Understanding and predicting material removal rate in abrasive waterjet milling of kerfs

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ABSTRACT

Titanium alloys are used in engineering applications due to their high strength-to-weight ratio. However, it is challenging to manufacture parts from it. On the other hand, abrasive waterjet (AWJ) has demonstrated its capabilities in milling parts in titanium alloys. However, AWJ milling technology is still nascent due to a lack of accurate control over material removal. The material removal rate (MRR) is one measure that decides productivity. Towards contributing to the acceptance of the AWJ milling technology, a model for accurate prediction of the MRR is proposed in this work. Hence, a suitable generic geometry that accurately mimics the material removal under various AWJ conditions is identified. By integrating the identified geometry (rectangle, trapezium, triangle) with the maximum erosion depth and the top kerf width, the MRR is predicted. Results show that the estimated MRR using a triangular kerf CP area correlate well with the experimental MRR.

1. Introduction

Titanium alloys are one of the advanced engineering difficult-to-machine ductile materials widely used in various applications as a structural component due to their excellent trade-off between strength-to-weight ratio. However, machining Titanium alloys is not a simple task with conventional machining approaches. Towards this, abrasive waterjet (AWJ) machining is a suitable technology for producing due to their unique features. Among the various non-conventional machining processes, AWJ milling is the most efficient technique from the energy utilization perspective for material removal from the workpiece surface (Hashish, 1989b). However, generating a 3D complex surface using controlled depth AWJ milling is still in the developing stage due to the inherent complexities of the high Mach number (M>3) jet characteristics and lack of control over the material removal. The material removal rate is a critical performance parameter that indicates the productivity of the machining process along with the unit manufacturing cost of the part. In AWJ milling, the shape of the kerf geometry generated in single-pass erosion at 90^0 jet impacts is defined with the help of two geometric dimensional characteristics, *i.e.*, maximum centerline erosion depth (h_{max}) and top kerf width (W_T). In the development of material removal models, the material removal rate (MRR) in AWJ cutting of ductile materials is approximated as the product of the rectangular-shaped kerf cross-section area and the jet traverse rate (Srinivas & Babu, 2009). On the other hand, AWJ cutting of multilayered structures of ductile materials evaluated the volume of material removed for 1 mm jet traverse length using the trapezoidal-shaped kerf cross-section area (Singh et al., 2020). However, the approximation of kerf CP using these geometric shapes is valid when the AWJ milling produces straight vertical kerf edges. The kerf edges generated in milling always remain curved due to the loss in kinetic power of abrasive particles in the jet plume that is maximum at the center of the jet axis and gradually reduces to a minimum towards its periphery. Hence, evaluating the MRR using the said geometry shape shows a large difference compared to the experimentally measured MRR or MRR evaluated using the area of the complete mean cross-sectional profile of the AWJ milled kerf. Hence, the present study focuses on understanding the influence of basic geometrical shapes used for approximating the actual kerf cross-sectional profile (CP) in

