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Multi-Performance Characteristics Optimisation for Titanium 6Al-4V ELI Using Taguchi and Weighted Utility Function

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Abstract: In the present study, a multi-response optimisation method based on the weighted utility concept is proposed for wire-cut electrical discharge machining of Titanium 6Al-4V ELI alloy. The machining attributes being explored are cutting rate, residual stress and micro-hardness of the machined surface. In this examination, Taguchi and Utility Function design of experimentation is arranged and executed as a robust design methodology. The investigation indicated that the utility function of cutting rate, residual stresses, and micro-hardness increases with increasing peak current and gap voltage, whereas it decreases with increasing wire feed rate and flushing pressure. Out of the six selected controllable parameters, the significant contributors to the overall utility function of the proposed alloy machining are flushing pressure, Peak current, Gap voltage, Duty cycle, and Wire feed rate. Wire tension is a less significant factor. Nonlinear relationships were observed for duty cycle and wire tension. Multi-response optimisation using the utility concept provides collective optimisation of both responses to improve the process mean.

Keywords: Multi-Performance Characteristics Optimisation, Titanium 6Al-4V ELI, Taguchi Method, Weighted Utility Function, Wire-cut EDM, Cutting Rate, Residual Stress, Micro-hardness.

1. Introduction

Ti6Al4V ELI and Ti-6Al-4V (grade 5) both offer an excellent combination of properties, including corrosion resistance, strength, and durability, and are commonly utilised for medical implants. Ti6Al4V likewise has various applications in the medical industry. The biocompatibility of Ti6Al4V is excellent, particularly when direct contact with tissue or bone is required. Ti6Al4V ELI (Grade 23) is fundamentally the same as Ti6Al4V (Grade 5); however, Ti6Al4V ELI contains reduced degrees of oxygen, nitrogen, carbon and iron. ELI is short for “Extra Low Interstitials”, and these lower interstitials give improved malleability and better crack toughness for the Ti6Al4V ELI material.

This alloy is an extraordinary biomaterial with higher biocompatibility (due to reduced oxygen levels—the maximum oxygen content is 0.13%—and increased nitrogen and iron) compared to Ti6Al4V, so Ti6Al4V ELI is chosen over Ti6Al4V. It conforms to ASTM F136 and is commonly referred to as implant-grade 6-4 Titanium [12]. Its biocompatibility makes it particularly suitable for surgical implant applications and other orthopaedic clinical tools and devices. Among its fundamental uses in the medical industry are orthopaedic implants, bone and joint replacements, dental root inserts, surgical clips, and cryogenic vessels.

Regardless of these benefits, this alloy comes under the classification of “hard-to-machine” material. Some difficult attributes of this composite are high hardness and coefficient of friction, poor resistance to abrasive and adhesive wear, and low thermal conductivity [4]. As advancements of MOSFET devices with ultra-quick recovery diodes able to work at ultra-high frequency (MHz) with pulse lengths of 50–1000 ns and full control of pulse shape, bipolar pulse in the Wire EDM process gives a successful answer for machining such combinations with complex shapes and profiles and improvements in reliability [7], [16]. The super-precise wire-cut EDM can give dimensional accuracy in the 1 µm class. The full utility of controllable factors could improve the overall machining performance of Ti6Al4V ELI. It has been observed in the literature that a specific setting of input-controllable factors for an optimum response characteristic in Ti6Al4V ELI machining may not be appropriate across different qualities [11].

In addition, the complex interrelationships and interdependencies among these attributes pose resistance to the ideal utility of this material for machining [6]. Accordingly, in this circumstance involving numerous quantifiable response attributes of wire cut EDM, an optimisation methodology is required to provide a unified standard for representing the overall ideal setting of process-controllable factors across all responses. These sorts of optimisation issues should be assessed by multi-response optimisation techniques [19]. Non-traditional machining methods continually seek ways to enhance profitability and productivity. Today, these endeavours regularly include high-level projects that utilise trendy expressions that incorporate cloud computing, data-driven manufacturing, cyber-physical frameworks and Industry 4.0.

These serious activities are astounding ideas and can deliver noteworthy outcomes. Notwithstanding, manufacturing realities frequently interfere with the execution of such aspiring plans, and a basic truth is the presence of

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uncontrolled waste in the manufacturing process [10]. Before discussing digitisation and improvement, it is important for a maker to examine its tasks, identify where waste occurs, and develop techniques to reduce or eliminate it. Controlling waste is the initial phase in setting up a manufacturing organisation to adopt advanced smart manufacturing processes.

