2011 WJTA-IMCA Conference and Expo
September 19-21, 2011 ● Houston, Texas
Paper

ENERGY BASED EVALUATION OF WATERJET PEENING FOR INDUSTRIAL APPLICATION

A. Chillman and M. Hashish
Flow International Corporation
Kent, WA 98032

M. Ramulu
Department of Mechanical Engineering
University of Washington, Seattle, WA 98105

C. Lavender and E. Stephens
Pacific Northwest National Laboratory
Richland, WA 99352

Y.C. Chen
Cummins, Inc.
Columbus, IN 47203

ABSTRACT

Waterjet peening provides an effective means for fatigue enhancement without inducing large scale degradation in surface topography. As opposed to many conventional peening processes that use solid particulates to induce compressive residual stresses in the subsurface layer, waterjet peening relies only on droplet impact, also making it a greener solution. Still, caution must be taken during waterjet peening to ensure proper selection of process conditions. If conditions are selected that are too aggressive, large scale pitting and erosion can occur. A recently proposed energy based evaluation method was used to determine the proper parametric combinations for waterjet peening by defining threshold conditions for erosion. Two case studies are analyzed where waterjet peening was employed on titanium and aluminum materials. Resulting surface roughness and residual stress profiles are presented for both material studies, in addition to fatigue results for the research surrounding the aluminum material. The results highlighted that waterjet peening can lead to notable fatigue improvements with aluminum components, and continued development efforts surrounding utilization for titanium are necessary based on the favorable initial results.

1. INTRODUCTION

Waterjets (WJ's) are utilized for a variety of surface preparation processes, including i.) cleaning, ii.) controlled milling, iii.) surface texturing and profiling, and iv.) peening. Currently, the selection of process parameters is made based upon iterative trial and error testing. This is time consuming and added difficulty exists if excess material availability is limited. A quantifiable means of determining target parametric ranges based upon the workpiece material is required to minimize waste.

Based on past investigations [1-2], it has been shown that the centerline energy density of a waterjet traversing over a flat plate is a controlling factor to the resulting depth. Also, it has been displayed that a threshold energy density level exists, below which large scale erosion is not initiated. In this study, application of this relationship to flat plate and cylindrical geometries will be performed with results for the processing of both titanium and aluminum materials included.

2. ENERGY DENSITY CALCULATIONS

The energy density ($\mathbf{E_{dA}}$), or energy per unit area, transferred from the waterjet to the workpiece can be described based upon the net power of the waterjet ($\mathbf{\dot{E}_{NET}}$) and the exposure time per unit area (t_e). This approach is based on uniform coverage of the region of interest. The net power of the waterjet can be expressed in terms of the process parameters by [2]:

$$\mathbf{\dot{E}_{NET}} = \frac{\pi\sqrt{2}}{4}\left(C_D\, P_S^{3/2}\, \rho_w^{-1/2}\, d_n^{\,2}\right) \tag{1}$$

where C_D is the coefficient of discharge, P_S is supply pressure, ρ_w is the density, and d_n represents the orifice diameter.

The energy density can be expressed as the function of the net power and exposure time per unit area by:

$$\mathbf{E_{dA}} = \dot{E}_{\mathbf{NET}} * t_e \tag{2}$$

The exposure time per unit area, when considering uniform coverage, can then be defined for basic geometries.

3. ENERGY EVALUATIONS FOR WJ IMPINGEMENT OF A TITANIUM ALLOY

The effect of waterjet and abrasive waterjet (AWJ) impingement on titanium alloys has been analyzed during past investigations [1,3-7]. The past studies performed during [1,6,7] have indicated that the influence of energy density level during waterjet surface preparation is a critical effector.

