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Optimization of Process Parameters for Optimum Metal Removal Rate in Wire EDM of AISI D2 Tool Steel Using Taguchi Method

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Abstract
Wire cut Electrical discharge machining is one of the most widely used un-conventional machining process for producing die and punches for blanking. Wire EDM has capacity to produce the complex shapes and profiles with highest accuracy and precision. It can machine any electrically conducting material irrespective of its hardness. However, the performance of WEDM process depends upon the various process parameters selected as well as material of the work-piece to be machined. A lot of research work has been reported regarding the optimization of process parameters used in WEDM process but to get higher metal removal rate with good surface finish on machined surface is still a difficult task to researchers. In the present work, cold worked D2 tool steel bar and heat treated D2 tool steel bars of 13mm diameters were machined by using 0.25mm diameter brass wire electrode with same process parameter. Along with the heat treatment the influence of various input process parameters such as (Ton, Toff, Ip, Sv) on the response characteristics (MRR) was investigated by using Taguchi L9 orthogonal array. Signal to noise ratio and ANOVA is also applied in order to determine the optimum process parameters for getting optimum metal removal rate. From the predicted optimum range of process parameters and confirmation experiments it's found that, for heat treated material metal removal rate increased as compared to cold worked D2 Tool steel material.

Keywords: *Unconventional machining processes, wire cut-EDM, Metal Removal Rate, Taguchi Method, Signal to Noise ratio, ANOVA, D2 Tool Steel, Heat Treatment*