Although numerous mathematical techniques have been proposed in the literature to solve such engineering and optimisation issues, the use of various measures of a dynamic technique helped reduce the computational effort involved [14]. Be that as it may, a portion of these strategies further complicate the solution of the multi-response problems in Wire Cut EDM, as they require complex numerical models. Shiau [17] proposed a combined neuro-fuzzy model and Taguchi approach to address an unpredictable parameter design issue with varying responses. Rao and Gandhi [13] applied a graph-theoretic approach to investigate the general machinability of work material. They convert the quantitative factors influencing the machinability measures into a qualitative scale. Dubey [3] used the Taguchi loss and utility functions to streamline multi-response electrochemical honing (ECH) machining. They affirmed the feasibility of this methodology across a wide range of ECH parameters and assessed that it provides the client with flexibility in selecting desirable-quality property. Tripathy et al. [18] demonstrated the feasibility of TOPSIS and grey relational analysis for enhancing multi-response performance variables in powder mixed EDM machining. Kumar et al. [8] analysed the turning of unidirectional glass-fibre-reinforced plastics using the Taguchi experimental design and utility concept.

They developed a utility model to assess the utility of surface roughness and metal removal rate across different controllable input factors and found that this methodology provides an appropriate answer to the multi-response optimisation issue. Sharma et al. [16] applied the Taguchi method and a utility function to enhance the coating quality produced by a low-pressure cold-spray process. As they indicated, the coating exhibited a multi-response paradigm that could be improved by applying the proposed technique.

2. Experimentation Details

Data information was obtained from a continuous examination of responses gathered on a Sprintcut (Dlx) CNC wire cut EDM. This machine is utilised for testing owing to its ELCAM window-based, full-featured part programming. A brass wire cathode with a diameter of 0.25 mm is utilised to erode cylindrical material rods. The travelling wire is constantly under specific tension, fed by a wire-feeding mechanism, and passes through extremely tight-tolerance diamond wire guides above and below the workpiece. Water is utilised as the dielectric and is flushed at high pressure from the upper and lower nozzles to form a water column around the wire. Titanium alloy Ti-6Al-4V ELI grade 23 was taken as the workpiece material. Among the three kinds of alloys (alpha-beta phase, alpha phase, beta phase) the chosen alloy is an alpha-beta-phased combination. The polarity of the workpiece has been chosen as positive. The experimental plan is based on a 1-factor-2-level and 5-factor-3-level (1×2, 5×3) L18 Orthogonal Array (OA). Here, Flushing Pressure, Peak Current, Gap Voltage, Duty cycle, Wire Tension, and Wire Feed Rate are considered the input controllable machining parameters, with each varied at three different levels in the influencing tests, as shown in Table 1. Then the output parameters, such as cutting rate, micro-hardness, and residual stresses, are recorded and confirmed for each trial.

Table 1. The controlled parameters and their levels of experimental design

Factor	Parameters	Level 1	Level 2	Level 3
A	Flushing Pressure	High (8)	Low (12)	-
B	Peak Current	90	120	150
C	Gap Voltage	20	30	40
D	Duty Cycle	60 (48,32) %	67.5 (112,54) %	75 (144,48) %
E	Wire Tension	3	7	11
F	Wire Feed Rate	2	3	4

The non-linear behaviour, if it exists, among the process input-controllable factors must be examined when multiple response levels are utilised. Accordingly, five factors were analysed at three levels. In this stage, Taguchi's mixed-level design is chosen, keeping two levels of Flushing pressure and the remaining five factors studied at three levels. The two-level controllable factor has 1 DOF, and the five three-level controllable factors have 10 DOF, i.e., the total DOF required is 11 [= (1×1) + (5×2)]. The most fitting orthogonal array for this situation is the L18 (2^1 × 3^7) OA with 17 [= 18−1] DOF. Standard L18 OA with the controllable factors assigned is utilised for the initial six columns. The unassigned columns were treated as errors. For every trial, tests were duplicated three times. In this work, the portable X-ray Residual Stress Analyser μ-X360, a non-destructive X-ray analyser from Pulstec Industrial Corporation Limited, was used to measure residual stress in wire-cut EDM-machined surfaces. The micro-hardness of the machined surfaces is estimated using an AEC1107 auto-turret-type computerised micro-hardness testing machine manufactured by Ashian Engineering Company, India. A 500 g load was applied for 10 minutes to quantify micro-hardness.