To characterize the response of Ti-6Al-4V to waterjet processing, a study was conducted utilizing both waterjet and water-air jet (WAJ) nozzles [8]. WAJ's are formed when air is injected or entrained, at a known flow rate (Q_A), into the jet stream to cause an accelerated breakdown of the waterjet into droplets; in contrast to the highly coherent initial region typically found at the nozzle exit of a waterjet. A Design of Experiments (DOE) approach was conducted utilizing the parametric levels presented in Table 1, resulting in 27 experimental runs. The DOE was performed using a quadratic design model (with interaction effects included) and a response surface (central composite full) design type. There was a single replicate group consisting of 3 runs. The variable P_A refers to the applied air flow rate when utilizing the WAJ. For all tests a 0.25 mm orifice exhibiting a 0.74 coefficient of discharge was used.

Table 1. Parametric levels for waterjet and water-air jet surface preparation of a Ti-6Al-4V material.

P_S *(MPa)*	**SOD** *(mm)*	**u** *(mm/s)*	**P_A** *(kPa)*
275	25.4	30	0
414	63.5	60	207
600	101.6	120	414

Ti-6Al-4V material conforming to MIL-T-9046 specification was used. The percent elongation at failure, yield strength, and ultimate tensile strength for the Ti-6Al-4V plate were 18.1%, 901 MPa (130.7 ksi), and 979 MPa (142 ksi) respectively. Regions of 13 mm thick plate were processed utilizing the rastering approach with 50 successive passes and a 0.4 mm lateral traverse.

After waterjet processing, the samples were inspected using contact surface profilometry using a MarSurf20 system, equipped with a 2.0 µm probe to characterize the resulting average roughness values (R_a). The surface profiles were measured in accordance with ASME B46.1, using a 5.6 mm traverse length, with a 0.8 mm cutoff length. The residual stress profiles were also evaluated by means of X-Ray Diffraction (XRD). Measurements were taken at 0, 25, 50, 75, and 125 µm below the surface level, with a chemical etching technique used to expose the subsurface layers prior to evaluation.

A region of the prepared sample is presented in Figure 1. The degree of material removal varied significantly; some samples exhibited no alteration while others experienced significant depth of removal.

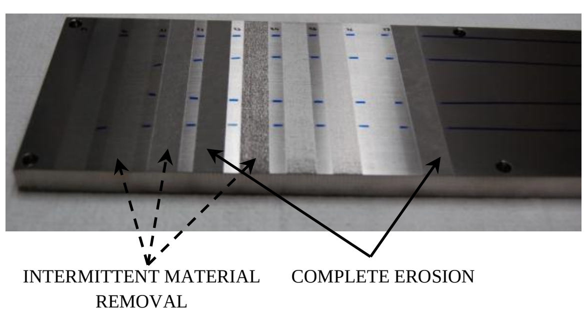

Figure 1. Optical evaluation of processed Ti-6Al-4V titanium plate.

The primary focus of this study was to analyze the effect of the energy density level on the resulting surface roughness and residual stress. The resulting average surface roughness values are presented in Figure 2. The presented data shows that the resulting surface roughness did not increase substantially as the energy density level increased from 0 – 0.5 kJ/mm^2. Also, roughness values ranging from 6 – 10 µm were measured for samples prepared at energy density levels above 0.7 kJ/mm^2. The region of 0.5 < $\mathbf{E_{dA}}$ < 0.7 kJ/mm^2 presented a transitional region. It appears that a threshold existed, but in the transitional region additional effectors, including jet structure, played an influential role. The two cases that resulted in an increased R_a value were processed using:

- *Run 21:* P_S: 600 MPa / SOD: 25.4 mm / u: 120 mm/s / d_n: 0.25 mm / Q_A: 0.15 m^3/min with a WAJ nozzle
- *Run 23:* P_S: 600 MPa / SOD: 101.6 mm / u: 120 mm/s / d_n: 0.25 mm with a WJ nozzle

Based on the results presented by Chillman et al [7], these standoff distance and air flow rate pairings were shown to tailor the jet structure in a means that led to the most aggressive material removal.

