International Journal of Engineering Sciences Paradigms and Researches (IJESPR)
Vol. 48, Special Issue, (TAME-2019, April 4-5, 2019)
(An Indexed, Referred and Impact Factor Journal approved by UGC- Journal No. 42581)
ISSN (Online): 2319-6564
www.ijesonline.com

MULTI PERFORMANCE CHARACTERISTICS OPTIMIZATION FOR HYBRID-WEDM UTILIZING TAGUCHI AND UTILITY FUNCTION

Sanjay Kumar[1], Sandeep Grover[2], R S Walia[3]

[1]Department of Mechanical Engineering YMCA University of Science and Technology, Faridabad-121006 INDIA

[2]Mechanical and Production Engineering Department Delhi Technological University, Delhi-110042, INDIA
E-mail: sanjaykpec@yahoo.co.in, TEL: 7838721130

Abstract

Abstract
The objective of this study was to check overall performance, which considered the relative commitment of surface roughness, cutting rate and residual stresses the quality attributes for Hybrid-WEDM. Ultrasonic vibration assistance in WEDM was used to meet the necessary discharge condition requirements efficiently and economically. In the accompanying, a system in light of utility idea and Taguchi strategy a philosophy has been proposed for deciding the ideal settings of process or parameters for multi-reaction/multi-qualities Hybrid-WEDM process. The multi- response streamlining of value attributes of Hybrid-WEDM has been completed in the accompanying areas. The main emphasis was given to optimize the precision and accuracy of the presented process for machining of High Carbon/High Chrome Tool Steel- AISI D3 materials. The present study has been carried out on the influence of four design factors: Continues/Discontinues vibration, Amplitude of vibration, Pulse-on time, Pulse-off time, Peak current and Wire feed rate. These were the most relevant parameters to be controlled for a normal Wire-EDM process. In this case, L27 Taguchi standard orthogonal array was chosen due to the number of factors and their levels in the study.The most favourable process parameters for the envisaged range of optimal Residual stress Surface rougness and Cutting rate were established.

***Keywords*:**Please provide a maximum of five keywords that describe the paper best.

1. Introduction

In recent years, ultrasonic vibration assisted Hybrid-WEDM have been developed to curve the limitations of normal Wire-EDM process. But the complex interdependency and interrelationship of performance restrain the best factors setting for which multiple responses could be optimized simultaneously. Although many mathematical techniques were available in literature to solve such types of

engineering optimization problems. The use of multiple criteria decision making methodology helped in reducing the computational effort involved (Rao, 2009). But some of these methods further complicated the optimization of the multi response problems of Hybrid-WEDM, as it required complicated mathematical models. Shiau, (1990) proposed a combined neuro-fuzzy model and Taguchi approach to resolve a complex parameter design problem with multiple responses. Rao and Gandhi (2002) applied graph theoretic approach to analysis the universal machinability of work material. They convert the quantitative variables affecting the machinability criteria into qualitative scale. Dubey, (2008) utilized the Taguchi loss function and utility function approach to optimize the multi-response electro-chemical honing machining (ECH). They confirmed the feasibility of this approach over vide range of parameters of ECH and also evaluated that this approach provide flexibility to the user for the selection of desirable quality attribute. Jangra et al., (2010) presented gray relationship analysis of multi-response optimization methodology to analysis machining of punching die D3 tool steel using wire-EDM process.Tripathy and Tripathy, (2016) proved the feasibility of TOPSIS and grey relational analysis for optimization of multi-response performance variable of powder-mixed EDM process.Kumar et al., (2012)analyzed the turning of unidirectional glass fiber-reinforced plastics utilizing Taguchi experimental design and utility concept. A utility model was developed by them to evaluate the utility of surface rough and metal removal rate for various input parameters and found that this approach provide appropriate solution for multi-response optimization problem. Kumar et al., (2017) proposed graph theoretic approach for analysis and modeling of Ultrasonic vibration assisted EDM process. They considered the qualitative as well as quantitative attribute on the same platform. An undertaking has been made through this investigation to check general Hybrid-WEDM execution, by considering the relative commitment of all the quality attributes at the same time. A strategy in light of utility capacity and Taguchi technique has been proposed for deciding the ideal settings of process or parameters for multi-reaction. The weighted-utility function for Hybrid -WEDM quality characteristics optimization is the novelty of the proposed study to identify the most appropriate combination of variable in conjunction with optimum utility of the process.