3. Material Examined

The work material used as the test specimen was Titanium 6Al-4V ELI (Grade-23) alloy in the form of round bars with a diameter of 10 mm and a cutting length of 200 mm. The chemical composition of the workpiece is 6% Al, 4% V, 0.20% O, 0.015% P, 0.2 Fe, 0.06 C and 89.65% Ti. This material is suitable for a wide variety of orthopaedic surgical implants, aerospace components and automotive applications. The mechanical characteristics of the titanium alloy (Grade-5) include Knoop hardness 354 HRC, ultimate tensile strength 44 GPa, percentage elongation at break 15%, Yield strength 790 MPa, and shear modulus 550 MPa.

4. Taguchi Weighted Utility Function Methodology

Utility can be characterised as the usefulness of a product or process with respect to clients' expectations. A product or process is typically assessed based on a set of quality attributes, some of which are conflicting. Accordingly, a combined measure is important for assessing overall performance and must consider the relative contributions of all quality characteristics. In the following, a methodology based on the utility concept and the Taguchi technique has been developed to determine the optimal settings of process- or input-controllable factors for a multi-response/multi-characteristic process or product. The multi-characteristic optimisation of the quality characteristics for wire-cut EDM of Titanium 6Al-4V ELI (Grade-23) combination has been completed. The overall optimal quality characteristic for Titanium 6Al-4V ELI machining can be represented by a unified index. Utility is the sum of the individual utilities of the process's quality characteristics. The basis of the weighted-utility methodology is to change the assessed objective response of every quality characteristic into a common index.

If Yi is the measure of effectiveness of an attribute (or quality characteristic) i and there are n attributes evaluating the outcome space, then the joint utility function can be expressed [1] as:

$$R\ (Y_1,\ Y_2,\ \ldots,\ Y_n) = f\ (R_1(Y_1),\ R_2(Y_2),\ \ldots,\ R_n(Y_n)) \qquad (1)$$

where Ri (Yi) is the utility of the i-th attribute as in Equation (1). The overall utility function is the sum of the individual utilities if the attributes are independent, and is given as follows:

$$R\ (Y_1,\ Y_2,\ \ldots,\ Y_n) = \Sigma\ [\ i = 1 \text{ to } n]\ R_i\ (Y_i) \qquad (2)$$

The attributes may be assigned weights based on the relative importance or priority of the characteristics. The overall utility function after assigning weights to the attributes can be expressed as:

$$R\ (Y_1,\ Y_2,\ \ldots,\ Y_n) = \Sigma\ [\ i = 1 \text{ to } n]\ W_i\ R_i\ (Y_i) \qquad (3)$$

where Wi is the weight assigned to attribute i. The sum of the weights for all the attributes must be equal to 1.

5. Utility Value Determination

A preference scale for each quality characteristic is constructed for determining its utility value. Two arbitrary numerical values (preference numbers), 0 and 9, are assigned to the just acceptable and the best value of the quality characteristic, respectively. The preference number (Pi) can be expressed on a logarithmic scale as follows [5]:

$$P_i = A \times \log\ (Y_i\ /\ Y_i') \qquad (4)$$

where Yi = value of any quality characteristic or attribute i, Yi' = just-acceptable value of quality characteristic or attribute i, and A = constant. The value of A can be found by the condition that if Yi = Y* (where Y* is the optimal or best value), then Pi = 9. Therefore:

$$A = 9\ /\ \log\ (Y^*\ /\ Y_i') \qquad (4a)$$

The overall utility can be calculated as follows:

$$U = \Sigma\ [\ i = 1 \text{ to } n]\ W_i\ P_i, \text{ subject to } \quad \Sigma\ W_i = 1 \qquad (5)$$

Among the various quality-characteristic types (smaller-the-better, higher-the-better, and nominal-the-better) suggested by Taguchi, the utility function would be the higher-the-better type. Therefore, if the utility function is maximised, the quality characteristics considered for its evaluation will automatically be optimised (maximised or minimised as the case may be).