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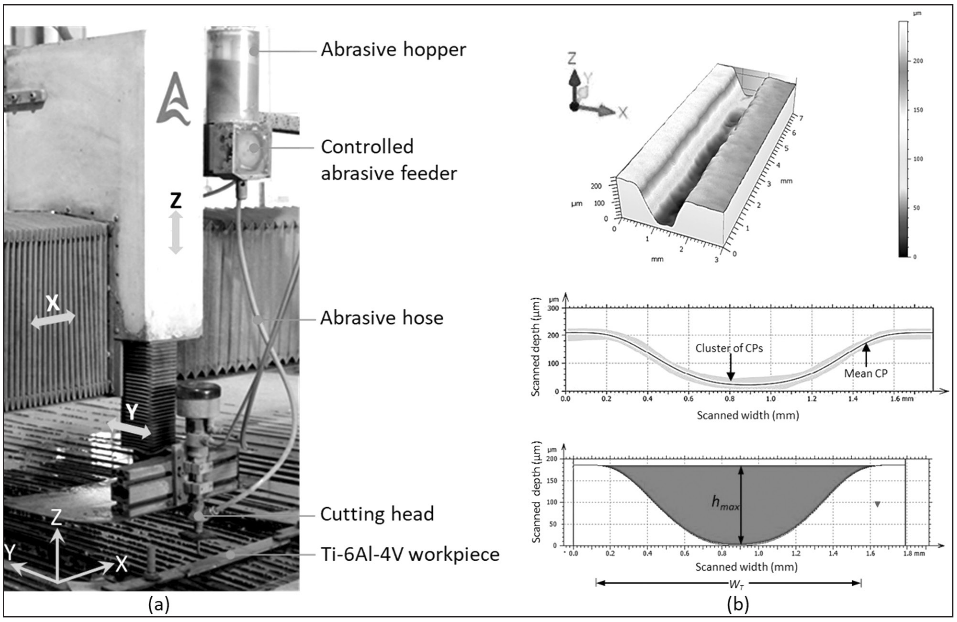

Fig. 1. Photograph of the (a) experimental setup employed for abrasive waterjet milling of Ti-6Al-4V workpiece, (b) extraction of kerf characteristics from optically scanned single-pass trench.

evaluating the MRR analytically. The objectives and scope of the study are presented in the following section.

2. Scope of the Work

The present work aims to understand one of the most important parameters, material removal rate, using a basic geometrical shape that suitably approximates the experimentally obtained MRR. Towards this, the rate of material removal phenomena involved in the kerf formation in the difficult-to-machine ductile material influenced by the varying AWJ milling process conditions was investigated. Hence, the activities in the present study include the following,

- Experimental trials were conducted on Ti-6Al-4V target material to study the variation in material removal rate by varying the waterjet pressure (*P*) and jet traverse rate (V_f), keeping other operating parameters constant.
- The actual MRR at different *P* and V_f were analyzed from the perspective of the kerf cross-section profile geometry and approximated using the basic geometrical shape (triangle, trapezium, and rectangle) representing the kerf CP.
- To assess the basic geometrical shape suitable for evaluating MRR, which nearly approximates the experimentally obtained MRR.
- To develop and validate a predictive model for MRR by taking into account the geometry identified.

Table 1
Operating parameters used in experimentation.

Operating parameters	
Waterjet pressure, *P* (MPa)	125, 200, 275, 350
Jet traverse rate, V_f (mm/min)	1000, 3000, 5000
Standoff distance, *SoD* (mm)	10
Orifice diameter, d_o (mm)	0.356
Focusing nozzle diameter, d_f (mm)	1.02
Focusing nozzle length, L_f (mm)	72
Abrasive mass flow rate, m_a (kg/min)	0.3
Abrasive particle diameter, d_a (μm)	180

3. Experimentation

The single-pass erosion by abrasive waterjets at a jet impingement angle of 90^0 under varying operating parameters (Table 1) was conducted to generate data for understanding the material removal rate. Towards this, a 3-axis AWJ machine tool (AQUAJET®-G3020) was employed (Fig. 1a). A rectangular strip (300 mm x 40 mm x 5 mm) of a Ti-6Al-4V was used in the experimental trials for generating the required CPs of the kerf milled in single-pass erosion to identify the operating range of process parameters' for AWJ milling from the pilot trails. From this, the suitable operating parameter ranges were identified (Table 1) and utilized in the shallow depth kerf milling. The trenches generated in single-pass erosion trails were scanned using a confocal microscope (LEXT® OLS4000), and the data were post-processed using the surface analysis software, MountainsMap®8 (Fig. 1b). The mean cross-sectional profiles of the 3D kerf generated by AWJs under varying process parameters were presented in Fig. 2.