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I. INTRODUCTION

Wire cut electrical discharge machining (WEDM) is widely used for machining chips free intricate shapes, slots and cavities etc. for example, sinking of dies for molding, die casting, press tools, plastic molding, wire drawing, compacting, cold heading, forging and extrusion [26]. Due to high dimensional accuracy and surface quality in machined surface it's application in aerospace, nuclear, and automotive industries, for machining difficult-to-machine materials is increasing tremendously. Wire cut EDM is used to machine any electrically conductive material irrespective of its hardness. Electric discharge machining, also known as spark erosion, electro erosion or spark machining is a process of metal removal based on the principal of erosion of metals by an interrupted electric spark discharge between the electrode tool (cathode) and the work piece (anode)[5]. The performance and accuracy of any machining process is based on choosing the proper combination of machining parameters. In WEDM, the improper selection of machining parameters causes short circuiting of wire and wire breakages which affects the quality of production[3]. In WEDM getting higher metal removal rate with minimum surface roughness value in machined surface is still a difficult task. Tarng et al. [1] obtained the optimal cutting parameters by simulated Annealing Algorithm and used artificial neural network technique for modeling the process responses such as surface roughness and cutting velocity. Huang et al. [2] investigated the effect of control variables on the performance measures, such as white layer depth on the surface of machined work piece, gap width and surface roughness. They established Mathematical models relating machining parameters and performance by regression and non-linear programming using the Feasible-direction algorithm in order to obtain the optimal machining parameters. S. Singh et. al.[3] determined the effect of pulsed current on metal removal rate, diameteral overcut, electrode wear and surface roughness in electric discharge machining of En-31 tool steel. Author found that, output responses increased with pulsed current and best material removal rate obtained with copper and aluminium electrode. Tosun et. al. [4] has been established the mathematical model by using regression equation in order to understand the effect of process parameters on the kerf width and MRR. Also significant process parameters found out by ANOVA. S. S. Mahapatra et al. [5] established the mathematical model by nonlinear regression analysis in order to understand the effect of control factors on output responses such as metal removal rate, surface finish and kerf width. Genetic algorithm is also applied for optimization of electrical discharge machining process. Rajeev Kumar et. al. [6] expressed the need of work in the optimization of process parameters in WEDM as even a single variable affects the performance of WEDM. M. Durairaja et al. [7] used Grey relational theory and Taguchi optimization (L9) technique, in order to optimize the cutting parameters in Wire EDM for SS304.By the ANOVA they observed that the pulse on time has major influence on the surface roughness (μm) and kerf width (mm). M M Dhobe et al. [8] investigated the effect of heat treatment and process parameters of Wire Electrical Discharge Machining (WEDM) like pulse on time (TON), pulse off time (TOFF), gap voltage (SV), peak current (IP) on surface roughness of AISI D2 tool steel. From the experimental work they observed that, the surface roughness increases with increase in pulse on time (TON) and peak current (IP) whereas decreases with increase in number of tempering cycles after hardening for the same process parameters. This means double tempering after hardening reduces surface roughness compared to single tempering. G. Selvakumar1 et al. [9] Used Taguchi experimental design (L9 orthogonal array) method and considered pulse-on time, pulse-off time, peak current and wire tension as input parameters for wire electrical discharge machining (WEDM) of 5083 aluminum alloy. Zahid A. Khan et al. [10] investigated the effect of the WEDM process parameters on the surface roughness average and the kerf width of the stainless steel (SS 304). By the Taguchi method and Grey relational analysis they found that, , the pulse ON time is the most significant controlled factor for the WEDM operation when the minimization of the both the surface roughness average and the kerf width are simultaneously considered. D. Sudhakara et al. [11] Determined the Optimum Surface Roughness in Wire Electric Discharge Machining of P/M Cold Worked Tool Steel (Vanadis-4E) by Taguchi Method. Brajesh Kumar Lodhi et. al.[12] optimized the machining variables such as pulse on time, pulse off time, peak current and wire feed by using L9 Orthogonal Array for better surface finish on machined surface in wire cut EDM of AISI D3 tool steel. By using ANOVA and signal to noise ratio they found that, discharge current is the most influential factor on the surface roughness. Goswami et al. [13] used Taguchi's design of experiments methodology for planning and designing the experiments in order to investigate the effect of machining parameters on the machining outputs (material removal rate and wire wear ratio) of Nimonic 80A in WEDM. scanning electron microscopy was performed on the machined samples to investigate the effect and microstructure of the samples after machining. Pulse-on time (Ton) and pulse-off time (Toff) have been found to be the most significant factors for MRR. The recast layer has been observed to increase with increase in pulse-on time and peak current. Prashant Sinha et al. [14] implemented a hybrid approach of Taguchi method (TM) and principal component analysis (PCA) used for multi-objective optimization (MOO)WEDM of AISI D3 tool steel to achieve better cut qualities within existing resources. G.Ugrasena et al. [15] optimized the process parameters in the wire EDM for HCHCr steel as a work material. By using Taguchi's L27 orthogonal array, process Parameters such as pulse-on, pulse-off, current and bed speed was varied. By ANOVA Analysis they determined that, the control factor 'Pulse -on' is having more effect on the response variables such as surface roughness, volumetric material removal rate and accuracy. Salunkhe et. Al. [16] investigated the effect of single and double austenitization treatments (DA) on the AISI cold worked D2 tool steel by heating the material to the austenitizing temperatures (950 to 1050^{0}C) followed by quenching and tempering at 540^{0}C and 200^{0}C sequentially. Their experimental results detected that, due DA significant growth in grains and increase in hardness takes place due to dissolution of carbide contents. Ashish Goyal [17] investigated the effect of process parameters on material removal rate (MRR) and surface roughness (Ra) in wire electric discharge machining of Inconel 625 by cryogenic treated tool electrode Cryogenic tool electrode provides better machining performance (maximum MRR and better surface roughness) as compared with normal tool electrode. The scanning electron microscopy (SEM) is used to identify the microstructure of the machined work piece. K.L.Uday et al. [18] predicted the angular error in wire-EDM taper cutting of AISI D2 tool steel by response surface methodology approach to reduce the experimental load on experiments were carried out. A. Muniappan et.al.[19] determined the optimal set of process paraeters in WEDM of metal matrix composites of silicon carbide and graphite in Al6061 combination by using Taguchi's L27 orthogonal Technique. They determined the best combination of input variables such as pulse on time, pulse off time, peak current, gap set voltage,wire feed and wire tension on cutting speed. Veeresh Murthy et al. [20] has been used Taguchi Technique in order to optimize the Wire EDM Machining Parameters for Optimum Material Removal Rate and Surface Finish in an Aluminum 7075-T651 Alloy. B. Selva Babu et al. [21] investigated the effect of input machining parameters on the Metal removal rate (MRR) and surface finish for the Aluminum 6061 on wire cut EDM process. By using Taguchi's design for experimentation work and ANOVA analysis they found that, peak current and pulse on have significant effect on MRR an surface roughness whereas results shows that the most influencing parameter is the current for both MRR as well as the surface roughness. Lalta Prasad et al.