Table 2. Experimental results of various response characteristics

Exp. No.	Cutting Speed (mm/min)			S/N (dB)	Residual Stresses (MPa)			S/N (dB)	Micro Hardness			S/N (dB)
	R1	R2	R3		R1	R2	R3		R1	R2	R3	
1	0.40	0.36	0.42	-8.16	103	109	98	-40.29	174	178	169	-13.08
2	1.73	1.72	1.79	4.84	235	211	256	-47.41	239	241	238	-3.68
3	1.66	1.78	1.55	4.38	156	145	166	-43.86	193	189	197	-12.04
4	1.33	1.36	1.11	1.94	181	198	165	-45.19	191	188	195	-10.91
5	2.04	2.19	1.80	5.98	241	221	256	-47.60	222	214	231	-18.59
6	1.80	1.82	1.78	5.10	261	248	276	-48.36	241	245	236	-13.08
7	1.90	1.80	1.95	5.48	244	238	249	-47.74	238	241	238	-4.77
8	2.24	2.21	2.23	6.95	306	312	294	-49.66	258	256	259	-3.68
9	2.23	2.16	2.33	6.99	241	245	237	-47.64	221	226	221	-9.21
10	0.98	1.01	1.09	0.20	54	66	44	-34.87	149	142	141	-12.79

Exp. No.	Cutting Speed (mm/min)			S/N (dB)	Residual Stresses (MPa)			S/N (dB)	Micro Hardness			S/N (dB)
	R1	R2	R3		R1	R2	R3		R1	R2	R3	
11	0.85	0.75	0.80	-1.97	119	125	110	-41.45	147	142	151	-13.08
12	2.17	2.12	2.22	6.72	282	295	274	-49.06	238	228	247	-19.56
13	1.73	1.75	1.72	4.78	199	188	212	-46.02	201	206	195	-14.82
14	1.50	1.51	1.48	3.50	188	201	178	-45.54	194	197	196	-3.68
15	2.15	2.16	2.01	6.46	257	266	251	-48.23	187	188	184	-6.37
16	2.09	1.90	2.11	6.13	218	221	210	-46.70	197	189	206	-18.59
17	1.87	1.95	1.75	5.35	222	226	216	-46.90	192	188	197	-13.08
18	2.62	2.69	2.59	8.41	312	325	304	-49.93	256	252	259	-10.91
Sum	31.29	31.24	30.73		3819	3840	3796		3738	3710	3760	

T_CR = overall mean of CR = 1.73;   T_RS = overall mean of RS = 212.13;   T_SR = overall mean of MH = 207.56.

6. The Algorithm

The stepwise procedure for carrying out multi-response optimisation using the utility concept and the Taguchi method is illustrated below. (i) Use the Taguchi matrix experimental design and analysis to find out the optimal value of each of the selected process responses. (ii) Construct a preference scale for each response based on its optimal value and minimum acceptable level (Eq. 4). (iii) Assign weights (Wi) based on experience and customer preference, keeping in view that the total sum of weights is equal to one. (iv) Find overall utility values for different experimental trial conditions, considering all the responses involved in multi-response optimisation (Eq. 5). (v) Use the values determined in the previous step as raw responses of different trial conditions of the experimental matrix; if trials are repeated, find S/N ratios (larger-is-better type), as the utility is a larger-the-better-type characteristic [15]:

$$(S/N)_{HB} = -10 \log \left[(1/N) \Sigma \left(1 / Y_j^2 \right) \right] \tag{6}$$

(vi) Analyse the results as per the standard procedure suggested by Taguchi (Roy 1990). (vii) Find the optimal settings of process parameters for mean and S/N utility based on the analysis performed. (viii) Predict optimal values of different response characteristics for the optimal parametric setting that maximises the overall utility. (ix) Conduct confirmation experiments to verify the optimal results.

7. Multi-Response Optimisation of Wire-cut EDM for Titanium 6Al-4V ELI

Taking into account the framework described in the previous section, the following case has been considered to obtain the optimal settings of the controllable factors of wire-cut EDM for Titanium 6Al-4V ELI, to predict the ideal values of the multi-response. The three quality attributes (CR, RS and MH) have been fused into the utility multi-response function. The Taguchi L18 orthogonal array (OA) [15] has been adopted for conducting the experiments. Flushing pressure (A), Peak Current (B), Gap Voltage (C), duty cycle (D), wire feed rate (E) and wire tension (F) are chosen as input process parameters. The observed values of the response parameters are given in Table 1. The objective responses (quality attributes) were Cutting rate (CR), Residual stresses (RS), and Micro Hardness (MH); when these were optimised independently, the results are presented in Table 2. Preference scales for these response attributes, developed from their ideal and least acceptable values, are presented in Table 3. Since the CR objective response is chosen as higher-the-better, the RS objective response as lower-the-better, and the MH objective response as nominal-the-better, their minimum acceptable values have been set to the minimum of the corresponding experimental trial outcomes. The test values are converted into composite utility values, as given in Table 4, using the separate preference scales and assigning weights of 0.33, 0.33, and 0.33 to CR, RS, and MH, respectively.