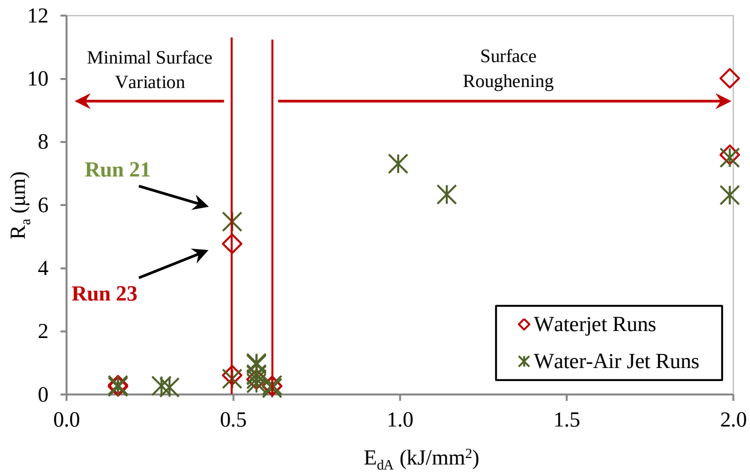

Figure 2. R_a displayed as function of energy density for WJ and WAJ surface processing of a Ti-6Al-4V alloy.

The resulting compressive residual stress versus depth curves were analyzed to determine the maximum achieved value for each run. Figure 3 displays the maximum compressive residual stress for each run as a function of the energy density. The trends exhibited suggest that the degree of residual stress imparted in the titanium material increased as the energy per unit area transferred to the workpiece increased from a low (0.15 kJ/mm^2) to mid (0.6 kJ/mm^2) level. As higher energy density levels were considered, the onset of erosion was reached, and substantial surface roughening occurred. The energy per unit area transferred to the workpiece was being utilized for (i) plastic deformation and (ii) generation of free surfaces, leading to lower achieved residual stress levels. Also, as material removal occurred, an unloading of the generated compressive stresses would be expected.

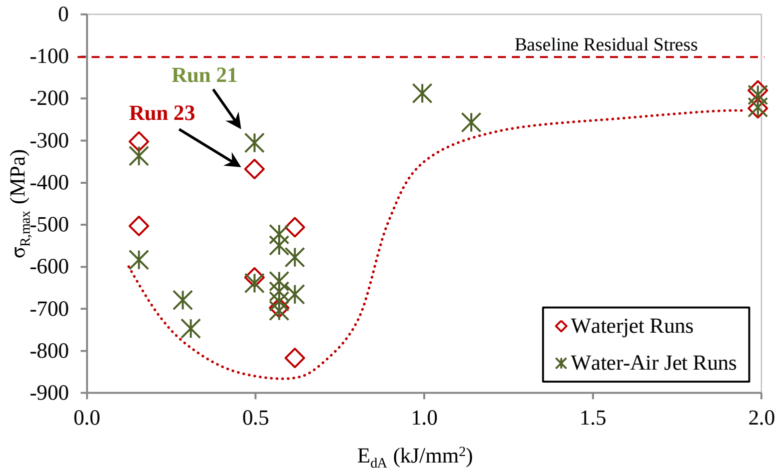

Figure 3. Maximum residual stress displayed as function of energy density for WJ and WAJ surface processing of a Ti-6Al-4V alloy.

For waterjet peening, the optimized conditions are those that induce minimal variation in surface quality while imparting the highest magnitude of compressive residual stress. The energy based approach suggested this occurs in the energy density regime of 0.4 to 0.6 kJ/mm^2 for the Ti-6Al-4V alloy.

While a DOE approach was considered, the results were presented as a function of the energy density transferred to the workpiece. The intent of this study was not to perform a complete Analysis of Variance (ANOVA), however the cumulative effects (Pareto) can provide further insight into the dominant process parameters. In this study the energy density was controlled by only the pressure and traverse rate. The standoff distance and air flow rate influenced the jet structure. A Pareto analysis was performed on the resulting average surface roughness and compressive residual stress – as presented in Figure 4. The results of the Pareto analysis suggest that the supply pressure and traverse rate were the only dominant contributors, and the impact of standoff and air flow were minimal in comparison.