[22] used Taguchi method and genetic algorithm in order to evaluate the metal removal rate, and surface roughness while machining of with zinc- EN-42 spring steel in wire electrical discharge machining. Because of the cryogenic treatment reduction in crystal vacancies takes place which improved the surface finish. Whereas cryogenically treated zinc-coated brass wire was used along with WS2 powder in dielectric fluid which increased MRR. Ajay Kumar, et al. [23] investigated Optimum machining parameters for the D2 steel in WEDM operation. Taguchi L16 (orthogonal array) applied for experimental design with four process input control parameters, i.e. wire speed, flushing pressure, gap voltage, and current are selected in order to understand its effect upon MRR and SR. ANOVA and Signal to Noise ratio based analysis shows that MRR is influenced by these input parameters in the order of current followed by gap voltage, wire speed and flushing pressure. Jitendra Kumar et al. [24] considered fuzzy modeling as an option to conventional demonstration technology to obtain optimum results in WEDM for various machining parameters. They have developed Fuzzy model in MATLAB to predict fuzzy response parameters which showed 90% accuracy. Sahil Sharma et al. [25] investigated the influence of process parameters such as pulse on time, pulse off time, peak current, wire tension on the Metal removal rate (MRR), gap current(Ig), machining time(MT) while the machining of AISI D2 die steel of 13 mm diameter by using L9 orthogonal array. By using signal to noise ratio and ANOVA they found that, T_{off} has been the most significant factor for MRR, gap current and time taken for machining. Based on the previous research work it's clear that, Optimum level of process parameters can be found out by using Taguchi Method to get optimum value of each response variable such as material removal rate and surface roughness. In WEDM MRR and Ra mostly influenced by pulse on time (Ton) and Peak Current (Ip). Cryogenic treatment and heat treatment of material affects the metal removal rate and surface quality obtained in the wire cut EDM operations. Multi-objective optimization and the optimal solution can be found out using Grey Relational Analysis and Principal Component Analysis. From the reported research work it's clear that, very few authors considered effect of heat treatment along with process parameters in WEDM of tool steel [3,8]. Actually, heat treatment is carried out on the tool steel to increase it's hardness, wear and abrasion resistance, ductility, toughness as well as for getting dimensional stability after machining process. Hence, to aid the further contribution in WEDM process, effect of heat treatment and process parameters are investigated to get optimum metal removal rate in wire cut electrical discharge machining of cold worked D2 tool steel and heat treated D2 tool steel.

II. MATERIALS AND METHODS

2.1 Working Material and wire electrode

In the present work, cold worked D2 tool steel bar and heat treated D2 tool steel bar of 13 mm diameter round bar were selected as a working material for carrying out experiments. D2 tool steel is a high carbon-chromium content material used in the manufacturing die, punches for blanking, milling cutters and press tools. Chemical composition of selected material is given in table1. Heat treated D2 tool steel bar was prepared by hardening it to the austenitization temperature at 980^0C for 30 minutes followed by oil quenching and double tempering at 200^0C and 185^0C for 2 hours successively. Heat treatment is mainly performed on the tool steel in order to get better dimensional stability, hardness and wear resistance. Due to the purposed heat treatment hardness of heat treated bar increased to 62 RC by Rockwell's hardness test. Further, both the bar machined on Wire cut EDM machine into similar pieces of 5mm thickness each. Brass wire of 0.25mm diameter is used as wire electrode. The machine set up used for experimentation work is shown in Fig. 1(a) and machined specimen are shown in Fig. 1(b).