2. Multi-response optimization through utility concept

A product or a procedure is regularly assessed based on certain number of value qualities, sometimes clashing in nature. Accordingly, a joined measure is important to check its overall performance, which must consider the relative commitment of all the quality attributes. In the accompanying, a system in light of utility idea and Taguchi strategy a philosophy has been advanced for deciding the ideal settings of process or parameters for multi-reaction/multi-qualities process or product. The multi-response streamlining of value attributes of Hybrid-WEDM has been completed in the accompanying areas.

2.1 The Concept of Utility

Utility can be characterized as the convenience of an item or a procedure in reference to the desires for the clients. The general helpfulness of a procedure/item can be spoken to by a bound together record named as Utility which is the aggregate of the individual utilities of different quality attributes of the procedure/item. The methodological reason for Utility approach is to change the evaluated response of every quality characteristics into a typical index. In the event that Xi is the measure of adequacy of a trait (or quality characteristics) i and there are n properties assessing the result space, than the joint Utility capacity can be communicated as in Equation (1):

$$U(X_1, X_2, \ldots X_n) = f(U_1(X_1), U_2(X_2) \ldots U_n(X_n)) \quad \ldots (1)$$

Where $U_i(X_i)$ is the utility of the i^{th} characteristic.

The general Utility function equation (2) is the whole of individual utilities if the attributes are independent, and is given as follows:

$$U(X_1, X_2, \ldots X_n) = \sum_{i=1}^{n} U_i(X_i) \quad \ldots (2)$$

The attribute might be doled out weights relying on the relative significance or needs of the qualities. The general utility function in the wake of appointing weights to the qualities can be communicated as Equation (3):

$$U(X_1, X_2, \ldots X_n) = \sum_{i=1}^{n} W_i U_i(X_i) \quad \ldots (3)$$

Where W_i is the weight doled out to the property 'i'. The total of the weights for every one of the factor must be equivalent to 1.

2.2 The Utility Value determination

An inclination scale for every quality characteristic is developed for deciding its utility esteem. Two self-assertive numerical qualities (inclination number) 0 and 9 are allocated to the simply adequate and the best estimation of the quality characteristic individually. The inclination number (Pi) can be communicated as Equation (4) on a logarithmic scale as takes after, (Gupta and Murthy, 1980):

$$P_i = A \times \log\left(\frac{X_i}{X_i^{'}}\right) \quad \ldots (4)$$

Where Xi = estimation of any quality value or characteristic *i*

$X_i^{'}$ = simply acceptable estimation of value or characteristic *i*

A = constant

The estimation of A can be found by the condition that if Xi = X* (where X* is the ideal or best esteem), at that point Pi = 9 Equation(4a).

In this manner,

$$A = \frac{9}{\log \frac{X^*}{X_i^{'}}} \quad \ldots\ldots (4a)$$

The general utility can be computed by Equation (5) as takes after:

$$U = \sum_{i=1}^{n} W_i P_i \quad \ldots (5)$$

Subject to the condition: $\sum_{i=1}^{n} W_i = 1$

Among different quality attributes compose viz. smaller the better, higher the better, and ostensible the better proposed by Taguchi, the Utility concept would be higher the better sort. In this manner, if the Utility concept is augmented, the quality attributes considered for its assessment will naturally be improved (amplified or limited by and large).

