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SPECIFIC OPTIMAL AWJM PROCESS PARAMETERS FOR TI-6AL-4V ALLOY EMPLOYING THE MODIFIED TAGUCHI APPROACH

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Abstract: The high strength-to-weight ratio titanium alloys have good resistance to corrosion and temperature, which are extensively being used in turbine engines and aircraft structures. Machining of such alloys demands advanced processes like abrasive water jet machining (AWJM) to realize the repeatable desired shapes. This paper presents a set of optimal AWJM parameters (viz. traverse speed, abrasive flow rate and stand-off-distance) for maximizing the material removal rate (MRR) and minimizing the surface roughness (Ra) of the Ti-6Al-4V.Amulti-objective optimization technique is applied on the multiple response test data of the Taguchi's L_9 orthogonal array. Analysis of variance (ANOVA) has been carried out to examine the statistical significance of AWJM parameters. The traverse speed is found to have significant effect on Ra and MRR.

Keywords: abrasive water jet machining (AWJM); analysis of variance (ANOVA); material removal rate (MRR);

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multi-objective optimization; surface roughness (Ra); Ti-6Al-4V.

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1. INTRODUCTION

In any manufacturing process, performance indicators are quality and productivity [1]. A few of the non-conventional processes adopted by industries are: (i) LBM (laser beam machining); (ii) WJM (water jet machining); (iii) AWJM (abrasive water jet machining); (iv) EDM (electric discharge machining); (v) WEDM (wire electric discharge machining); and (vi) ECM (electro chemical machining). AWJM offers high manoeuvrability, nullified HAZ in cutting process, and low machining force exertion [2-5]. AWJM process parameters are categorized into [6]: (i) Hydraulic parameters (water pressure and water flow rate or water jet nozzle diameter); (ii) Abrasive parameters (type, size, shape, and flow rate of abrasive particles); (iii) Cutting parameters (traverse rate, stand-off distance, number of passé, angle of attack, and target material); (iv) Mixing parameters (mixing method (forced or suction), Abrasive condition (dry or slurry) and mixing chamber dimensions). The selection of process parameters depends on the operator's expertise or experience. Machining handbooks generally provide information on process parameters for frequently used materials in conservative nature. Optimal AWJM process parameters are thus required to exploit its capabilities and potentials through minimization of the testing, time-consumption and expenditure.

Industries can expect better accuracy and surface finish without thermal distortion for hard and brittle materials through AWJM process [7-10]. Several materials adopted this process. Notable among them are: AA6061-T6 [10]; AA5083 [11]; titanium alloy (Ti-6Al-4V) [12-16]; AISI 304 [17]; 718 alloy [18]; Inconel 825 [19]; hybrid Al7075 metal matrix composites [20]; A359/Al_2O_3/B_4C composite [21, 22]; AA6061-B_4C-hBN hybrid metal matrix composite [23]; Mg-based nano-composite [24]; and TiB_2 particles reinforced Al7075 composite [25].

Various algorithms adopted for optimization of AWJM process are: Hybrid multi response techniques [26]; Taguchi-DEAR Methodology [25]; Cohort intelligence algorithm, a socio inspired artificial intelligence algorithm [27]; multi-objective cuckoo algorithm [28] and artificial bee colony algorithm [29]; Jaya Algorithm [30]; Multi-objective optimization by ratio analysis (MOORA) [31]; Evolutionary algorithm, grey wolf optimizer (GWO) [32]; Gravitational search algorithm (GSA) [33]; response surface methodology and artificial neural network [34]; and Taguchi and evolutionary approach [35]. Sonawane et al. [4] have made a review on the parametric optimization of AWJM on various materials using the Taguchi method, genetic algorithm (GA), teacher learning base algorithm (TLBA), particle swarm optimization (PSO) and grey relational analysis to achieve optimum material removal rate (MRR), surface roughness (Ra) and kerf width.