Since Titanium 6Al-4V ELI (Grade-23) is fundamentally a difficult-to-cut material, an enhancement in the cutting rate prompts higher residual stresses. While investigating the impact of surface micro-hardness on biocompatibility, it was found that a slight increase in hardness in EDM-treated materials could be useful in biomedical orthodontic applications [2]. Hence, equal weights have been allocated to CR, RS and MH. These weights can be adjusted based on the client's preference, and ideal parametric settings can be determined according to the method's strategy. Results were analysed utilising analysis of variance (ANOVA) and the F-ratio. A significance level of 0.05 was picked for this trial. The ANOVA results (Tables 7 and 8) show that Flushing pressure, Peak current, Gap Voltage, Duty cycle and wire feed rate altogether impact both the mean and the S/N utility for the proposed alloy's machined surface. The main effects of the utility S/N data are shown in Tables 5 and 6.

Table 3. Optimal setting and values of process parameters (individual quality-characteristic optimisation)

Response Characteristics	Optimal level of process parameters	Significant process parameters	Predicted optimal value of quality characteristic
CS	A2 B3 C3 D2 E2 F3	B, C, D, E	3.02 mm/min
RS	A2 B1 C1 D1 E3 F2	B, C, D, E	60.78 MPa
MH	A2 B2 C2 D3 E1 F2	A, B, C, D, E, F	0.49 µm

8. Construction of Preference Scales

The following is the stepwise procedure for transforming experimental data into utility data.

Preference scale for Cutting Rate (P_CR): Y* = optimal value of cutting rate = 3.02 (refer to Table 2); Yi' = just-acceptable value of CR = 0.36 (all observed values of CR are greater than 0.36). Using Equation (4a):

$$A\_CR = 9 / \log (Y^* / Y_i') = 9.74$$

$$P\_CR = 9.74 \times \log (Y\_CR / 0.36) \tag{7}$$

Preference scale for Residual stresses (P_RS): Y* = optimal value of RS = 60.78 (refer Table 2); Yi' = just-acceptable value of RS = 325 (all observed values of RS are lesser than 325). Using Equation (4a):

$$A\_RS = 9 / \log (Y^* / Y_i') = -12.36$$

$$P\_RS = -12.36 \times \log (Y\_RS / 325) \tag{8}$$

Preference scale for Micro Hardness (P_MH): Y* = optimal value of MH = 206.16; Yi' = just-acceptable value of MH = 195. Using Equation (4a):

$$A\_MH = 9 / \log (Y^* / Y_i') = 360$$

$$P\_MH = 360 \times \log (Y\_MH / 195) \tag{9}$$

9. Calculation of Utility Value

Equal weights (1/3 each) have been allocated to the chosen quality attributes, assuming each of the qualities is equally important. These weights can be varied depending on the case or client requirements, if any [9]. The following relation was utilised to compute the utility function on the basis of the experimental trials:

$$U(n,r) = P\_CR(n,r) \times W\_CR + P\_RS(n,r) \times W\_RS + P\_SR(n,r) \times W\_SR \tag{10}$$

where W_CR = 0.33; W_RS = 0.33; 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 4.

Table 4. Calculated utility data based on responses

Trial No.	Utility values — R1	R2	R3	S/N ratio (dB)
1	197.87	198.80	196.52	45.92
2	214.83	215.44	214.51	46.65
3	204.47	203.62	205.32	46.21
4	203.36	202.41	204.34	46.17
5	211.21	209.57	212.98	46.50
6	215.13	216.08	213.93	46.65
7	214.68	215.29	214.68	46.64
8	218.67	218.22	218.93	46.79
9	211.10	212.18	211.19	46.51
10	192.26	189.47	189.93	45.60
11	189.97	187.92	191.41	45.56
12	214.61	212.28	216.61	46.63
13	206.19	207.58	204.51	46.28
14	204.26	204.95	204.87	46.22
15	202.32	202.54	201.43	46.11
16	205.26	202.96	207.64	46.25
17	203.74	202.68	205.02	46.18
18	218.45	217.60	219.08	46.78