Table 1: Experimental results of various response characteristics

Exp. No.	Cutting Rate (mm/min)			S/N Ratio (	Residual stresses (MPa)			S/N Ratio (dB)	Surface Roughness (µm)			S/N Ratio (
	R1	R2	R3		R1	R2	R3		R1	R2	R3	

				dB)								dB)
1	0.43	0.45	0.46	-7.01	198	185	198	-45.75	2.22	3.32	3.38	-2.33
2	2.9	2.82	2.98	9.24	252	260	266	-48.28	3.02	3.00	2.98	-9.54
3	5.22	5.32	5.26	14.43	292	295	287	-49.29	3.22	3.86	3.76	-11.18
4	2.39	2.41	2.45	7.66	134	136	142	-42.76	1.62	1.84	1.76	-4.82
5	4.63	4.65	4.54	13.27	225	256	265	-47.93	3.10	3.02	3.11	-9.76
6	3.52	3.51	3.47	10.88	302	310	305	-49.71	3.18	3.53	3.43	-10.59
7	1.45	1.47	1.43	3.23	235	234	220	-47.23	1.68	1.36	1.47	-3.57
8	2.76	2.78	2.66	8.73	226	227	216	-46.97	2.36	2.96	2.52	-8.38
9	4.16	4.18	4.08	12.34	284	298	286	-49.23	3.5	3.06	3.42	-10.45
10	3.51	3.58	3.45	10.91	291	287	268	-49.01	3.32	3.08	2.98	-9.91
11	1.92	1.88	1.92	5.60	193	218	265	-47.13	1.56	1.62	1.58	-4.01
12	3.75	3.83	3.77	11.56	268	243	243	-48.01	2.96	2.64	2.84	-8.99
13	3.63	3.75	3.65	11.31	175	183	234	-45.98	1.60	1.52	1.57	-3.88
14	4.45	4.57	4.73	13.22	221	226	231	-47.08	2.06	1.86	1.97	-5.87
15	3.53	3.75	3.79	11.33	126	134	136	-42.42	1.58	1.60	1.59	-4.03
16	2.76	2.88	2.78	8.96	170	167	174	-44.63	2.06	1.66	1.87	-5.44
17	3.37	3.49	3.36	10.64	231	154	167	-45.44	1.90	1.72	1.83	-5.19
18	4.23	4.35	4.24	12.61	267	265	284	-48.70	1.65	2.06	2.04	-5.69
	58.61	59.67	59.02		4090	4078	4187		41.59	41.71	42.1	
	$\overline{T}_{CR}$ = Overall mean of CR= 3.28				$\overline{T}_{RS}$ = Overall mean of RS= 228.80				$\overline{T}_{SR}$ = Overall mean of SR=2.32			

2.3 The Algorithm

The stepwise system for completing multi-response improvement with Utility concept and Taguchi strategy is shown as:

1. Use the Taguchi framework trial plan and examination to discover the ideal estimation of every one of the chosen process response.
2. Construct an inclination scale for every response in view of their ideal esteem and least worthy level (Eq. 4).
3. Assign weights (Wi) in light of the experience and client preference, keeping in see that the aggregate entirety of weights is equivalent to 1.
4. Find general utility qualities for various test preliminary conditions considering every one of the response associated with multi- response enhancement (Eq. 5).
5. Use the qualities decided in stage 4 as crude response of various preliminary states of the test framework. On the off chance that preliminaries are rehashed, discover S/N ratio (HB compose), as the utility is a higher-the-better write trademark [Roy (1990)]
6. Analyze the outcomes according to the standard technique recommended by Taguchi [Roy (1990)].
7. Find the ideal settings of process parameters for mean and S/N utility in view of the investigation performed in stage 6.
8. Predict ideal estimations of various response qualities for the ideal parametric setting that augments the general utility as decided in stage 7.
9. Conduct affirmation tests to check the ideal outcomes.

2.4 Utility for the Model of CR, RS and SR

In view of the system created in the past section, following case have been considered to get the ideal settings of the procedure parameters of Hybrid-WEDM for foreseeing the ideal estimations of joined responses. All the three quality attributes (CR, RS and SR) have been incorporated into utility response. Taguchi L27 symmetrical exhibit (OA) [Roy (1990)] has been adopted for directing the investigations. Type of vibration, amplitude of vibration (B), peak current (C), duty cycle (D), workpiece thickness (E) and wire feed rate (F) are chosen as information parameters. The watched estimations of response parameters are given in Table 1 Response parameters (quality attributes) were Cutting rate (CR), residual stresses (RS) and surface roughness (SR), when these were advanced independently; the outcomes of results was delivered in Table 2.