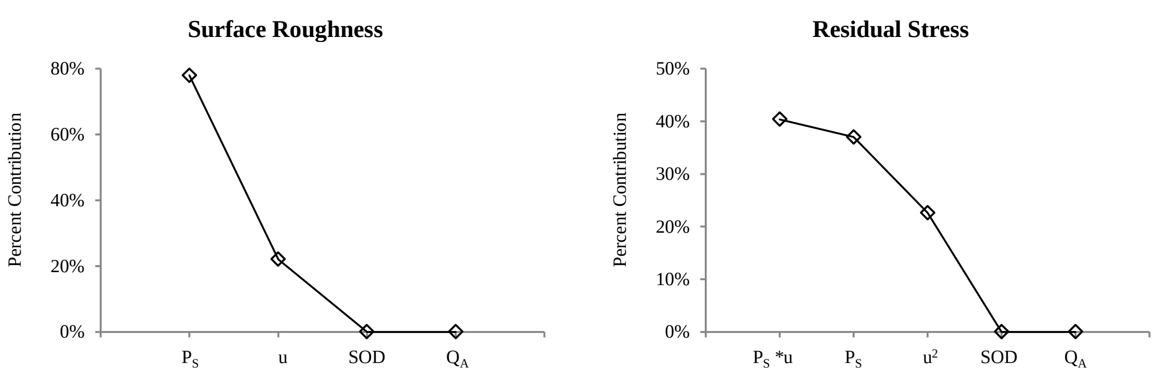

Figure 4. Pareto chart displaying cumulative effect of WJ parameters on R_a and residual stress for Ti-6Al-4V surface processing.

The analysis presented in this section highlights that the energy density was the controlling parameter for both surface roughening and residual stress generation during the surface preparation of a Ti-6Al-4V alloy; however waterjet structure must also be considered to ensure complete process control.

4. WJ PEENING OF AN ALUMINUM ALLOY

A fatigue based investigation into the benefits of waterjet peening for an aluminum alloy using waterjet and water-air jet nozzles was also performed. A similar DOE approach was utilized to reduce the required number of test runs, with the outputs of interest being the residual stress and surface roughness parameters during waterjet processing of cylindrical dog-bone specimens (see Figure 5). Based on the results of the screening study, three conditions were chosen for the processing of samples for rotating bending fatigue (RBF) testing.

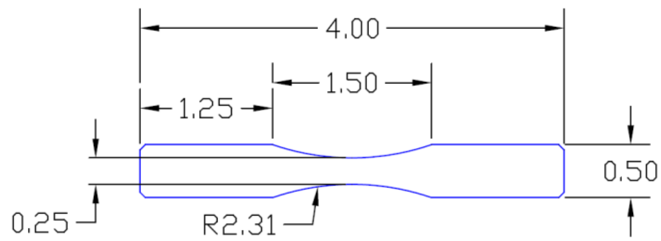

Figure 5. Sample geometry for waterjet surface preparation of aluminum samples.

The parametric conditions considered for this testing are presented in Table 2. Again, three pressure, standoff, traverse rate, and air pressure levels were considered. The rotational speed of the samples was fixed at 500 rpm, and a single traversing pass was made axially along the rotating sample. A 0.25 mm diameter diamond orifice was used for this testing and a 0.76 mm mixing tube was used for the WAJ test cases. The DOE reduced the test plan to 26 cases.

Table 2. Parametric levels for DOE approach to waterjet surface preparation of aluminum alloy.