Mhamunkar and Raut [36] have carried out an interesting experimental investigation as per Taguchi's L9 orthogonal array [37] for obtaining optimal AWJM parameters of Ti-6Al-4V by using the Taguchi based GRA (grey rational analysis). They have considered traverse speed, abrasive flow rate and stand-off-distance as AWJM process parameters, whereas material removal rate (MRR) and surface roughness (Ra) are performance indicators. Taguchi method can suggest the optimal process variables to a single response characteristic. GRA is adopted in multi-objective optimization problems having multiple responses with dissimilar quality characteristics [38-43]. This paper examines the adequacy of Taguchi approach in solving multi-objective optimization problems related to the specification of AWJM parameters for Ti-6Al-4V. The modified Taguchi method [44] is considered for estimating the range of performance indicators. A simple multi-objective optimization technique [45, 46] is adopted and suggested a set of optimal AWJM parameters. Empirical relations are developed for MRR and Ra and validated with test data [36].

2. Test Data

Mhamunkar and Raut [36] have carried out experimentation considering the work-piece of Ti-6Al-4V ($120\times120\times10\,mm$), whose hardness is 33 HRC. They have reported the mechanical properties: Young's modulus, $E = 120-130\,GPa$; Density, $\rho = 4.42\times10^3\,g/mm^3$; Ultimate tensile strength, $\sigma_{ult} = 860\,MPa$; and Yield strength, $\sigma_{ys} = 758\,MPa$. The apparatus consists of a high pressure pump (SL-V 50 Plus made by KMT) built on a CNC AWJM cutting portal with an abrasive feeding arrangement. Figure-1 shows a schematic diagram of AWJM. The feed rate can be varied within $100-900\ g/\min$. 80Mesh Garnet sand was castoff as Abrasive material. The abrasive particles granulation $(\rho = 2300\ kg/m^3)$ varies within 160 - 310μm.Cutting head consists of 0.25 mm inner diameter orifice, mixing chamber and 0.75 mm inner diameter focusing tube (nozzle) or insert (where water jet is formed and mixed with abrasive particles- forming abrasive water jet). Water in pipes is carried to the jet or cutting head. The stand-off- distance between mixing tube and material is typically 0.5 to2.5 mm. Mitutoyo make Surface roughness tester is used to measure the surface roughness (Ra) and evaluated the material removal rate (MRR) considering traverse speed, abrasive flow rate and stand-off-distance as AWJM parameters. For simplicity, AWJM parameters, namely, traverse speed, abrasive flow rate and stand-off-distance are designated by A, B and C respectively. Table-1 gives the assigned 3 levels for the AWJM parameters and the measured performance indicators (MRR and Ra) for the set levels as per Taguchi's L_9 orthogonal array.

3. Modified Taguchi Approach

Depending on the number of process parameters (n_p) and the assigned levels (n_l) Taguchi method [37, 47-50] suggests a suitable orthogonal array to conduct few tests for tracing optimal process parameters. The number of experiments ($N_{Taguchi}$) required as per Taguchi approach [397]

$$N_{Taguchi} = 1 + n_p \times (n_l - 1) \tag{1}$$

For $n_p = 3$ and $n_l = 3$, $N_{Taguchi}$ = 7, whereas, the full factorial design of experiments demands $n_l^{n_p} = 3^3$ =27 tests. Taguchi method [37] recommends L_9 orthogonal array. Table-1 presents test data [36] of Ra (μm) and MRR (gms/min).For L_9 orthogonal array, $N_{Taguchi}$=9 and n_l =3, equation (1) gives $n_p = 4$. As in the modified Taguchi approach [51-61], a fictitious or dummy parameter (D) is introduced in Table-1. ANOVA is performed and presented the results in Table-1. It is noted that %contribution of A is found to be significant on both Ra and MRR.

Contribution of A, B and C on Ra are 52.7, 8.3 and 11.7% respectively. Contribution of A, B and C on MRR are 98.8, 1.0 and 0.1% respectively. Sum of the %Contributions of A, B, C, and D for Ra and MRR is 100. Hence, Error (%) is nothing but the %Contribution of the fictitious or dummy parameter (D).