Table 2: Optimal setting and values of process parameters (individual quality characteristics optimization)

Response Characteristics	Optimal level of process parameters	Significant process parameters	Predicted optimal value of quality characteristics
CR	A2B2C3D3E3F2	A, B, C, D, E, F	6.45 mm/min
RS	A2B2C1D1E2F3	A, B, C, D, E, F	86.53 MPa
SR	A2B3C1D1E1F3	A, B, C, D, E, F	0.49 µm

Following is the stepwise procedure for transforming experimental data into utility data.

2.4.1.Construction of preference scales

a) Preference scale for Cutting Rate (P_{CR}):

X* = Optimal value of Cutting Rate =6.45 (refer Table 2)

$X_i^{'}$ = Just acceptable value of CR = 0.42 (All the observed values of CR are greater than 0.42)

Using Equation (4a) for calculating A_{CR}

$$A_{CR} = \frac{9}{\log \frac{X^*}{X_i^{'}}} = 7.59$$

Following equation is obtained from Equation 4:

$$P_{CR} = 7.59 \times \log\left(\frac{X_{CR}}{0.42}\right)$$

…..(6)

b) Preference scale for Residual stresses (P_{RS}):

X* = Optimal value of RS = 86.53 (refer Table 2)

$X_i^{'}$ = Just acceptable value of RS = 315 (All the observed values of RS are lesser than 315)

Using Equation (4a) for calculating A_{RS}

$$A_{RS} = \frac{9}{\log \frac{X^*}{X_i^{'}}} = -16.36$$

Following equation is obtained from Equation (4):

$$P_{RS} = -16.36 \times \log\left(\frac{X_{RS}}{315}\right)$$

…..(7)

c) Preference scale for SR (P_{SR}):
X* = Optimal value of SR = 0.49 (refer Table 2)

$X_i^{'}$ = Just acceptable value of SR = 3.9 (All the observed values of SR are lesser than 3.9)

Using Equation (4a) for calculating A_{SR}

$$A_{SR} = \frac{9}{\log\frac{X^*}{X_i^{'}}} = -10.05$$

Following equation is obtained from Equation (4):

$$P_{SR} = -10.05 \times \log\left(\frac{X_{SR}}{3.9}\right)$$

…..(8)

2.4.2. Calculation of Utility Value

Meet weights (1/3 each) have been allocated to the chosen quality attributes expecting every one of the qualities is similarly imperative. Be that as it may, these weights can be differed relying on the case or client prerequisites, assuming any.

The accompanying connection was utilized to compute the utility function in view of the exploratory preliminaries:

$$U(n,r) = P_{CR}(n,r) \times W_{CR} + P_{RS}(n,r) \times W_{RS} + P_{SR}(n,r) \times W_{SR}$$

…. (9)

Where

$$W_{CR} = 0.33; \quad W_{RS} = 0.33; \quad W_{SR} = 0.33$$

n is the trial number (n = 1,2,3,….,18) and *r* is the repetition number (r = 1,2,3). The calculated Utility values are shown in Table 3.

Table 3: Calculated Utility data based on responses

Trail No.	Utility values			S/N ratio (dB)
	R1	R2	R3	
1	2.79	2.88	2.71	8.92
2	2.99	2.90	2.92	9.35
3	3.19	2.93	3.02	9.67
4	5.16	4.95	4.93	14.00
5	3.73	3.47	3.32	10.87
6	2.71	2.49	2.56	8.23
7	3.25	3.58	3.58	10.77
8	3.55	3.22	3.52	10.68
9	2.89	2.98	2.89	9.31
10	2.73	2.89	3.06	9.19
11	4.12	3.76	3.36	11.38
12	3.16	3.57	3.45	10.58
13	5.01	5.01	4.36	13.56
14	4.32	4.44	4.34	12.80
15	5.77	5.67	5.65	15.11
16	4.41	4.81	4.51	13.19
17	4.03	5.16	4.84	13.25
18	4.14	3.87	3.69	11.79

R1, R2, R3 = repetitions of experiments against each of the trial conditions.