The material removal rate in abrasive waterjet milling depends on the setting and control parameters. The setting parameters are those that cannot be varied during milling. This involves the type of abrasives used, waterjet pressure, and the abrasive mass flow rate. On the contrary, control parameters can be modified during AWJ milling, which includes the jet traverse rate (V_f) and standoff distance (*SoD*). In the present study, the *P*, $\dot{m}_a$, and *SoD* were considered as setting parameters and V_f as a control parameter to control the MRR.

4. Evaluation of Material Removal Rate with Basic Geometrical Shape of the Kerf Cross-Section

In this section, the kerf characteristics, such as the cross-section area generated by the abrasive waterjet in single-pass erosion, were studied under varying operating parameters (*P* and V_f). In addition, the material removal rate was evaluated using the experimentally obtained top kerf width (W_T) and maximum centerline erosion depth (h_{max}) by assuming the shape of the kerf milled by AWJs as one of the basic geometrical shapes, such as rectangle, trapezium, and triangle, respectively. This enables us to understand the effect of the basic geometrical shape employed in evaluating the MRR that accurately mimics the material removal rate obtained from AWJ milling experiments. Figure 3 presents the schematic of the experimentally generated kerf CP area approximation with the basic geometrical shapes. The cross-section area of the kerf milled by AWJs was evaluated using Eq. 1, as

$$\left.\begin{aligned} A_{act} &= \int_{-W_T}^{W_T} h_l(x)\,dx \\ A_{Rec} &= h_{max}\,W_T \\ A_{Trap} &= 0.5\,h_{max}\,(d_f + W_T) \\ A_{Tri} &= 0.5\,h_{max}\,W_T \end{aligned}\right\} \quad \text{..................(1)}$$

where A_{act}, A_{Rec}, A_{Trap}, and A_{Tri} are the cross-section area of the actual-, rectangular-, trapezoidal-, and triangular-, shaped kerf.

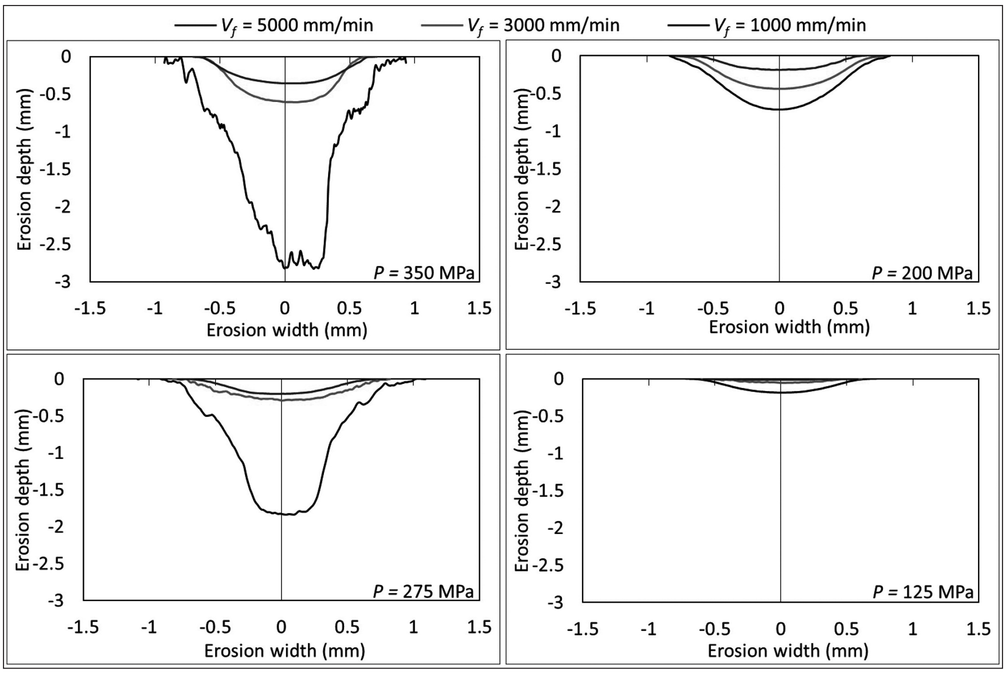

Fig. 2. Mean cross-sectional profiles of the kerfs milled by abrasive waterjets under varying process parameter conditions.