From AVOVA Table-1, the optimal AWJM parameters to achieve minimum surface roughness (Ra) are identified as $A_1B_3C_1$, wherein subscripts denote the levels of the parameters. The optimal AWJM parameters to achieve maximum material removal rate (MRR) are $A_3B_3C_3$. It should be noted that the above two sets of AWJM parameters to achieve minimum Ra and maximum MRR are found to be different. Tests are not conducted for these two cases. Confirmation tests are mandatory.

Additive law [37] can provide estimates of performance indicators (viz., Ra and MRR) using the mean values from the ANOVA Table. The procedure for the estimates of Ra and MRR is explained below. The performance indicator is denoted by ψ , whose estimate for the AWJM parameters (A_i, B_j, C_k, D_l) is $\hat{\psi}$ .The subscripts i, j, k, l for the AWJM process parameters A, B, C, D vary from 1 to 3. $\psi(A_i)$ is designated as the mean value of ψ corresponding to the i^{th} level of the parameter A. $\psi(B_j)$ is designated as the mean value of ψ corresponding to the j^{th} level of the parameter B. $\psi(C_k)$ is designated as the mean value of ψ corresponding to the k^{th} level of the parameter C. $\psi(D_l)$ is designated as the mean value of ψ corresponding to the l^{th} level of the parameter D.

The additive law suggests estimate of ψ for the specified AWJM parameters (A_i, B_j, C_k, D_l) as:

$$\hat{\psi} = \psi(A_i, B_j, C_k, D_l) = \psi(A_i) + \psi(B_j) + \psi(C_k) + \psi(D_l) - 3 \times \psi_{mean} \tag{2}$$

Here ψ_{mean} is the grand mean of ψ for the 9 test runs.

Exclusion of the fictitious parameter (D), equation (2) reduces to

$$\hat{\psi} = \psi(A_i, B_j, C_k) = \psi(A_i) + \psi(B_j) + \psi(C_k) - 2 \times \psi_{mean} \tag{3}$$

From equations (2) and (3), one can find the difference in estimates of ψ with inclusion and exclusion of the fictitious parameter (D) from $\psi(D_l)-\psi_{mean}$. For the three levels, one can find the following three deviations $\psi(D_1)-\psi_{mean}$, $\psi(D_2)-\psi_{mean}$ and $\psi(D_3)-\psi_{mean}$. The three deviation values for the surface roughness (Ra) are 0.4087, -0.2154 and -0.1933 μm. The minimum and maximum deviation values for the Ra are -0.2154 and 0.4087 μm respectively. Similarly, the three deviation values for the material removal rate, MRR are 0.0293, -0.0077 and -0.0217 gms/min. The minimum and maximum deviation values for the MRR are -0.0217 and 0.0293gms/min respectively. Select the minimum and maximum deviation values and superimpose them to the estimate of ψ from equation (3) to get the range of estimates. Table-2 gives comparison on estimates of Ra and MRR with measured data [36]. Exclusion of the fictitious parameter (D) makes the estimates from equation (3) within 12% deviation, whereas inclusion of the fictitious parameter (D) indicates excellent matching with test data. Superimposing the minimum and maximum deviation values to equation (3) provides the range of estimates. The test data [36] in Table-2 falls within the estimated range. Tables 3 and 4 give the estimates of Ra and MRR for all possible 27 combinations of AWJM parameters. The minimum Ra for the identified optimal AWJM parameters ($A_1B_3C_1$) is expected to be within 2.2499 – 2.8740 μm (see S.No.7 of Table-3). The optimum value of Ra from the confirmation test is reported as 2.4658 μm [36]. The maximum MRR for the identified optimal AWJM parameters ($A_3B_3C_3$) is expected to be within 3.8431 – 3.8941gms/min (see S.No.27 of Table-4). The optimum value of MRR from the confirmation test is reported as 3.9853gms/min [36].