P_s	SOD	u	P_A	d_n	Mixing Tube Dia.	Rotational Speed	No. of Passes
(MPa)	*(mm)*	*(mm/s)*	*(kPa)*	*(mm)*	*(mm)*	*(rpm)*	*(#)*
68.9	25.4	1.1	0				
120.7	50.8	6.4	207	0.25	0.76	500	1
172.4	101.6	10.6	414				

After processing, XRD and contact profilometry were again utilized to determine the maximum residual stress and surface roughness values. The energy density for each processing run of the cylindrical specimens was also calculated. The relationship between the average roughness, absolute value of the normalized residual stress, and energy density is presented in Figure 6. As the energy density range increased from $\mathbf{E_{dA}} < 0.01$ kJ/mm^2 to $0.02 < \mathbf{E_{dA}} < 0.03$ kJ/mm^2, an increase in residual stress was discovered. Overlap in resulting residual stress existed in the 0.02 – 0.05 kJ/mm^2 range; while minimal increase in surface roughness occurred. As the energy density increased above the 0.1 kJ/mm^2 level, considerable roughening was noted. Cases with significant roughening exhibited lower resulting residual stress values which agreed with the results from the titanium investigation.

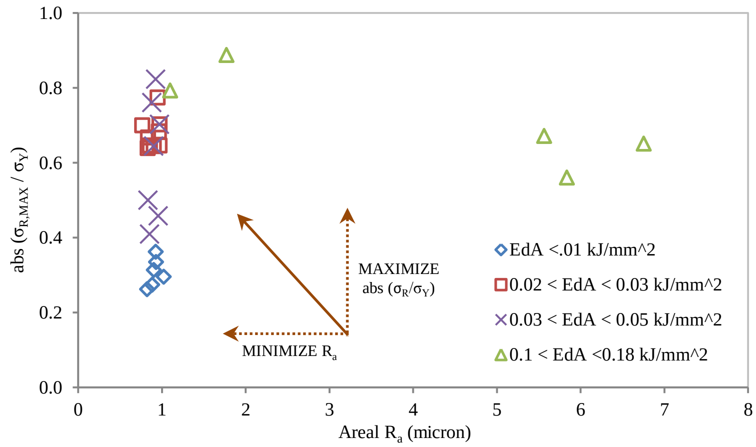

Figure 6. Abs (normalized residual stress) as a function of average roughness for WJ peening trials on an aluminum alloy.

Three conditions were selected from the screening study for the processing of fatigue samples, as presented in Table 3. The cases chosen were at different energy density levels, and it can be observed that as the energy density increased, the areal roughness also increased. Further surface evaluation was performed on the samples selected for the fatigue study. A Zygo surface scanning unit (white light scanning interferometer) was used to map the surfaces to evaluate the degree of pitting. Isolated pits were found to exist for Set A and Set C, with large scale pitting and erosion found on the sample from Set B (Set A is shown in Figure 7).

Table 3. Conditions for preparation of aluminum fatigue samples.

Run No.	P_S *(MPa)*	u *(mm/s)*	E_{dA} *(kJ/mm²)*	SOD *(mm)*	Q_A *(m³/min)*	abs ($\sigma_{R,max}$ / σ_y) *(MPa)*	Areal R_a *(µm)*
Set A	68.9	1.1	0.046	101.6	0	0.76	0.9
Set B	172.4	1.1	0.183	25.4	0	0.89	1.76
Set C	120.7	1.1	0.107	50.8	0.07	0.79	1.02

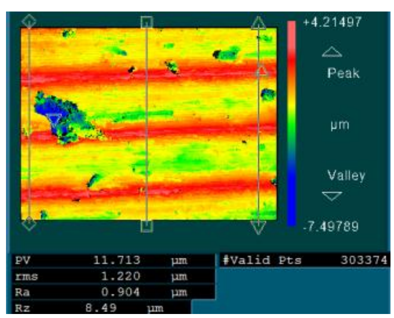

Figure 7. Surface scans for sample from Set A aluminum waterjet peened specimens.

Even with the variations in resulting surface topography, all three waterjet peening conditions resulted in considerable improvement in fatigue performance in the high cycle regime, as presented in Figure 8. A 40 to 50% increase in the stress amplitude relating to the 10^7 cycle life was noted, regardless of which of the three waterjet peening conditions were used. Set A and Set C showed the largest improvement, which were the lower energy density conditions that also exhibited lower levels of surface roughening.

