj MS	F	P
Current	2	0.0016740	0.0008370	627.75	0.000
Tool	2	0.0000827	0.0000413	31.00	0.004
Error	4	0.0000053	0.0000013		
Total	8	0.0017620			

S = 0.00115470

Analysis of Variance for Δd, using Adjusted SS for Tests

Source	DF	Seq SS	Adj MS	F	P
Current	2	0.0002889	0.0001444	5.20	0.077
Tool	2	0.0000222	0.0000111	0.40	0.694
Error	4	0.0001111	0.0000278		
Total	8	0.0004222			

S = 0.00527046

From the above ANOVA analysis and main effects plots it can be summarised that:

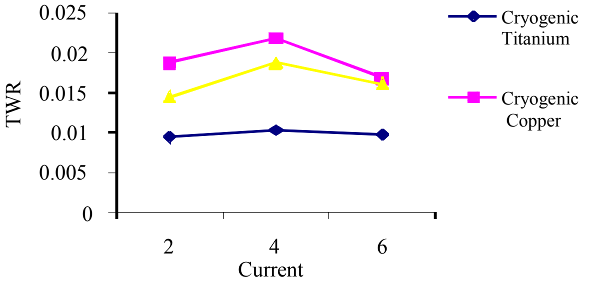
1. For the cryogenic Ti workpiece a minimum value of TWR (i.e. 0.00943443 gm/min) was achieved with the cryogenic Ti tool and the current was 2 Amps.
2. For the cryogenic Ti workpiece a maximum value of MRR (i.e. 0.018746269 gm/min) was achieved with the cryogenic Cu tool and the value of the current was 6 Amps.
3. For the cryogenic Ti workpiece a minimum value of SR (i.e. 0.587 μm) was achieved with the cryogenic Ti tool and the value of the current was 2 Amps.
4. For the cryogenic Ti workpiece a minimum value of Δd (i.e. 0.02 mm) was achieved with the cryogenic Ti tool and the value of the current was 2 Amps.

On the same lines, ANOVA analysis for set 2, 3 and 4 was conducted. Based upon ANOVA analysis and main effects plots, the general conditions for optimization were obtained. The overall optimized values of TWR, MRR, SR and Δd are summarized as:

1. The overall optimized value of TWR was achieved with a combination of a cryogenic titanium workpiece, cryogenic titanium tool and 2 Amp current.
2. The overall optimized value of MRR was achieved with a combination of a non-cryo treated titanium workpiece, non-cryo treated copper tool and 6 Amp current.
3. The overall optimized value of SR was achieved with a combination of a cryogenic titanium workpiece, cryogenic titanium tool and 2 Amp current.
4. The overall optimized value of Δd was achieved with a combination of a cryogenic titanium workpiece, cryogenic titanium tool and 2 Amp current.

Table 4. Factors description for cryogenically treated/non-treated electrode and workpiece

Factors	Level Description Setup 1			Level Description Setup 2			Level Description Setup 3			Level Description Setup 4		
	1	2	3	1	2	3	1	2	3	1	2	3
Current(A)	2	4	6	2	4	6	2	4	6	2	4	6
Tool	Cryogenic Ti	Cryogenic Cu	Cryogenic CuCr	Non-Cryo treated Ti	Non-Cryo treated Cu	Non-Cryo treated CuCr	Cryogenic Ti	Cryogenic Cu	Cryogenic CuCr	Non-Cryo treated Ti	Non-Cryo treated Cu	Non-Cryo treated CuCr
Work piece	Cryogenic Ti	Cryogenic Ti	Cryogenic Ti	Non-Cryo treated Ti	Non-Cryo treated Ti	Non-Cryo treated Ti	Non-Cryo treated Ti	Non-Cryo treated Ti	Non-Cryo treated Ti	Cryogenic Ti	Cryogenic Ti	Cryogenic Ti



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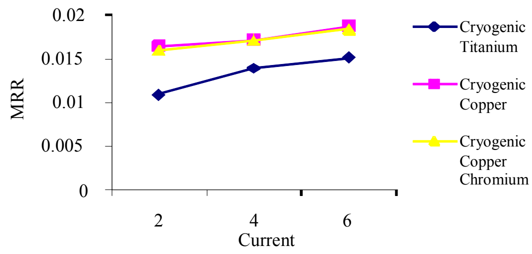