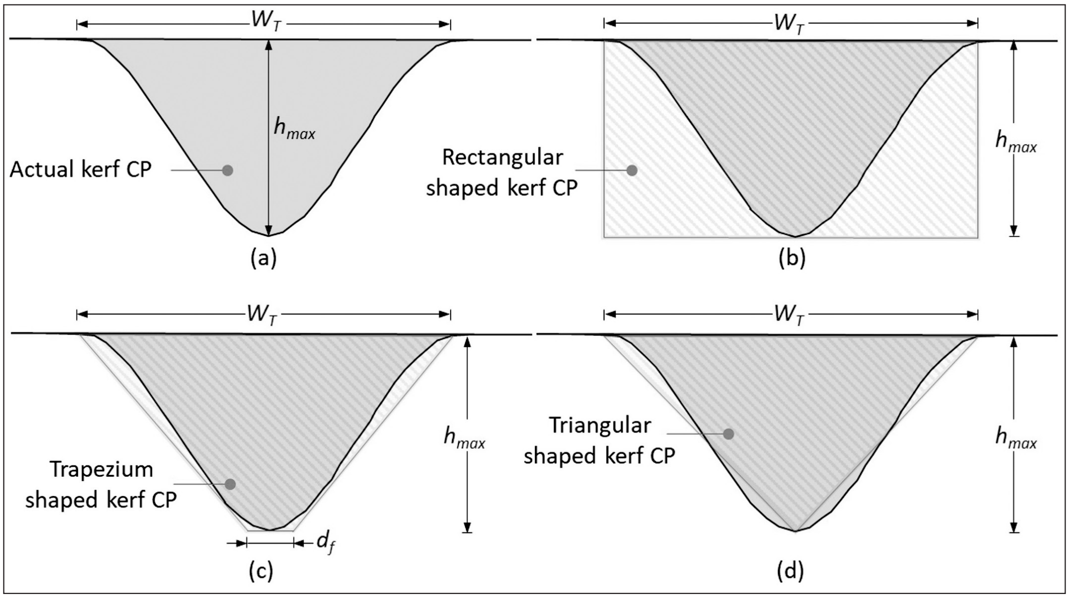

Fig. 3. Schematic of kerf shapes: (a) actual, (b) rectangular, (c) trapezium, and (d) triangular.

According to the material/volume removal rate definition, the volume of material removed per unit of time by traversing the high-velocity abrasive waterjet was evaluated using Eq. 2.

$$MRR = A_k V_f \qquad ....(2)$$

where A_k is the cross-section area of the kerf, V_f is jet traverse rate.

Therefore, using Eq. (1) and Eq. (2), the MRR was evaluated by approximating the area of the kerf CPs with the basic geometrical shapes. Figure 4 presents the effect of geometrical shape employed in evaluating material removal rate under varying abrasive waterjet operating conditions. Note that the MRR calculated apart from the actual ones were evaluated using the maximum centerline erosion depth and top kerf width, *i.e.*, the actual MRR was evaluated by considering the whole cross-sectional profile of the kerf, and h_{max} and W_T were considered as the geometrical dimensions of the basic shapes considered in the present work. The detailed understanding gained from these evaluations was presented and discussed in detail in section 6. Following this, the generic geometric shapes employed to approximate the actual kerf CP for predicting the MRR were assessed for its generalization.