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

10. Analysis of Utility Data for Optimal Setting of Process Parameters

The average and main responses in terms of utility values and S/N ratio (Tables 5 and 6) are plotted in Figures 1 to 6. It can be observed from Figures 1 to 6 that the 1st level of Flushing pressure (A1), 3rd level of peak current (B3), 3rd level of Gap Voltage (C3), 2nd level of duty cycle (D2) and 2nd level of wire feed rate (E2) are expected to yield maximum values of the utility and S/N ratio within the experimental range. Table 8 shows that all parameters have a significant impact (at the 95% confidence level) on the utility function. From the S/N

ANOVA for utility (Table 7), the wire tension is the least effective on the general utility of the Titanium 6Al-4V ELI (Grade-23) alloy machining. The ideal utility estimates, and hence the response attributes under consideration, are predicted at the above levels of the significant parameters.

Table 5. Main effects of utility S/N data (CR, RS and MH)

Level	Flushing Pressure	Peak current	Gap Voltage	Duty cycle	Wire Feed Rate	Wire Tension
L1	46.44821	46.09504	46.14287	46.07526	46.29759	46.40962
L2	46.17993	46.32089	46.31743	46.57962	46.43154	46.32052
L3	*	46.52629	46.48190	46.28733	46.21308	46.21207
L2−L1	-0.26828	0.225849	0.174558	0.504355	0.13395	-0.0891
L3−L2	*	0.205404	0.164473	-0.29228	-0.21845	-0.10844

Table 6. Main effects of utility raw data (CR, RS and MH)

Level	Flushing Pressure	Peak current	Gap Voltage	Duty cycle	Wire Feed Rate	Wire Tension
L1	210.20	201.99	202.99	201.38	206.75	209.30
L2	203.91	207.0917	207.18	213.34	209.80	207.24
L3	*	212.08	211.00	206.44	204.61	204.62
L2−L1	-6.29	5.10	4.19	11.96	3.05	-2.06
L3−L2	*	4.99	3.82	-6.90	-5.19	-2.61

Table 7. ANOVA for utility raw data (CR, RS and MH)

Source	SS	DOF	V	P	F-Ratio
Flushing Pressure	533.97	1	533.9695	13.86699	-13.0299
Peak current	915.776	2	457.888	23.78236	-11.1734
Gap Voltage	578.0518	2	289.0259	15.01179	-13.0299
Duty cycle	1297.594	2	648.7968	33.69802	-15.832
Wire Feed Rate	2048.922	2	1024.461	53.20974	-24.9989
Wire Tension	197.5079	2	98.75397	5.129207	-2.4098
Error	-1721.17	42	-40.9802		-44.6981
T	3850.652	53			100

Significant at 95% confidence level. SS: Sum of Squares; DOF: Degrees of Freedom; V: Variance. F-tabulated = 4.07 (one factor) and 3.22 (other parameters).

Table 8. ANOVA for utility S/N data (CR, RS and MH)

Source	SS	DOF	V	P	F-Ratio
Flushing Pressure	0.323895	1	0.323895	14.18622	83.12778
Peak current	0.558355	2	0.279177	24.45529	71.651
Gap Voltage	0.344927	2	0.172463	15.10739	44.2628
Duty cycle	0.769555	2	0.384778	33.70563	98.75334
Wire Feed Rate	0.145612	2	0.072806	6.377652	18.68573
Wire Tension	0.117443	2	0.058722	5.143877	15.07092
Error	0.023378	6	0.003896		1.023934
T	2.283165	17	*		100

Significant at 95% confidence level. SS: Sum of Squares; DOF: Degrees of Freedom; V: Variance. F-tabulated = 4.07 (one factor) and 3.22 (other parameters).

11. Optimal Values of Quality Characteristics

The normal values of all the response characteristics at the ideal levels of the significant controllable factors with respect to the utility function are recorded in Table 3. The ideal values of the predicted means (μ) of the various response attributes can be obtained from the following equation:

$$\mu\_Utility = A1 + B3 + C3 + D2 + E2 - 4T = 226.428 \quad (11)$$

The 95% confidence interval of the confirmation experiments (CI_CE) can be computed [15] by using the following equation:

$$CI\_CE = \sqrt{\left[F\alpha(1, f_e)\, V_e \left(1/n\_eff + 1/R \right) \right]} \quad (12)$$

where $F\alpha(1, f_e)$ = the F-ratio at the confidence level of $(1-\alpha)$ against DOF 1 and error degrees of freedom f_e; R = sample size for confirmation experiments; V_e = error variance; n_eff = N / (1 + DOF); N = total number of trials; and DOF = total degrees of freedom associated with the estimate of the mean response.