Table 1 Chemical composition of D2 tool steel material

Chemical Component	**C**	**Mn**	**Cr**	**Ni**	**Mo**	**S**	**P**	**Si**	**V**	**W**
Percentage	1.52	0.35	11.63	0.26	0.36	0.010	0.009	0.35	0.12	0.01

2.2 Conduction of experiments

All the experiments on cold worked D2 tool steel bar and heat treated bar carried out on Wire EDM Machine (Make: Electronica Pvt Ltd. Model: Elektra Sprintcut 734) as shown in Fig. 1(a). For performing the experiments four machining parameters like Pulse on (Ton), Pulse Off (Toff), Peak current (Ip) and spark set gap voltage (Sv) were selected to study the influence on Metal removal rate (MRR). All

2.2.1 Pulse on Time

The pulse on time is the time in micro second during which current flows and sparking occurs in the gap between the wire electrode and work-piece resulting in material removal. With increasing pulse on time metal removal rate and surface roughness increases.

2.2.2 Pulse Off Time

This is the time in micro seconds between the two simultaneous sparks occurring between the work-piece and wire electrode. Voltage is being cut off during this part of cycle. During this time reionisation of dielectric fluid takes place.

2.2.3 Peak current

It is the maximum value of current carried through the wire electrode during each pulse. Peak current increases the cutting rate.

2.2.4 Spark set gap voltage

It is the actual reference voltage in the gap between the wok-piece and wire electrode.

(a) (b)

Fig. 1 *(a) Wire EDM machine Set up (b) Machined Specimen*

Table 2 Process parameters with their level

Sr. No.	Process Parameters	LEVELS 1	LEVELS 2	LEVELS 3	Range
1	Pulse on time (A)	105	115	125	105-125
2	Pulse off time (B)	40	50	60	40-60
3	Spark gap set voltage(C)	15	30	45	15-45
4	Peak current(D)	70	90	110	70-110

Table 3 Taguchi L9 Orthogonal array for selected material

EXP. NO.	Process Parameters				Performance parameeters For Cold Worked D2 Tool Steel		Performance parameeters for heat treated D2 Tool Steel	
	Ton (µs)	Toff (µs)	Sv (V)	Ip (A)	MRR		MRR	
					(mm^3/min)	S/N Ratio	(mm^3/min)	S/N Ratio
1	105	40	15	70	3.26	10.264	3.26	10.264
2	105	50	30	90	3.71	11.387	3.71	11.387
3	105	60	45	110	2.34	7.384	2.34	7.3843
4	115	40	30	110	6.82	16.675	6.82	16.675
5	115	50	45	70	6.16	15.791	6.16	15.791
6	115	60	15	90	6.78	16.624	6.78	16.624
7	125	40	45	90	10.54	20.456	10.54	20.456
8	125	50	15	110	7.21	17.1587	7.21	17.158
9	125	60	30	70	6.11	15.7208	6.11	15.720

The metal removal rate is Volume of material removed by machine tool per unit time. The metal removal rate (mm^3/min) was calculated by the following formula:

$$MRR = \frac{(W1-W2)}{\rho \times t} \times 1000$$

Where,
W1 = initial weight of working material before machining (gm)
W2 = Final weight of working material after machining (gm)
t = Machining time in Minute
ρ = density of D2 Tool Steel (7.70 gm/cm^3)
By using Taguchi L9 Technique or orthogonal array as shown in Table 3 and input prameters with three levels shown in Table 2 experiments were carried out for both the material. Further ANOVA analysis is carried out by using Minitab19 software in order to determine the most influencing parameters on the metal removal rate. The "larger the better" characteristic selected to calculate the values of S/N ratio for metal removal rate as shown in equation (1).
For higher the better:

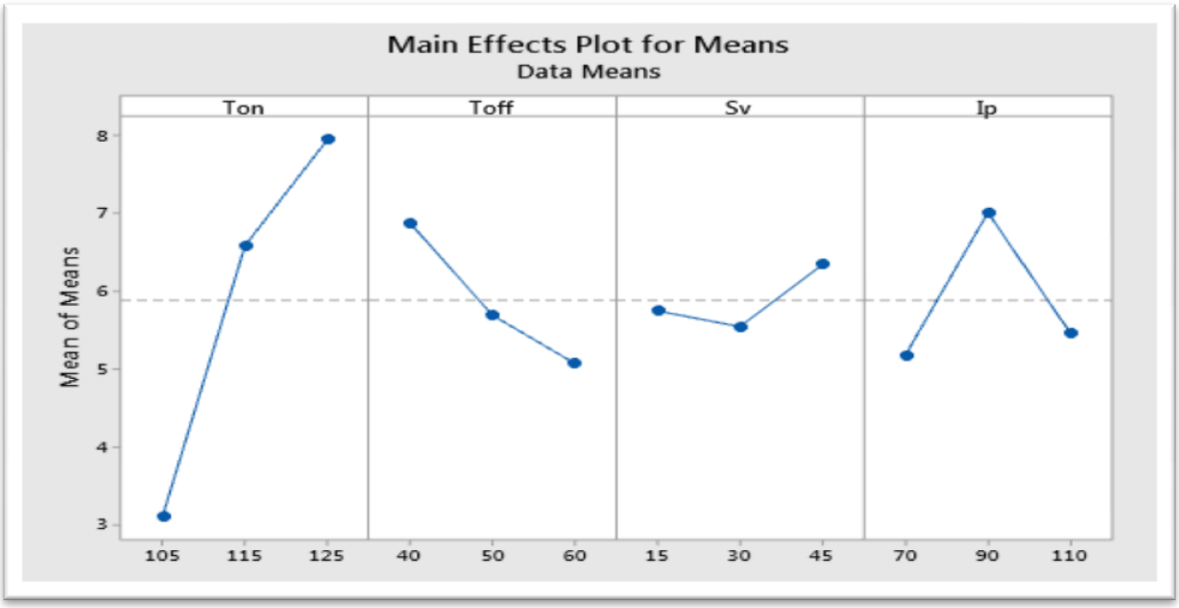
$$(S/N)_{HB} = -10 \times \log(\Sigma(1/Y^2)) \quad (1)$$

Where, Y= Response Value

III. RESULTS AND DISCUSSION

3.1 Influence of Input parameters on MRR for cold worked D2 Tool steel

Experiments were performed by using L9 Taguchi Technique in order to study the effect of various process parameters on (Ton, Toff, Sv and Ip) on the MRR. As per the graphs provided by MINITAB 19 software (Fig.2) it is clear that, MRR increases with increasing Pulse on time and with increasing pulse off time MRR decreases. At the third level of Ton gets higher MRR whereas as at higher level of Pulse off time gets lower MRR. Further it can also see that, spark set voltage has very slight effect on MRR as there is no much more difference in the values of MRR for initial and final levels. Up to the second level of Peak current MRR increases and after this it drops down suddenly. From the rank and delta value displayed in Table 4 and Table 5 Ton has the highest effect on MRR followed by Toff, Ip and Sv. From the values of S/N ratio its clear that, levels having highest value gives maximum MRR hence, optimal combination of parameters would be A3B1C1D2. From the Fig.2 and Table 4 it is clear that, Sv is less significant parameter hence by pooling it pooled ANOVA analysis carried out. From the Table 6 Ton has the highest contribution (81.41%) in the process of metal removal rate.