3. Analysis of Utility data for optimal setting of process parameters

The average and main response in terms of Utility values and S/N ratio (Tables 4 and 5) are plotted in Figure 1 to 6. It can be observed from Figure 1 to6 that the 2nd level of type of vibration (A_2), 2nd level of amplitude of vibration (B_2), 3rd level of peak current (C_3), 3rd level of duty cycle (D_3), 2nd level of work piece thickness (E_2), and 2nd level of wire feed rate (F_2) are expected to yield a maximum values of the utility and S/N ratio within the experimental range.

It can be seen from Table 6 that all the parameters did huge impact (at 95% confidence level) on the utility function. Then again, from Table 7 indicates that the types of vibration, amplitude of vibration are the most astounding donors of general utility of Hybrid-WEDM process. In this way, other immaterial parameters for S/N ratio can be taken as economy factor. The ideal estimations of utility and hence the ideal estimations of response attributes in thought are anticipated at the above levels of significant parameters.

Table 4: Main Effects of Utility Raw Data (: CR, RS and SR)

Level	Type of vibration	Amplitude of vibration	Peak current	Duty cycle	Workpiece thickness	Wire feed rate
L1	3.30	3.14	3.92	4.14	3.48	3.61
L2	4.23	4.33	3.78	3.67	4.18	3.67
L3	*	3.83	3.59	3.48	3.64	4.01
L2-L1	0.93	1.19	-0.15	-0.48	0.70	0.06
L3-L2		-0.50	-0.19	-0.18	-0.54	0.34

Table 5: Main Effects of Utility S/N Data (: CR, RS and SR)

Level	Type of vibration	Amplitude of vibration	Peak current	Duty cycle	Workpiece thickness	Wire feed rate
L1	10.20	9.85	11.61	12.00	10.65	10.87
L2	12.32	12.43	11.40	11.15	12.15	11.07
L3	*	11.50	10.78	10.63	10.97	11.83
L2-L1	2.12	2.58	-0.22	-0.84	1.50	0.20
L3-L2	*	-0.93	-0.61	-0.52	-1.180	0.76

Table 6: ANOVA for Utility raw data (CR, RS and SR)

SOURCE	SS	DOF	V	P	F-Ratio
Type of Vibration	11.59	1	11.59	27.04	54.51
Amplitude of Vibration	12.909	2	6.45	30.10	30.35
Peak current	1.009	2	0.50	2.33	54.51
Duty Cycle	4.159	2	2.08	9.69	9.77
Workpiece Thickness	2.66	2	1.33	6.20	6.25
Wire Feed Rate	1.63	2	0.82	3.81	3.84
ERROR	8.93	42	0.21	20.83	
T	42.86	53		100	

Significant at 95% confidence level, SS: Sum of Squares; DOF: Degree of Freedom; V: Variance; F-Fisher test factor tabulated for Type of vibration: 4.07, F-Fisher test factor tabulated for other parameters: 3.22.

Table 7 ANOVA Utility S/N Data: (CR, RS and SR)

SOURCE	SS	DOF	V	P	F-Ratio
Type of Vibration	20.19	1	20.19	29.65	13.57
Amplitude of Vibration	20.49	2	10.25	30.09	6.89
Peak current	2.20	2	1.10	3.22	0.74
Duty Cycle	5.70	2	2.85	8.36	1.91
Workpiece Thickness	7.52	2	3.76	11.03	2.53
Wire Feed Rate	3.09	2	1.54	4.53	1.04
ERROR	8.93	6	1.49	13.11	
T	68.11	17	*	100	

Significant at 95% confidence level, SS: Sum of Squares; DOF: Degree of Freedom; V: Variance; F-Fisher test factor tabulated for Type of vibration: 5.99, F-Fisher test factor tabulated for other parameters: 5.14.