Cutting Rate:

$$\mu\_Utility = A1 + B3 + C3 + D2 + E2 - 4T = 2.98$$

where A1 = 1.69, B3 = 2.15, C3 = 2.10, D2 = 2.03, E2 = 1.93 (Table 6) and T_CR = 1.73 (Table 2). From ANOVA: N =

54, f_e = 40, V_e = 0.038, n_eff = 5.4, R = 3, F0.05(1,40) = 4.0847. From Eq. (12), CI_CE = ±0.28. The predicted optimal range for CR is 2.70 < μ_CR < 3.26.

Residual Stresses:

$\mu_{Utility} = A1 + B3 + C3 + D2 + E2 - 4T = 377.2$

where A1 = 218.22, B3 = 256.67, C3 = 252.28, D2 = 252.33, E2 = 246.22 (Table 6); T_RS = 212.13 (Table 2). From ANOVA: N = 54, f_e = 40, V_e = 256.2708, n_eff = 5.4, R = 3, F0.05(1,40) = 4.0847. From Eq. (12), CI_CE = ±23.29. The predicted optimal range for residual stresses is 353.91 < μ_RS < 400.49.

Micro Hardness:

$\mu_{Utility} = A1 + B3 + C3 + D2 + E2 - 4T = 290.55$

where A1 = 219.96, B3 = 227.44, C3 = 222.67, D2 = 232.44, E2 = 218.28 (Table 6); T = 207.56 (Table 2). From ANOVA: N = 54, f_e = 40, V_e = 124.52, n_eff = 5.4, R = 3, F0.05(1,40) = 4.0847. From Eq. (12), CI_CE = ±16.23. The predicted optimal range for MH is 274.32 < μ_MH < 306.78.