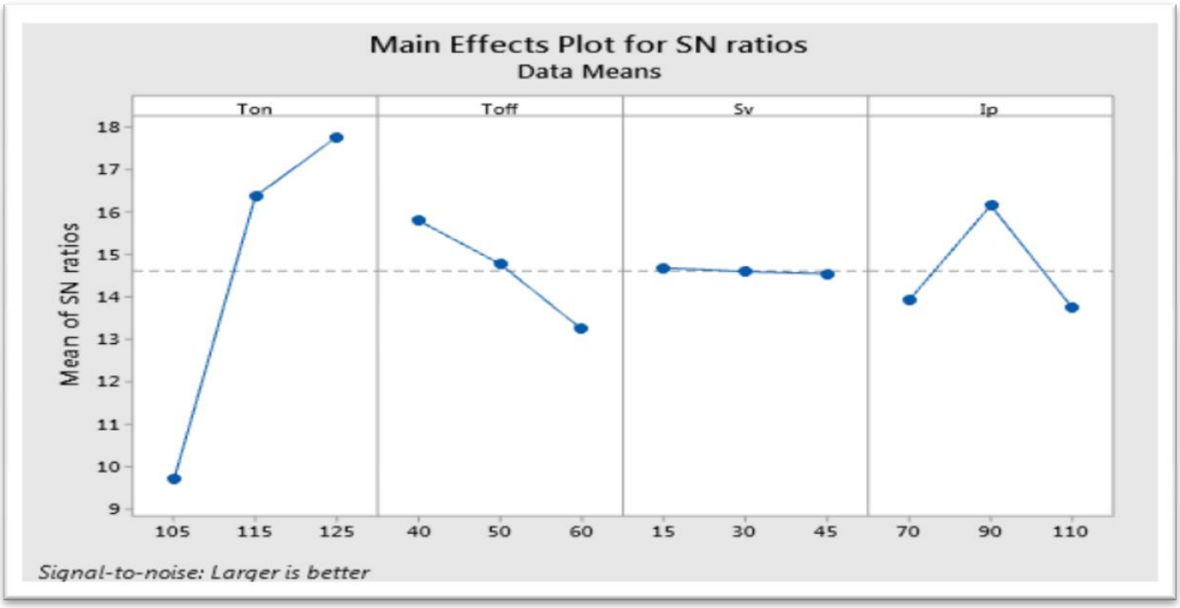


Fig.2 *Effect of input parameters on MRR (mean and S/N Data)*

Table 4 Response table for signal to noise ratio [MRR]

Level	Ton	Toff	Sv	Ip
1	9.679	15.799	14.683	13.926
2	16.364	14.779	14.595	16.156
3	17.779	13.243	14.544	13.740
Delta	8.100	2.556	0.138	2.417
Rank	1	2	4	3

Table 5 Response table for Means [MRR]

Level	Ton	Toff	Sv	Ip
1	3.103	6.873	5.750	5.177
2	6.587	5.693	5.547	7.010
3	7.953	5.077	6.347	5.457
Delta	4.850	1.797	0.800	1.833
Rank	1	3	4	2

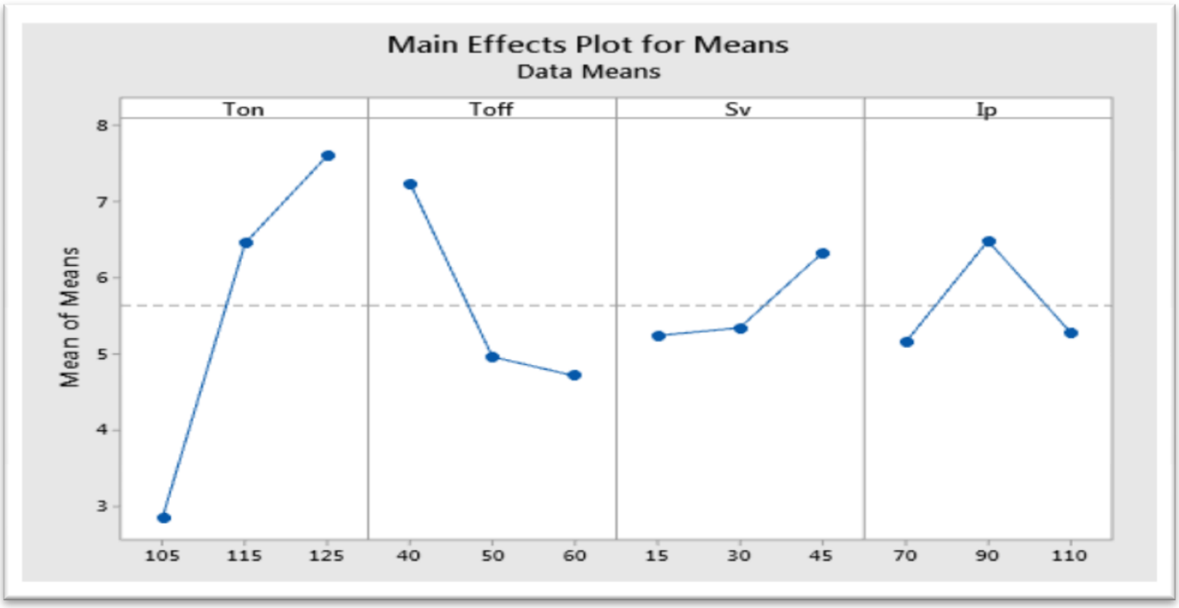
Table 6 Pooled ANOVA Table For means [MRR]