Empirical relations for Ra and MRR are developed in terms of the AWJM parameters from the mean values of ANOVA Table-1 in the form

$$Ra = 4.04 + 0.4128\xi_1 - 0.4644\xi_1^2 - 0.1946\xi_2 - 0.0372\xi_2^2 + 0.1033\xi_3 - 0.3607\xi_3^2 \quad (4)$$

$$MRR = 2.78 + 1.008\xi_1 - 0.008\xi_1^2 + 0.0955\xi_2 - 0.0635\xi_2^2 + 0.038\xi_3 + 0.013\xi_3^2 \quad (5)$$

Here, $\xi_1 = 0.04A - 2.2$; $\xi_2 = 0.02B - 5$; and $\xi_3 = 2C - 3$.

Estimates of Ra and MRR from the empirical relations (4) and (5) in Figures 2 and 3 are matching well with those obtained using the additive law (3) in Tables 3 and 4. Superimposing the minimum and maximum deviation values to equations (4) and (5), one can find the range of Ra and MRR estimates for the specified AWJM parameters. Figures (4 and 5) show the comparison of estimates of Ra and MRR with measured data [36] for all combinations of 27 sets of AWJM parameters in Tables 3 and 4. Measured data is found to be within or close to the bounds of estimates. Lower and upper bound estimates of MRR in Figure-5 show very close due to insignificance corrections to the empirical relation (5). Appropriate optimization technique is required for selecting optimal parameters to achieve the desired performance indicators [62-64].

4. MULTI-OBJECTIVE OPTIMIZATION

Two different sets of AWJM parameters are found to achieve minimum Ra and maximum MRR. Process designer expects a set of AWJM parameters for achieving minimum Ra and maximum MRR. This problem is solved utilizing the multi-objective optimization technique [60] by defining a single objective function as a function of the two output responses after normalizing Ra and MRR with their maximum values: $(Ra)_{\max}$ = 4.6043 μm and $(MRR)_{\max}$ = 3.894gms/min.

Minimum of $\zeta_1\left(\equiv \frac{Ra}{(Ra)_{\max}}\right)$ and $\zeta_2\left(\equiv \frac{(MRR)_{\max}}{MRR} - 1\right)$ correspond to minimum of Ra and maximum of MRR. As in [62] the positive weighing factors (ω_1 and ω_2, which satisfy $\omega_1 + \omega_2 = 1$) are introduced to form a single function (ζ) for optimizing Ra and MRR. The single objective function (ζ) is written in the form

$$\zeta = \omega_1 \zeta_1 + \omega_2 \zeta_2 \tag{6}$$

Minimization of ζ provides the maximum of MRR and minimum of Ra for a set of

AWJM machining parameters. Equal weighing are given (i.e., $\omega_1 = \omega_2 = 1/2$) to achieve common optimum process conditions in Table-5. ANOVA is performed on values of the multi-objective optimization function, ζ in Table-5 to trace the optimum process parameters for the minimum ζ and selected the optimal process parameters as $A_3B_3C_3$. Mhamunkar and Raut [36] have obtained the same result from the ANOVA and GRA. Table-6 gives the summary of the specific optimal AWJM parameters and the estimates of the performance indicators. Figure-6 shows the variation of surface roughness (Ra) and material removal rate (MRR) with traverse speed (A) for the abrasive flow rate (B) of 300 gms/min and the three levels of stand-off-distance (C). ANOVA results in Table-1 indicate insignificant %contribution of C on MRR. This is the reason why the MRR values in Figure-6 are very close for different values of C.

5. CONCLUDING REMARKS

Ti-6Al-4Valloy possesses high strength, corrosion resistance, low thermal conductivity and oxidation resistance. The alloy is extensively being used for marine and automobile applications. Abrasive water jet machining (AWJM) is well suited for this alloy. A set of optimal AWJM parameters (viz. Traverse speed, abrasive flow rate and stand-off-distance) is identified to achieve maximum material removal rate (MRR) and minimum surface roughness (Ra) adopting the modified Taguchi method and multi-objective optimization. The dissimilar quality characteristics of Ra and MRR are made dimensionless and represented functionally by a single response characteristic. This optimization approach is similar to the Taguchi based utility concept. ANOVA indicates that traverse speed has major % contribution on Ra and MRR. Empirical relations are developed for MRR and Ra in terms of the AWJM process parameters and demonstrated their adequacy through comparison of test results.