4. Optimal values of quality characteristics (predicted means)

The average values of all the response characteristics at the optimum levels of significant parameters with respect to utility function are recorded in Table 1. The optimal values of the predicted means (μ) of different response characteristics can be obtained from the following Equation (10):

The normal estimations of all the response characteristics at the ideal levels of noteworthy parameters concerning utility function are recorded in Table 3. The ideal estimations of the anticipated means (μ) of various response attributes can be obtained from the accompanying condition (10):

$$\mu_{Utility} = A2 + B2 - 3\overline{T}$$

…..(10)

Where, A_2-Second level of type of vibration, B_2-Second level of amplitude of vibration and

International Journal of Engineering Sciences Paradigms and Researches (IJESPR)
Vol. 48, Special Issue, (TAME-2019, April 4-5, 2019)
(An Indexed, Referred and Impact Factor Journal approved by UGC- Journal No. 42581)
ISSN (Online): 2319-6564
www.ijesonline.com

$\overline{T}$ = Overall mean. The 95% confidence interval of confirmation experiments (CI_{CE}) can be computed [Roy (1990)] by using the following equation (11):

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]}$$

….. (11)

Where, $F_{\alpha}(1, f_e)$ = The F-ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e., R = Sample size for conformation experiments, V_e = Error variance, $n_{eff} = \frac{N}{1+DOF}$, N= total number of trials, and DOF= Total degrees of freedom associated in the estimate of mean response.

a) Cutting Rate:

$$\mu_{CR} = A_2 + B_2 - \overline{T} = 3.99$$

Where A_2 = 3.52, B_2 = 3.75 (Table 5) and T_{CR} = 3.28 (Table 2)

The following values have been obtained by the ANOVA:

N = 54, f_e = 42; v_e = 0.42, n_{eff} = 4.5, R= 3, $F_{0.05}$ (1, 42) = 4.0764

From Equation(11), CI_{CE} = ±0.98

The predicted optimal range (for conformation runs of three experiments) for CR is given by CI_{CE}: $3.01 < \mu_{CR} < 4.97$

b) Residual Stresses:

$$\mu_{RS} = A2 + B2 - \overline{T} = 194.62$$

Where A2 = 215.59, B2 = 207.83 from (Table 5): T_{RS} = 228.80 (Table 2)

The following values have been obtained by the ANOVA:

N = 54, f_e = 42; v_e =1016.052, n_{eff} = 4.5, R= 3, $F_{0.05}$ (1, 42) = 4.0764

From Equation (11), CI_{CE} = ± 48.16

The predicted optimal range (for conformation runs of three experiments) for Residual stresses is given by CI_{CE}: $146.46 < \mu_{RS} < 242.78$

c) Surface Roughness:

$$\mu_{SR} = A2 + B2 - \overline{T} = 1.93$$

Where A2 = 2.03, B2 = 2.22 (Table 5): T_{SR} = 2.32 (Table 2)

The following values have been obtained by the ANOVA:

N = 54, f_e = 42; v_e = 0.08, n_{eff} = 4.5, R= 3, $F_{0.05}$ (1, 42) = 4.0764

From Equation 11, CI_{CE} = ± 0.43

The predicted optimal range (for conformation runs of three experiments) for SR is given by CI_{CE}: $1.50 < \mu_{SR} < 2.36$