Source	DOF	Adj. SS	Adj. MS	F	P	%Contribution
Pulse on Time	2	1.81171	0.905855	170.10	0.006	81.41
Pulse Off Time	2	0.18701	0.093506	17.56	0.054	8.40
Peak Current	2	0.21577	0.107887	20.26	0.047	9.69
Error	2	0.01065	0.005325			0.47
Total	8	2.22515				100

3.2 Influence of Input parameters on MRR for heat treated D2 Tool steel

Experiments were performed by using L9 Taguchi Technique in order to study the effect of various process parameters on (Ton, Toff, Sv and Ip) on the MRR. As per the graphs provided by MINITAB 19 software (Fig.3) it is clear that, MRR increases with increasing Pulse on time and with increasing pulse off time MRR decreases. At the third level of Ton gets higher MRR whereas as at higher level of Pulse off time gets lower MRR. Further it can also see that spark set voltage has very slight effect on MRR as there is no much more difference in the values of MRR for initial and final levels. Up to the second level of Peak current MRR increases and after this it drops down suddenly. From the rank and delta value displayed in Table 7 and Table 8

Ton has the highest effect on MRR followed by Toff, Ip and Sv. From the values of S/N ratio it's clear that, a level having highest value gives maximum MRR hence, optimal combination of parameters would be A3-B1-C3-D2. From the Fig.3 and Table 8 it is clear that, Sv is less significant parameter hence by pooling it pooled ANOVA analysis carried out. From the Table 9 Ton has the highest contribution (76.52%) in the process of metal removal rate.