5. Material Removal Modelling

The material removal modelling approach for predicting the MRR obtained by traversing the abrasive waterjet at a normal jet impingement angle to the target Ti-6Al-4V alloy material surface was discussed in the following. The key elements for predicting the kerf CP produced in single-pass AWJ milling were (i) evaluation of the abrasive particle velocity at the focusing nozzle exit, (ii) modelling the effective top kerf width as a function of waterjet pressure and jet traverse rate, and (iii) evaluation of the maximum centerline erosion depth using Hashish depth-of-cut model. The activities of evaluating the abrasive particle velocity, top kerf width, and maximum centerline erosion depth were presented in the following:

- *Evaluation of abrasive particle velocity at the focusing nozzle exit*

The pure water pressurized by the ultra-high-pressure pump (BFT® ECOTRON 40.45) transforms into a supersonic waterjet at the orifice exit. The actual velocity of the pure waterjet along the axis of the jet at the orifice exit (V_w) was obtained from Bernoulli's law by Eq. (3) as,

$$V_w = C_d \sqrt{\frac{L}{P(1-n)}\left[\left(1+\frac{P}{L}\right)^{1-n} - 1\right]} \left(\sqrt{\frac{2P}{\rho_w}}\right) \qquad ....(3)$$

where P is waterjet pressure, ρ_w is water density, L = 300 MPa, and n = 0.1368 at 25^0 C, C_d is the discharge coefficient.

Through the momentum balance, the velocity of the abrasive particles (V_p) in the surrounding waterjet flowing through the focusing nozzle was evaluated using Eq. (4) (Hashish, 2003).