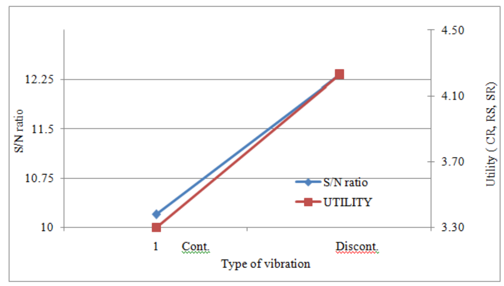

Figure. 1: Effect of Type of Vibration on S/N ratio and Utility

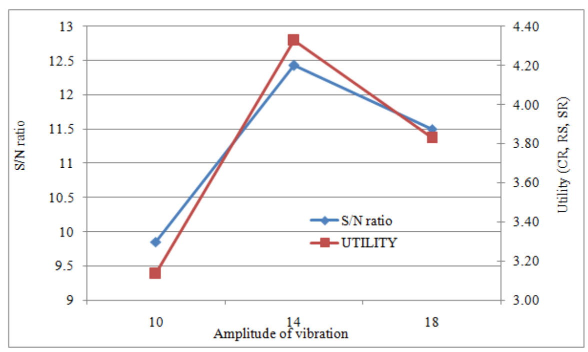

Fig. 2 Effect of Amplitude of Vibration on S/N ratio and Utility

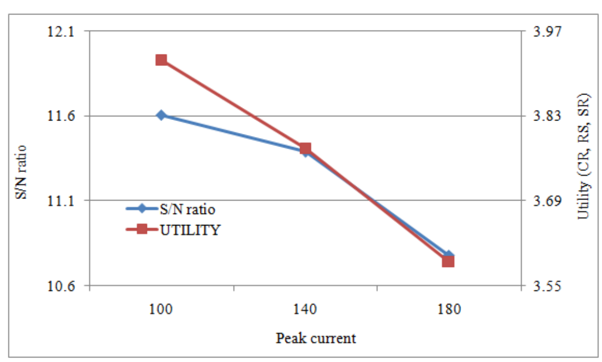

Figure 3 Effect of Peak current on S/N ratio and Utility

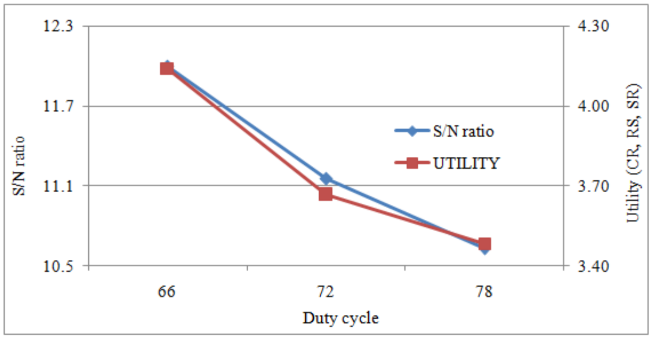

Figure 4 Effect of Duty cycle on S/N ratio and Utility

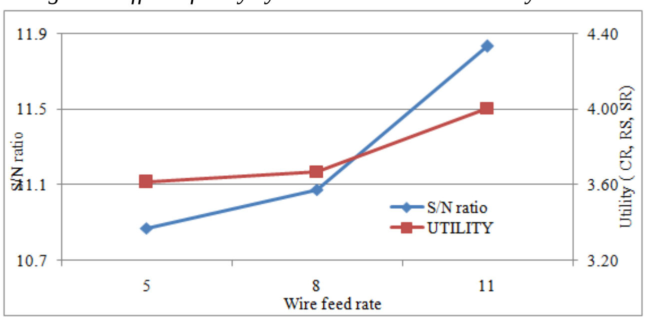

Figure 5 Effect of Wire feed rate on S/N ratio and Utility

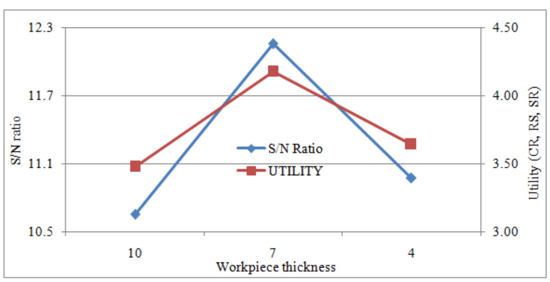

Figure 6 Effect of Workpiece thickness on S/N ratio and Utility

The data from Table 4 and 5 were plotted in Figures (1-6). It is clear from the Figure 1 that discontinuous vibration increase the overall utility of Hybrid-WEDM process. Whereas, the utility for the proposed process is maximum for second level of amplitude of vibration as indicated in Figure 2. The peak current and duty cycle increase the cutting rate but decrease the utility function. It is clear for Figure 3 and 4 that the best utility was obtained at first level of peak current and duty cycle. Although the involvement of wire feed rate for the performance of Hybrid-WEDM was negligible but the higher level of wire feed rate desired to obtain maximum utility as shown in Figure 5. The utility function is uncertain under workpiece thickness. In Figure 6 the maximum utility is attained at second level of workpiece thickness.

5. Conclusion

Higher amplitude was desirable to create a strong string effect in the discharge gap by producing large pressure gradient to enhance flushing. However, amplitude of vibration increased beyond 14µm has negative effects on response. This was caused by the insufficient time interval to clear the gap from contaminated. A noteworthy contrast seen in the surface roughness and residual stresses, while machining with continuous and discontinuous ultrasonic vibration helped Wire EDM. The most favourable significance of process parameters for the envisaged range of optimal Residual stresswere like so: Type of Vibration (A, 2nd level), Amplitude of Vibration (B, 2nd level) = 14µm , Peak Current (E, 1st level)=100 Amp., Duty cycle (F, 1st level) = 66%, Workpiece