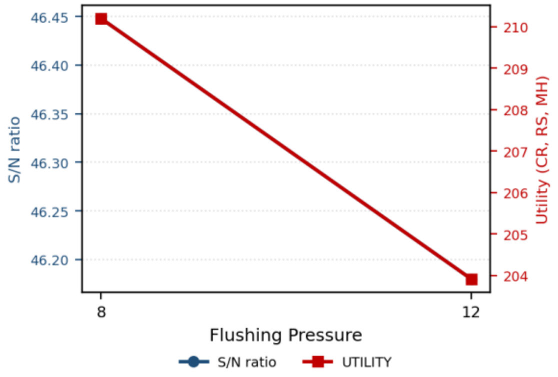

Figure 1. Effect of Flushing Pressure on S/N ratio and Utility

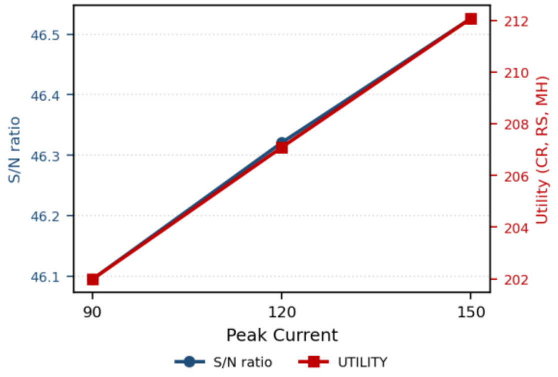

Figure 2. Effect of Peak Current on S/N ratio and Utility

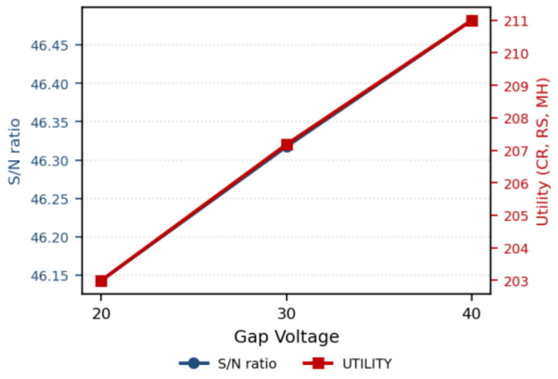

Figure 3. Effect of Gap Voltage on S/N ratio and Utility

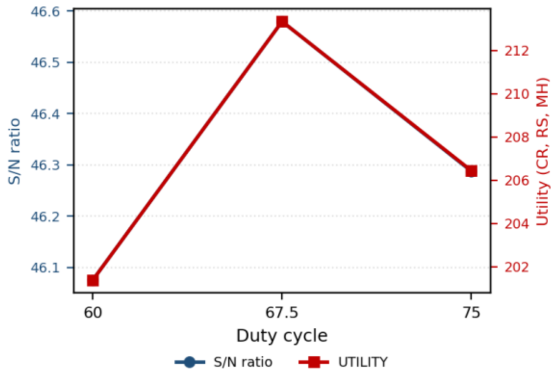

Figure 4. Effect of Duty Cycle on S/N ratio and Utility

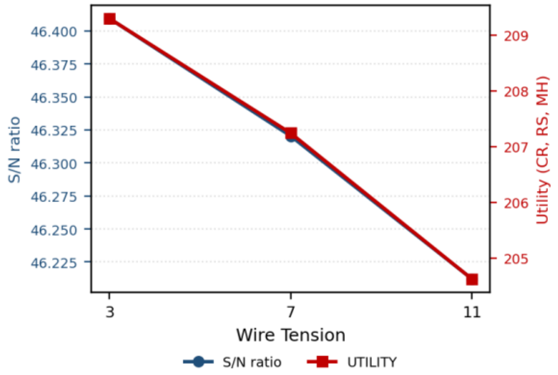

Figure 5. Effect of Wire Tension on S/N Ratio and Utility

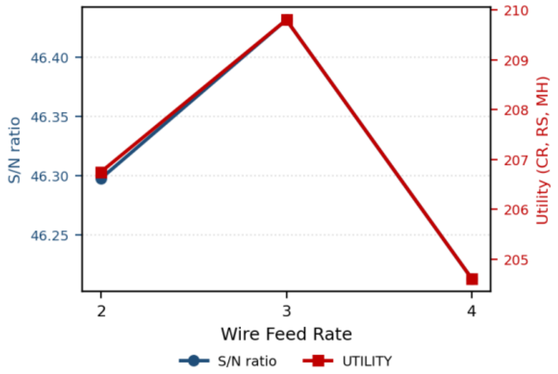

Figure 6. Effect of Wire Feed Rate on S/N ratio and Utility

The data from Tables 5 and 6 were plotted in Figures 1–6. It is clear from Figure 1 that lower flushing pressure (8 units) increases the overall utility of the wire-cut EDM process for Titanium 6Al-4V ELI alloy. The utility of the proposed process is maximum for the third level of peak current and gap voltage, as indicated in Figures 2 and 3. The wire feed rate and wire tension increase the cutting rate but decrease the utility function. It is clear from Figures 4 and 6 that the best utility was obtained at the second level of duty cycle and wire feed rate. Although the effect of wire tension on the performance of the wire-cut EDM process for Titanium 6Al-4V ELI alloy was negligible, a lower level of wire tension is desired to maximise utility, as shown in Figure 5. In Figure 6, the maximum utility is attained at the second level of wire feed rate.

12. Conclusion

Titanium-based alloys are gaining prominence day by day due to their unique mechanical properties. In this work, we explore the machining of Titanium 6Al-4V ELI using wire-cut EDM, focusing on cutting rate, residual stress, and microhardness of the machined surfaces. Higher flushing pressure is attractive for achieving a strong jet effect in the discharge gap by creating a large pressure difference in the dielectric medium; however, during wire-cut EDM of the 11 mm Titanium 6Al-4V ELI bar, it is less critical. A 75% duty cycle increased the negative effects on the utility function for machining the proposed alloy. This was caused by insufficient time to clear the contaminant gap. An important difference could be observed in the gap voltage and duty cycle for micro-hardness and residual stresses during wire EDM machining of the composite. The most favourable significant values of process parameters for the envisaged utility of optimal cutting rate, residual stresses and micro-hardness were as follows: Flushing pressure (A, 1st level) = 8 (M/C unit), peak current (B, 3rd level) = 120 AMP, gap voltage (C, 3rd level) = 40 M/C unit, duty cycle (D, 2nd level) = 67.5%, and wire feed rate (E, 2nd level) = 3 mm/min.

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