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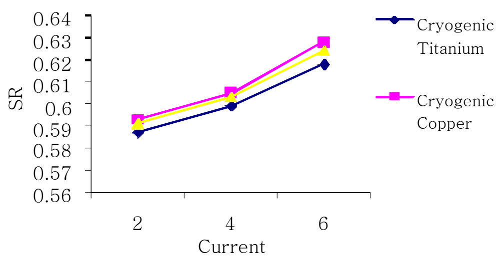

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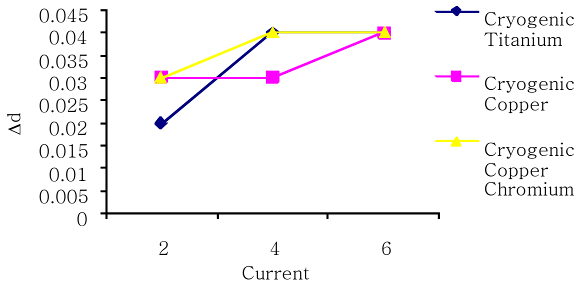
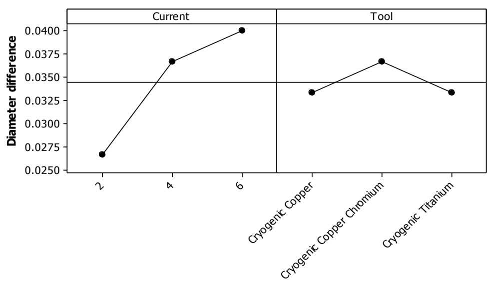


(d)

Figure 5. Machining parameters versus current for cryogenically treated electrode and cryogenically treated workpiece



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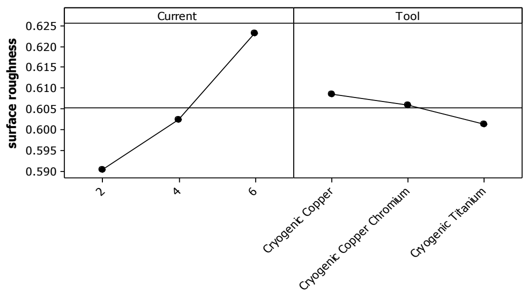

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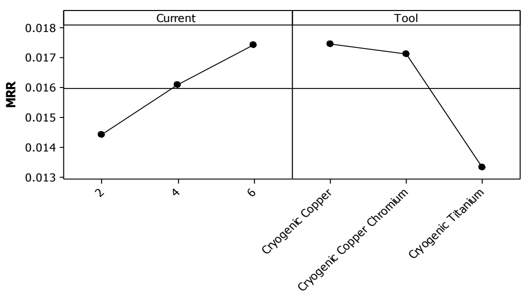

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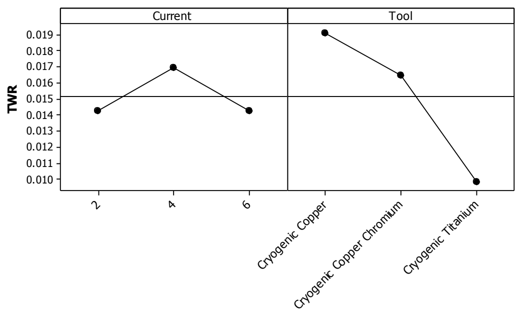

(d)

Figure 6. Main effects Plot by ANOVA analysis from average value for (a) Δd(b) SR(c) MRR (d) TWR

CONCLUSIONS

The results of the present study show that, with the help of cryogenic treatment, machining parameters like MRR, TWR SR and Δd improve significantly when machined on EDM with CP Ti as the workpiece. The results are in line with the observations made by other investigators. For checking the adequacy of the model, verification experiments were conducted and it was found that MRR showed an improvement of 60.39%, TWR showed an improvement of 58.77%, SR showed an improvement of 07.99% and Δd showed an improvement of 80.00%.

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Nomenclatures

Adj MS	adjustable mean square
DF	degree of freedom
MRR	material removal rate
Seq SS	sum of squares
SR	surface roughness
t	machining time in minutes for '01mm' fixed depth of cut in work-piece, measured with stopwatch.
TWR	tool wear rate
V_1	initial weight of tool in gm (before machining)
V_2	final weight of tool in gm (after machining)
W_1	initial weight of work-piece in gm (before machining)
W_2	final weight of work-piece in gm (after machining)
Δd	dimensional accuracy

Greek symbols

Δ	Accuracy
μ	Micron