Thickness (C, 2nd level) = 7mm and Wire feed rate (D, 3rd level) = 11 mm/min. The most favourable significance of process parameters for the envisaged range of optimal material erosion ratewere as follows: Type of Vibration (A, 2nd level)= discountinous, Amplitude of Vibration (B, 2nd level) = 14µm , Peak Current (E, 3rd level)=180 Amp., Duty cycle (F, 3rd level) = 78%, Workpiece Thickness (E, 3rd level) = 4 mm and Wire feed rate (D, 2nd level) = 8 mm/min.

References

Dubey, A.K., 2008. Multi-response optimization of electro-chemical honing process using utility-based Taguchi approach. Int. J. Adv. Manuf. Technol.

Gupta, V., Murthy, P.., 1980. An Introduction to Engineering Design Method. Tata McGraw-Hill, New Delhi.

Jangra, K., Jain, A., Grover, S., 2010. Optimization of multiple-machining characteristics in wire electrical discharge machining of punching die using Grey relational analysis. J. Sci. Ind. Res. (India). 69, 606–612.

Kumar, S., Meenu, Satsangi, P.S., Sardana, H.K., 2012. Optimization of surface roughness in turning unidirectional glass fiber reinforced plastics (UD-GFRP) composites using polycrystalline diamond (PCD) cutting tool. Indian J. Eng. Mater. Sci. 19, 163–174.

Kumar, S., Grover, S., Walia, R.S., 2017b. Analyzing and modeling the performance index of ultrasonic vibration assisted EDM using graph theory and matrix approach. Int. J. Interact. Des. Manuf. 12, 225–242. https://doi.org/10.1007/s12008-016-0355-y

Rao, S.S., 2009. Engineering Optimization. https://doi.org/10.1002/9780470549124

Rao, R.V., Gandhi, O.P., 2002. Failure cause analysis of machine tools using digraph and matrix methods.

Int. J. Mach. Tools Manuf. 42, 521–528.

Roy, R., 1990. A primer on the Taguchi method. Comput. Integr. Manuf. Syst. 5, 246. https://doi.org/10.1016/0951-5240(92)90037-D

Shiau, G.H., 1990. A study of the sintering properties of iron ores using the Taguchi's parameter design. J. Chinese Stat. Assoc. 28, 253–275.

Tripathy, S., Tripathy, D.K., 2016. Multi-attribute optimization of machining process parameters in powder mixed electro-discharge machining using TOPSIS and grey relational analysis. Eng. Sci. Technol. an Int. J. 19, 62–70. https://doi.org/10.1016/j.jesth.2015.07.010.