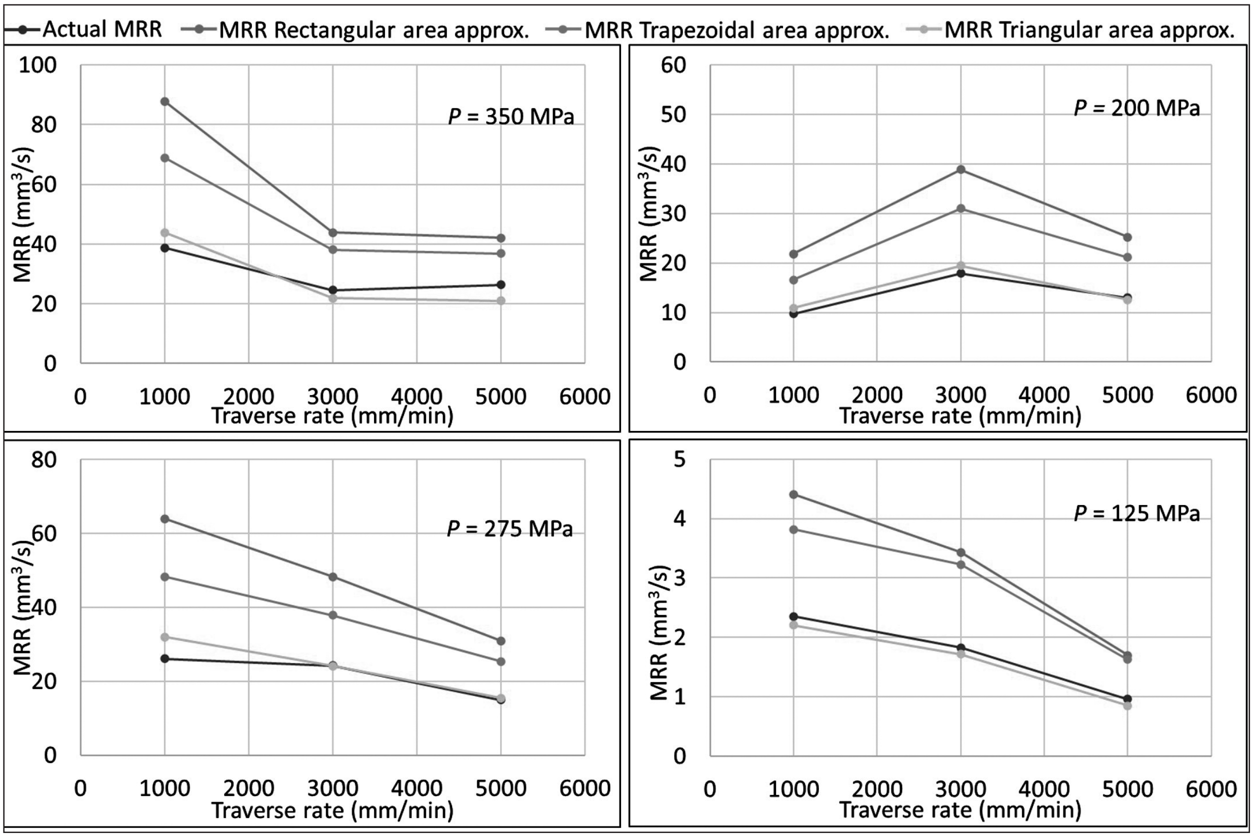

Fig. 4. Geometrical shape affects the material removal rate under varying AWJ conditions.

$$L_f = \frac{1}{K}\left[\frac{\left(\frac{V_p}{V_w}(1+R)\right)}{1-\left(\frac{V_p}{V_w}(1+R)\right)} - ln\left(\frac{\left(\frac{V_p}{V_w}(1+R)\right)}{1-\left(\frac{V_p}{V_w}(1+R)\right)}\right)\right] \quad ....(4)$$

where $K = \left(\frac{3C_d\,(1+R^2)}{4S_p d_a}\right)$, *R* is the loading ratio, S_p is the specific gravity of the abrasive particle.

- *Depth of cut model*

In the present study, a modified depth-of-cut model proposed by Hashish (1989a) was employed to predict the maximum centerline erosion depth for the deformation wear mode of the material removal mechanism that occurs at near-normal impacts. The depth of cut due to deformation wear mode (h_d) is expressed as,

$$h_d = \frac{1}{\frac{\pi\, d_j\, \sigma\, V_f}{2\, C_1\, \dot{m}_a\,(V_p - V_c)^2} + \frac{C_f\, V_p}{d_j\,(V_p - V_c)}} \quad ....(5)$$

where C_1 is an effective abrasive fraction, C_f is the coefficient of friction on the kerf wall, C_k is the characteristic velocity, V_c is threshold velocity, and σ is the flow stress.

- *Determination of effective jet diameter*

The 'd_j' is the diameter of the jet plume at the jet-material interaction zone, which is equal to the effective jet diameter (d_{eff}). The abrasive waterjet diverges in the mixing chamber and from the tip of the focussing nozzle into the atmospheric air. This leads to a reduction in the velocity of AWJ in both axial and radial directions (Srinivasu & Axinte, 2011). Consequently, the abrasive particles in the jet plume diverge with water and impact the workpiece at varying angles locally. Towards this, there is a need to evaluate the jet plume divergence angle (ϕ_{eff}), which results in the effective jet diameter (d_{eff}). Note that the ϕ_{eff} depends on the jet flow dynamics, type of target material, and AWJ operating parameters. In the present work, for the given Ti-6Al-4V target material, the ϕ_{eff} was evaluated through a regression equation modelled as a function of AWJ operating parameters, *i.e.*, waterjet pressure and traverse rate. Therefore, the d_{eff} was evaluated using Eq. (6).

$$\phi_{eff} = c_1 P + c_2\, V_f \quad ....(6)$$

where c_1 and c_2 are the parameters specific to the AWJ operating conditions and the type of

