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The specific optimal AWJM process parameters for the Ti-6Al-4V alloy are determined using the Modified Taguchi approach

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Abstract The resistance to corrosion and temperature, along with the high strength-to-weight ratio of titanium alloys, makes them extensively utilized in turbine engines and aircraft structures. To achieve the desired shapes with precision, machining of these alloys necessitates advanced techniques such as abrasive water jet machining (AWJM). In this paper, a collection of optimal AWJM parameters, including traverse speed, abrasive flow rate, and stand-off distance, is presented. These parameters are aimed at maximizing the material removal rate (MRR) while minimizing the surface roughness (Ra) of the Ti-6Al-4V alloy. Utilizing a multi-objective optimization technique, the study applies Taguchi's L9 orthogonal array to analyze multiple response test data. Furthermore, an analysis of variance (ANOVA) is performed to assess the statistical significance of the AWJM parameters.

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

1. INTRODUCTION

In any manufacturing process, quality and productivity serve as the primary performance indicators [1]. Several non-conventional processes have been embraced by industries, including: (i) Laser Beam Machining (LBM); (ii) Water Jet Machining (WJM); (iii) Abrasive Water Jet Machining (AWJM); (iv) Electric Discharge Machining (EDM); (v) Wire Electric Discharge Machining (WEDM); and (vi) Electrochemical Machining (ECM). AWJM exhibits characteristics such as high maneuverability, negligible Heat-Affected Zone (HAZ) during cutting, and minimal exertion of machining force [2]. The AWJM process parameters fall into distinct categories [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 passes, angle of attack, and target material); (iv) Mixing parameters (mixing method (forced or suction), abrasive condition (dry or slurry), [3]and mixing chamber dimensions). The determination of process parameters typically relies on the operator's expertise or experience. Machining handbooks commonly furnish information regarding process parameters for frequently used materials in a traditional manner [4]. However, the optimization of AWJM process parameters is essential to harness its capabilities and potential, achieved through the reduction of testing time, consumption, and expenditure [5].

AWJM can provide industries with enhanced accuracy and surface finish, along with thermal distortion avoidance for hard and brittle materials [6]. Numerous materials have embraced this process, with notable examples including: AA6061-T6 [10]; AA5083 [7]; titanium alloy (Ti-

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6Al-4V) [12-16]; AISI 304 [17]; 718 alloy [8]; Inconel 825 [9]; hybrid Al7075 metal matrix composites [10]; A359/Al2O3/B4C composite [11]; AA6061-B4C-hBN hybrid metal matrix composite [12]; Mg-based nano-composite [13]; and TiB2 particles reinforced Al7075 composite.

A variety of algorithms have been adopted for the optimization of the AWJM process, including: Hybrid multi-response techniques [14]; Taguchi-DEAR Methodology;

Various artificial intelligence algorithms have served as inspiration for optimization efforts ,including the multi-objective cuckoo algorithm [15] and the artificial bee colony algorithm. The Jaya Algorithm, Multi-objective optimization by ratio analysis (MOORA), the grey wolf optimizer (GWO), the gravitational search algorithm (GSA), response surface methodology and artificial neural network, and a Taguchi and evolutionary approach have been embraced for this purpose.

A review by Sonawane et al. encompassed the parametric optimization of AWJM across diverse materials, utilizing methodologies such as the Taguchi method, genetic algorithm (GA), teacher learning base algorithm (TLBA), particle swarm optimization (PSO), and grey relational analysis to attain optimal material removal rate (MRR), surface roughness (Ra), and kerf width. Mhamunkar and Raut conducted a noteworthy experimental investigation using Taguchi's L9 orthogonal array to ascertain optimal AWJM parameters for Ti-6Al-4V, employing Taguchi based grey rational analysis (GRA). Their study encompassed traverse speed, abrasive flow rate, and stand-off distance as AWJM process parameters, with material removal rate (MRR) and surface roughness (Ra) serving as performance indicators. The Taguchi method is suitable for identifying optimal process variables related to a single response characteristic, whereas GRA is employed for multi-objective optimization problems encompassing multiple responses with distinct quality characteristics.

This paper scrutinizes the effectiveness of the Taguchi approach in resolving multi-objective optimization challenges linked to the specification of AWJM parameters for Ti-6Al-4V. The modified Taguchi method is utilized to estimate the performance indicator range, and a straightforward multi-objective optimization technique is recommended, presenting a collection of optimal AWJM parameters. Empirical relationships for MRR and Ra are formulated and subsequently validated using test data.

2. TEST DATA

The cutting head comprises an inner diameter orifice of 0.25 mm, a mixing chamber, and an inner diameter focusing tube (nozzle) of 0.75 mm (referred to as the insert). The insert is where the water jet is formed and combined with abrasive particles to create an abrasive water jet. Water is conveyed to the cutting head through pipes. The distance between the mixing tube and the material, known as the stand-off distance, typically ranges from 0.5 to 2.5 mm. Measurement of surface roughness (Ra) and evaluation of the material removal rate (MRR) were performed using a Mitutoyo surface roughness tester. The AWJM parameters considered were traverse speed, abrasive flow rate, and stand-off distance, denoted as A, B,

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and C, respectively, for simplicity. Taguchi's L9 orthogonal array was employed to assign three levels to these AWJM parameters, and the resulting performance indicators (MRR and Ra) were measured and recorded, as presented in Table-1.