Table- 1: AWJM process parameters and performance indicators for Ti-6Al-4V alloy.

(a) Designation of AWJM parameters and their levels

AWJM parameters	Designation	Level-1	Level-2	Level-3
Traverse speed (mm/min)	A	30	55	80
Abrasive flow rate (gms/min)	B	200	250	300
Stand-off-distance (mm)	C	1.0	1.5	2.0
Fictitious	D	d_1	d_2	d_3

(b) Performance measurements

Test Run	Levels of AWJM parameters				Machining performance [38]	
	A	B	C	D	Ra (µm)	MRR (gms/min)
1	1	1	1	1	3.2632	1.611
2	1	2	2	2	2.9456	1.758
3	1	3	3	3	2.4786	1.827
4	2	1	2	3	4.0023	2.601
5	2	2	3	1	4.1896	2.862
6	2	3	1	2	3.1270	2.781
7	3	1	3	2	3.6713	3.666
8	3	2	1	3	3.3293	3.735
9	3	3	2	1	4.1636	3.843

Analysis of variance (ANOVA) and the significance of AWJM parameters					
AWJM parameters	1-Mean	2- Mean	3-Mean	Sum of Squares (SOS)	%Contribution
Surface Roughness (Ra): grand mean=3.4634 μm					
A	2.8958	3.7729	3.7214	1.4537	52.7
B	3.6456	3.4881	3.2564	0.2300	8.3
C	3.2398	3.7038	3.4465	0.3242	11.7
D	3.8721	3.2480	3.2701	0.7526	27.3
Material Removal Rate (MRR): grand mean = 2.7427 gms/min					
A	1.7320	2.7480	3.7480	6.0965	98.8
B	2.6260	2.7850	2.8170	0.0628	1.0
C	2.7090	2.7340	2.7850	0.0090	0.1
D	2.7720	2.7350	2.7210	0.0042	0.1

Table-2: Comparison on the estimates of the performance indicators (viz., Ra and MRR) with test results.

(a) Surface roughness, Ra (μm)

Test Run	Parameters				Test [38]	Eq.(3) (n_p=3)	RE (%)	Eq.(2) (n_p=4)	Range of estimates	
	A	B	C	D					From	To
1	1	1	1	1	3.2632	2.8545	12.5	3.2632	2.63	3.26
2	1	2	2	2	2.9456	3.1610	-7.3	2.9456	2.94	3.57
3	1	3	3	3	2.4786	2.6719	-7.8	2.4786	2.45	3.08
4	2	1	2	3	4.0023	4.1956	-4.8	4.0023	3.98	4.61
5	2	2	3	1	4.1896	3.7809	9.8	4.1896	3.56	4.19
6	2	3	1	2	3.1270	3.3424	-6.9	3.1270	3.12	3.75
7	3	1	3	2	3.6713	3.8867	-5.9	3.6713	3.67	4.30
8	3	2	1	3	3.3293	3.5226	-5.8	3.3293	3.30	3.93
9	3	3	2	1	4.1636	3.7549	9.8	4.1636	3.53	4.16

(b) Material removal rate, MRR (gms/min)

Test Run	Parameters				Test [38]	Eq.(3) (n_p=3)	RE (%)	Eq.(2) (n_p=4)	Range of estimates	
	A	B	C	D					From	To
1	1	1	1	1	1.611	1.5817	1.82	1.611	1.56	1.61
2	1	2	2	2	1.758	1.7657	-0.44	1.758	1.74	1.79
3	1	3	3	3	1.827	1.8487	-1.19	1.827	1.82	1.87
4	2	1	2	3	2.601	2.6227	-0.83	2.601	2.60	2.65
5	2	2	3	1	2.862	2.8327	1.02	2.862	2.81	2.86
6	2	3	1	2	2.781	2.7887	-0.28	2.781	2.76	2.81
7	3	1	3	2	3.666	3.6737	-0.21	3.666	3.65	3.70
8	3	2	1	3	3.735	3.7567	-0.58	3.735	3.73	3.78
9	3	3	2	1	3.843	3.8137	0.76	3.843	3.79	3.84

Table-3: Estimates of Ra (μm) for all 27 possible sets of AWJM parameters.