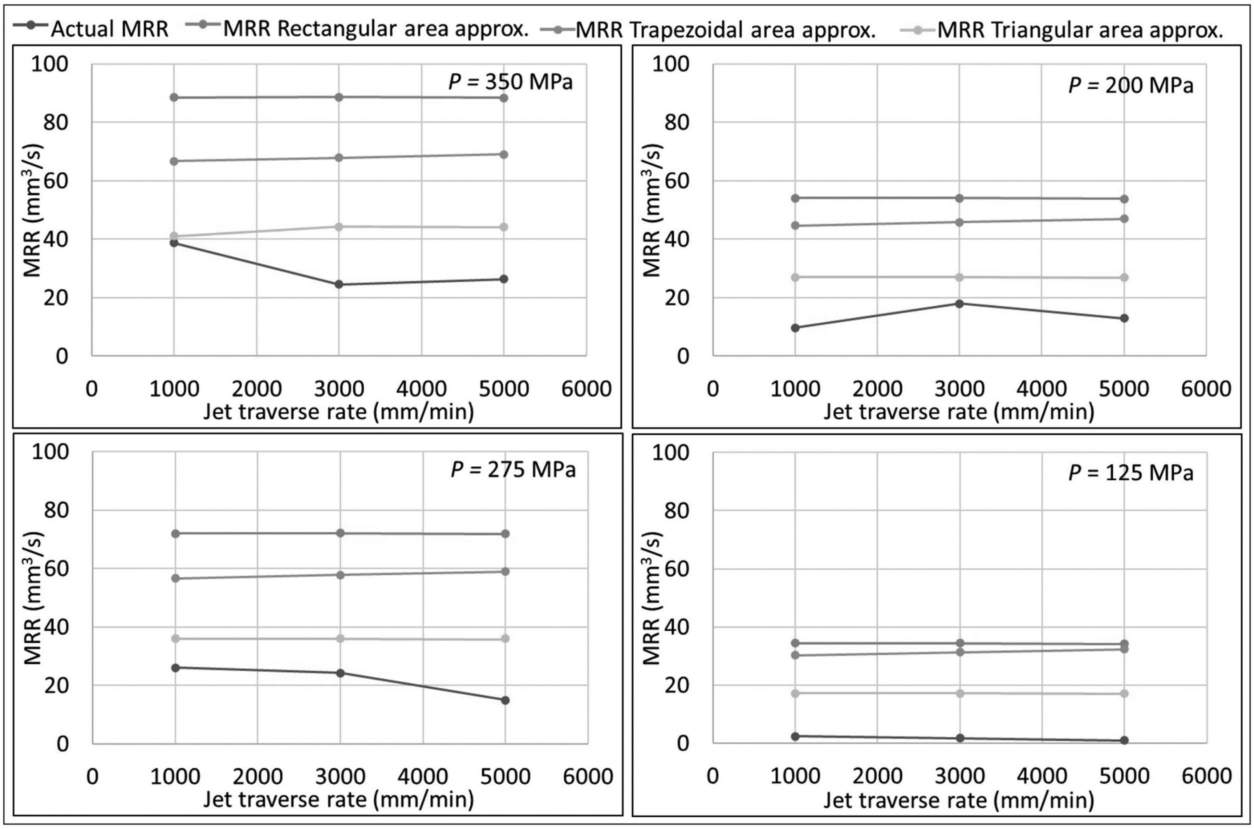

Fig. 5. Influence of geometrical shape on the predicted material removal rate under varying AWJ conditions.

material employed. The parameters obtained for the present study configuration were 8.5e-03 and -1.370e-04, respectively. Therefore, the effective jet diameter of the jet plume at the jet-material interaction zone was evaluated using Eq. (7).

$$d_{eff} = 2\,SoD\,\tan\left(\phi_{eff}\right) + d_f \qquad ....(7)$$

Hence, Eq. (6) and Eq. (7) were used to predict the maximum centerline erosion depth and effective top kerf width in single-pass erosion by AWJs. In turn, these were used for evaluating the MRR analytically by approximating the kerf CPs with the basic geometrical shapes (Fig. 3).