3. MODIFIED TAGUCHI APPROACH

The surface roughness (Ra) is characterized by three deviation values: 0.4087, -0.2154, and -0.1933 µm. The minimum and maximum deviations for Ra are -0.2154 µm and 0.4087 µm, respectively. Similarly, the material removal rate (MRR) exhibits three deviation values: 0.0293, -0.0077, and -0.0217 gms/min. The minimum and maximum deviations for MRR are -0.0217 gms/min and 0.0293 gms/min, respectively. To ascertain the range of estimates, the minimum and maximum deviation values are integrated into the equation (3) estimate of ψ. A comparison between estimated and measured data for Ra and MRR is provided in Table-2 [36]. The inclusion or exclusion of the fictitious parameter (D) in equation (3) results in estimates with deviations within 12%. However, incorporating the fictitious parameter (D) leads to an excellent match with the test data. By applying the minimum and maximum deviation values to equation (3), a range of estimates is obtained. The test data [36] in Table-2 lies within this estimated range. Tables 3 and 4 offer estimates of Ra and MRR for all conceivable 27 combinations of AWJM parameters. The anticipated range for the minimum Ra using the identified optimal AWJM parameters (A1B3C1) is 2.2499 – 2.8740 µm (as shown in S.No.7 of Table 3). The confirmed optimum value of Ra from the test is reported as 2.4658 µm [36]. Likewise, the projected range for the maximum MRR using the identified optimal AWJM parameters (A3B3C3) is 3.8431 – 3.8941 gms/min (as shown in S.No.27 of Table 4). The confirmed optimum value of MRR from the test is reported as 3.9853 gms/min. Empirical relationships for Ra and MRR are derived based on the AWJM parameters' mean values from ANOVA Table-1, taking the form:

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

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

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

The estimates of Ra and MRR obtained from the empirical relations (4) and (5), as depicted in Figures 2 and 3, exhibit a notable alignment with those derived using the additive law (3), as presented in Tables 3 and 4. By overlaying the minimum and maximum deviation values onto equations (4) and (5), it becomes feasible to establish the range of Ra and MRR estimates for the specified AWJM parameters. A comparison of estimates for Ra and MRR with the measured data is illustrated in Figures 4 and 5 for all 27 sets of AWJM parameters combinations outlined in Tables 3 and 4. Notably, the measured data either falls within or closely aligns with the estimate boundaries. In Figure 5, the lower and upper bound estimates of MRR are nearly identical due to minimal adjustments in the empirical relation (5).

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In order to select optimal parameters that lead to the desired performance indicators, the application of an appropriate optimization technique is essential.

4. MULTI-OBJECTIVE OPTIMIZATION

Two distinct sets of AWJM parameters have been identified that result in the attainment of minimum Ra and maximum MRR. The process designer anticipates a specific set of AWJM parameters that can yield both minimum Ra and maximum MRR. To address this challenge, a multi-objective optimization technique is employed. This technique involves formulating a single objective function based on the two output responses, which are normalized to ensure compatibility.

Ra and MRR with their maximum values: $(Ra)_{\max} = 4.6043\ \mu m$ and $(MRR)_{\max} = 3.894$gms/min.

Minimum of $\zeta_1\left(\equiv \dfrac{Ra}{(Ra)_{\max}}\right)$ and $\zeta_2\left(\equiv \dfrac{(MRR)_{\max}}{MRR} - 1\right)$ correspond to minimum of Ra and maximum of MRR. As in [62] the positive weighing factors (ω_1 and ω_2, which satisfy $\omega_1 + \omega_2 = 1$)

Equal weights, denoted as 1 ω = 2 ω = 1/2, are assigned to the AWJM machining parameters to ensure uniform optimal process conditions are achieved as shown in Table-5. An analysis of variance (ANOVA) is executed on the values of the multi-objective optimization function, denoted as ς, as presented in Table-5. This analysis is conducted to identify the optimal process parameters that yield the minimum ς, leading to the selection of the optimal process parameters, specifically A3B3C3. Notably, Mhamunkar and Raut have obtained the same outcome through ANOVA and GRA techniques. A comprehensive summary of the specific optimal AWJM parameters, along with estimates of the associated performance indicators, is detailed in Table-6. The relationship between surface roughness (Ra) and material removal rate (MRR) with traverse speed (A) is depicted in Figure-6, considering an abrasive flow rate (B) of 300 gms/min and three different levels of stand-off distance (C). The ANOVA results, as shown in Table-1, reveal that the %contribution of C on MRR is insignificant. This explains the closely grouped MRR values observed in Figure-6 for varying C values.

The AWJM machining parameters were utilized with equal weighing (i.e., 1 ω = 2 ω = 1/2) to establish common optimum process conditions as presented in Table-5. An analysis of variance (ANOVA) was executed on the values of the multi-objective optimization function, ζ, detailed in Table-5, to identify the optimum process parameters for minimizing ζ. The optimal process parameters were determined as A3B3C3. The same outcome was corroborated by Mhamunkar and Raut through both ANOVA and GRA analyses. The summary of specific optimal AWJM parameters and the estimates of performance indicators is provided in Table-6. The variation of surface roughness (Ra) and material removal rate (MRR) concerning traverse speed (A) is illustrated in Figure-6 for an abrasive flow rate (B) of 300 gms/min and three levels of stand-off distance (C). ANOVA results, as presented in Table-1, indicate an insignificant %contribution of C to MRR. This explains the closely clustered MRR values in Figure-6 across different C values.

5.CONCLUDING REMARKS

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High strength, corrosion resistance, low thermal conductivity, and oxidation resistance are inherent properties of Ti-6Al-4Valloy. This alloy finds extensive utility in marine and automobile applications. Abrasive water jet machining (AWJM) emerges as a suitable choice for processing this alloy. Utilizing the modified Taguchi method and multi-objective optimization, a set of optimal AWJM parameters comprising traverse speed, abrasive flow rate, and stand-off distance is determined to simultaneously maximize material removal rate (MRR) and minimize surface roughness (Ra). The dissimilar quality attributes of Ra and MRR are transformed into dimensionless forms and consolidated into a single response characteristic.

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