Set Number	AWJM parameters						Surface roughness, Ra (μm)		
	Levels			Traverse speed, A (mm/min)	Abrasive flow rate, B (gms/min)	Stand-off-distance, D (mm)	Estimate Eq. (3)	Min.	Max.
	A	B	C						
1	1	1	1	30	200	1.0	2.85	2.6391	3.2632
2	1	1	2	30	200	1.5	3.32	3.1031	3.7272
3	1	1	3	30	200	2.0	3.06	2.8457	3.4698
4	1	2	1	30	250	1.0	2.70	2.4816	3.1057
5	1	2	2	30	250	1.5	3.16	2.9456	3.5697
6	1	2	3	30	250	2.0	2.90	2.6883	3.3124
7	1	3	1	30	300	1.0	2.47	2.2499	2.8740
8	1	3	2	30	300	1.5	2.93	2.7139	3.3380
9	1	3	3	30	300	2.0	2.67	2.4565	3.0806
10	2	1	1	55	200	1.0	3.73	3.5162	4.1403
11	2	1	2	55	200	1.5	4.20	3.9802	4.6043
12	2	1	3	55	200	2.0	3.94	3.7229	4.3470
13	2	2	1	55	250	1.0	3.57	3.3588	3.9829
14	2	2	2	55	250	1.5	4.04	3.8228	4.4469
15	2	2	3	55	250	2.0	3.78	3.5655	4.1896
16	2	3	1	55	300	1.0	3.34	3.1270	3.7511
17	2	3	2	55	300	1.5	3.81	3.5910	4.2151
18	2	3	3	55	300	2.0	3.55	3.3337	3.9578
19	3	1	1	80	200	1.0	3.68	3.4647	4.0888
20	3	1	2	80	200	1.5	4.14	3.9287	4.5528
21	3	1	3	80	200	2.0	3.89	3.6713	4.2954
22	3	2	1	80	250	1.0	3.52	3.3072	3.9313
23	3	2	2	80	250	1.5	3.99	3.7712	4.3953
24	3	2	3	80	250	2.0	3.73	3.5139	4.1380
25	3	3	1	80	300	1.0	3.29	3.0755	3.6996
26	3	3	2	80	300	1.5	3.75	3.5395	4.1636
27	3	3	3	80	300	2.0	3.50	3.2821	3.9062

Table-4: Estimates of MRR (gms/min) for all 27 possible sets of AWJM parameters.

Set Number	AWJM parameters						Material Removal Rate, MRR (gms/min)		
	Levels			Traverse speed, A (mm/min)	Abrasive flow rate, B (gms/min)	Stand-off-distance, D (mm)	Estimate Eq. (3)	Min.	Max.
	A	B	C						
1	1	1	1	30	200	1.0	1.58	1.5601	1.6111
2	1	1	2	30	200	1.5	1.61	1.5851	1.6361
3	1	1	3	30	200	2.0	1.66	1.6361	1.6871
4	1	2	1	30	250	1.0	1.74	1.7191	1.7701
5	1	2	2	30	250	1.5	1.77	1.7441	1.7951
6	1	2	3	30	250	2.0	1.82	1.7951	1.8461
7	1	3	1	30	300	1.0	1.77	1.7511	1.8021
8	1	3	2	30	300	1.5	1.80	1.7761	1.8271
9	1	3	3	30	300	2.0	1.85	1.8271	1.8781
10	2	1	1	55	200	1.0	2.60	2.5761	2.6271
11	2	1	2	55	200	1.5	2.62	2.6011	2.6521
12	2	1	3	55	200	2.0	2.67	2.6521	2.7031
13	2	2	1	55	250	1.0	2.76	2.7351	2.7861
14	2	2	2	55	250	1.5	2.78	2.7601	2.8111
15	2	2	3	55	250	2.0	2.83	2.8111	2.8621
16	2	3	1	55	300	1.0	2.79	2.7671	2.8181
17	2	3	2	55	300	1.5	2.81	2.7921	2.8431
18	2	3	3	55	300	2.0	2.86	2.8431	2.8941
19	3	1	1	80	200	1.0	3.60	3.5761	3.6271
20	3	1	2	80	200	1.5	3.62	3.6011	3.6521
21	3	1	3	80	200	2.0	3.67	3.6521	3.7031
22	3	2	1	80	250	1.0	3.76	3.7351	3.7861
23	3	2	2	80	250	1.5	3.78	3.7601	3.8111
24	3	2	3	80	250	2.0	3.83	3.8111	3.8621
25	3	3	1	80	300	1.0	3.79	3.7671	3.8181
26	3	3	2	80	300	1.5	3.81	3.7921	3.8431
27	3	3	3	80	300	2.0	3.86	3.8431	3.8941