6. Results and Discussion

From Fig. 4, it can be observed that the MRR evaluated using Eq. (2) by approximating the shape of the AWJ milled kerf CPs with basic geometrical shapes follows the trend of the actual MRRs. This proves that the area of the actual kerf CPs can be approximated using the basic geometrical shapes considered. However, a large deviation was observed between the actual MRR and the calculated ones with rectangular- and trapezoidal-shaped kerf CP area approximations compared to triangular-shaped ones (Fig. 4). This can be explained as follows: the overall area between the actual kerf edges and rectangular/trapezoidal-shaped kerf CP edges was higher relative to the triangular-shaped ones. Furthermore, the triangular-shaped kerf CP edges start from either side of the top kerf width ends to the maximum centerline erosion depth; the actual kerf CP may have a higher chance of intersecting with the curved edges of the kerf CP. This results in a significant reduction in approximating the actual kerf CP, enabling a better estimation of MRR. Furthermore, the kerf edges generated in AWJ milling always remain curved due to the loss in kinetic power of abrasive particles in the jet plume that is maximum at the center of the jet axis and gradually reduces to a minimum towards its periphery (Srinivasu & Axinte, 2011). Towards the above-said reasons, the best shape that can be used for approximating the area of kerf CP, relative to the regularly employed rectangular-shaped kerf CP area approximation, was the triangular-shaped followed by the trapezoidal-shaped kerf CP.

On the other hand, the predicted h_{max} (Eq. 5) and W_T (Eq. 7) were used to evaluate the MRR by considering the basic geometrical shapes representing the actual kerf CPs (Fig. 5). From this, it can be observed that the MRR was significantly influenced by the basic geometrical shape employed for approximating the kerf CP area. A similar phenomenon was observed in the MRR, which was evaluated by considering the actual values of h_{max} and W_T with the basic geometrical shapes used for the kerf CP area approximation (Fig. 3). Therefore, from the material removal model, it was understood and proved that the prediction of MRR by utilizing the basic geometrical shapes approximation representing the actual kerf CP area was feasible. Although the proposed approach has approximated the MRR with less error, error exists. This can be attributed to the error in predicting the maximum erosion depth and the top kerf width. The model predicted the MRR using the identified geometric shapes rectangular, trapezoidal, and triangular shapes with a root mean square error of 14.96 mm^3/s, 34.45 mm^3/s, and 46.74 mm^3/s, respectively.

Hence, there is a need to develop better models for predicting the h_{max} and W_T. Employing better prediction models to predict the dimensional characteristics of the kerf geometry enables a better approximation of MRR by employing the triangular-shaped kerf CP area approximation compared to other geometric shapes (rectangular/ trapezoidal).

7. Conclusions

The current work aims to understand the influence of basic geometrical shapes to approximate the kerf geometry for evaluating the MRR in Ti-6Al-4V target material. The following were the critical conclusion drawn from the present study:

- From the material removal modelling perspective, the prediction of MRR by utilizing the kerf CP area approximation with the basic geometrical shapes is feasible. Hence, the MRR evaluated experimentally and using the material removal model are strongly influenced by the geometry employed for approximating the AWJ milled kerf geometry.
- Among the geometries considered, the triangular-shaped kerf CP area approximation is the best shape that can be used for approximating the experimentally obtained kerf CP area against the regularly employed rectangular and trapezoidal- shapes. Hence, the triangular-shaped kerf CP area was most suitable for the prediction of MRR analytically.
- The model predicted the MRR using the identified geometric shapes, *i.e.*, rectangular, trapezoidal, and triangular shapes, with a root mean square error of 14.96 mm^3/s, 34.45 mm^3/s, and 46.74 mm^3/s, respectively. Hence, there is a need for developing a better MRR model, which in turn demands better models to accurately predict the geometrical characteristics of the kerf CP, *i.e.*, maximum erosion depth and top kerf width.

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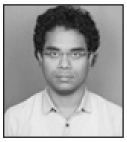

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