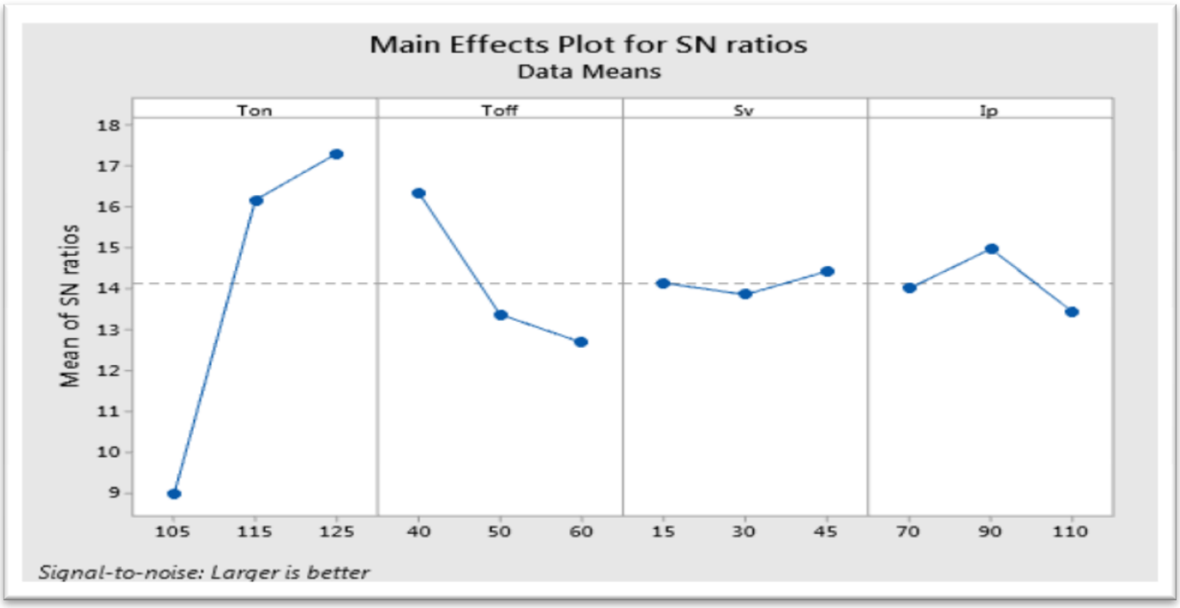


Fig.3 *Effect of input parameters on MRR (mean and S/N Data)*

Table 7 Response Table For Means [MRR]

Level	Ton	Toff	Sv	Ip
1	2.850	7.233	5.240	5.147
2	6.453	4.963	5.343	6.483
3	7.607	4.713	6.327	5.280
Delta	4.757	2.520	1.087	1.337
Rank	1	2	4	3

Table 8 Response Table For S/N Ratio [MRR]

Level	Ton	Toff	Sv	Ip
1	8.945	16.345	14.128	13.993
2	16.151	13.359	13.842	14.959
3	17.286	12.678	14.412	13.429
Delta	8.341	3.667	0.570	1.530
Rank	1	2	4	3

Table 9 ANOVA table for means [MRR]

Source	DOF	Adj. SS	Adj. MS	F	P	%Contribution
Ton	2	1.87298	0.93649	48.63	0.020	76.52
Toff	2	0.44487	0.22243	11.55	0.080	18.17
Ip	2	0.09132	0.04566	2.37	0.297	3.73
Error	2	0.03852	0.01926			1.5
Total	8	2.44768				100

3.3 Confirmation Experiment

By taking above predicted optimum process parameters range confirmation experiments were performed on both the material. Predicted and experimental results (Table 10) showed 4.92% and 4.56% variation which is less than 10% hence proposed methodology used and predicted optimal parameters range is correct.

Table 10 Predicted Optimal Values and Results of Confirmation Experiments for Cold-worked D2 Tool Steel

Performance Response	Optimal Condition	Predicted Value	Experimental value	% of error
MRR for Cold Worked D2 Tool Steel	A3B1C1D2	9.94	9.45	4.92
MRR FOR Heat Treated D2 Tool Steel	A3B1C3D2	10.74	10.25	4.56

IV. CONCLUSION

In the present investigation experiments were carried out on cold worked D2 tool steel and heat treated D2 Tool Steel by Taguchi L9 orthogonal array. The effect of various process parameters such as Ton, Toff, Sv and Ip is determined. From the results and ANOVA analyses following conclusions were obtained:

1. For both the material cold worked D2 tool steel and heat treated D2 tool steel Pulse on time has the highest effect on metal removal rate.
2. ANOVA results of MRR for cold worked D2 tool steel shows that, percentage contribution of Ton (81.41%), Toff (8.4%) and Ip (9.69%).
3. ANOVA results of MRR for cold worked D2 tool steel show the percentage contribution of Ton (76.52%), Toff (18.17%) and Ip (13.73%).
4. From the confirmation experiments metal removal rate for heat treated material increased as compared to cold worked D2 tool steel material.
5. For cold worked D2 tool steel material the optimal setting of parameters is found to be A3-B1-C1-D2.
6. For heat treated D2 tool steel material the optimal setting of parameters is found to be A3-B1-C3-D2.

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