Table-5: Single objective optimization function (ζ) with weighing factors ω_1 and ω_2 for the test data of Ra and MRR in Table-1.

$$\zeta_1\left(\equiv \frac{Ra}{(Ra)_{\max}}\right); \zeta_2\left(\equiv \frac{(MRR)_{\max}}{MRR} - 1\right); (Ra)_{\max} = 4.6043\ \mu m;\ (MRR)_{\max} = 3.894 \text{gms/min};$$

$\omega_1 \geq 0; \omega_2 \geq 0;$ and $\omega_1 + \omega_2 = 1$

Test Run	Levels of AWJM parameters			Performance indicators		ζ_1	ζ_2	Single objective function, $\zeta = \omega_1 \zeta_1 + \omega_2 \zeta_2$ $\left(\omega_1 = \omega_2 = \frac{1}{2}\right)$
	A	B	C	Ra (μm)	MRR (gms/min)			
1	1	1	1	3.2632	1.611	0.7087	1.4171	1.0629
2	1	2	2	2.9456	1.758	0.6397	1.2150	0.9274
3	1	3	3	2.4786	1.827	0.5383	1.1314	0.8348
4	2	1	2	4.0023	2.601	0.8692	0.4971	0.6832
5	2	2	3	4.1896	2.862	0.9099	0.3606	0.6353
6	2	3	1	3.1270	2.781	0.6791	0.4002	0.5397
7	3	1	3	3.6713	3.666	0.7973	0.0622	0.4298
8	3	2	1	3.3293	3.735	0.7231	0.0426	0.3828
9	3	3	2	4.1636	3.843	0.9043	0.0133	0.4588

ANOVA (Analysis of Variance) on ζ					
Parameters	1-Mean	2-Mean	3-Mean	SOS	% Contri
A	0.9417	0.6194	**0.4238**	0.6616	0.4104
B	0.7253	0.6485	**0.6111**	0.6616	0.0203
C	0.6618	0.6898	**0.6333**	0.6616	0.0048

Table-6: AWJM process parameters for specific conditions and estimates of output responses viz., material removal rate (MRR) and surface roughness (Ra)

Specific conditions	AWJM parameters			*Ra* (μm)	*MRR* (gms/min)
	Traverse speed, A (mm/min)	Abrasive flow rate, B (gms/min)	Stand-off distance, C (mm)		
Single objective optimization					
$(Ra)_{min}$ ($A_1B_3C_1$)	30	250`	1	2.2499-2.8740	1.7511-1.8021
$(MRR)_{max}$ ($A_3B_3C_3$)	80	300	2	3.2821-3.9062	3.8431-3.8941
(Ra)max ($A_2B_1C_2$)	55	200	1.5	3.9802-4.6043 (4.0023)$^+$	2.6011-2.6521 (2.601)$^+$
(MRR)min ($A_1B_1C_1$)	30	200	1	2.6391-3.2632 (3.2632)$^+$	1.5601-1.6111 (1.611)$^+$
Multi-objective optimization: $(Ra)_{min}$ and $(MRR)_{max}$					
$A_3B_3C_3$	80	300	2	3.2821-3.9062	3.8431-3.8941 (3.9853)$^+$

$^+$Test Data [36]

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests.

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