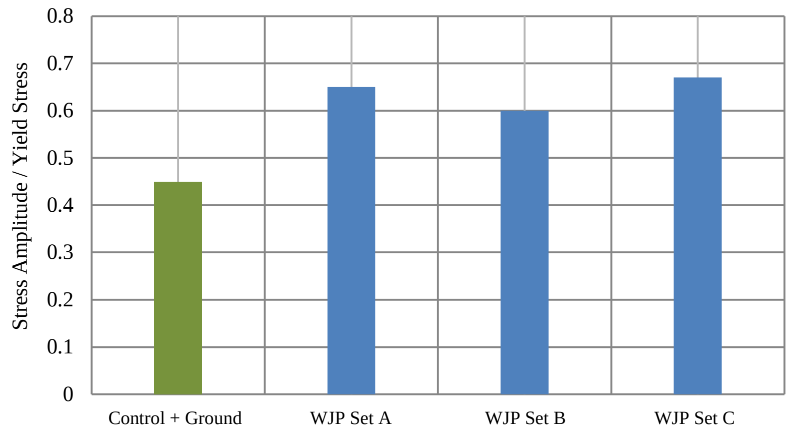

Figure 8. Norm. stress Amplitude at 10^7 cycle life for Set A, Set B, and Set C waterjet peened aluminum RBF samples.

The results from the waterjet peening investigations on an aluminum alloy showed agreement with past studies. In 2002, Soyama [9] performed a fatigue study to investigate the benefits of cavitation shotless peening on an aluminum JIS AC4CH alloy. The resulting residual stress normalized to yield strength resulted in a value of 0.88, similar to that attained in this study. Also, Soyama documented a 30% increase in the high cycle region with the failure occurring 300 to 400 µm below the surface of the sample. The residual stress field depths found in this study extended to 200 µm, in agreement with the results from Soyama. It should be noted that past waterjet peening results for a 7075-T6 aluminum alloy published by Kunaporn and Ramulu [10-12] also noted similar findings.

5. CONCLUSIONS

The results of this study indicate that the energy density was a dominant effector of the resulting surface topography during waterjet surface processing. Key conclusions from this study include:

- The threshold energy density at which erosion occurred was found to be:
  - 0.5 – 0.7 kJ/mm^2 for Ti-6Al-4V titanium material
  - 0.1 – 0.15 kJ/mm^2 for the aluminum alloy

- Once the onset of erosion occurred, the level of residual stress generated in all samples decreased. This can be attributed to the consumption of energy for (i) plastic deformation and (ii) generation of free surface, as well as the unloading of residual stress during material removal.

- The RBF results for the aluminum alloy showed improvements of 40 to 50% in stress amplitude at the 10^7 cycle life for all three selected processing conditions, proving the benefits of waterjet peening for industrial applications in need of fatigue enhancement.

- The energy density transferred to the workpiece served as a predictive means of resulting erosion as long as jet structure considerations were also taken into account.

6. REFERENCES

[1] Chillman, A. "Energy-Based Modeling of Ultra High-Pressure Waterjet Surface Preparation Processes including Milling, Peening, and Texturing Applications." Ph.D. Dissertation. University of Washington, 2010.

[2] Chillman, A., Hashish, M., and Ramulu, M. "Energy Based Modeling of Ultra High-Pressure Waterjet Surface Preparation Processes." *Journal of Pressure Vessel Technology, ASME. Accepted June 2011, Pending Publication*.

[3] Arola, D., McCain, M., Kunaporn, S., and Ramulu, M. "Waterjet and Abrasive Waterjet Surface Treatment of Titanium: A Comparison of Surface Texture and Residual Stress." *Wear.* Vol. 249, 2002, pp. 943 – 950.

[4] Shipway, P.H., Fowler, G., and Pashby, I.R. "Characteristics of the Surface of a Titanium Alloy Following Milling with Abrasive Waterjets." *Wear.* Vol. 238, 2005, pp. 123 – 132.

[5] Arola, D., Alade, A.E., and Weber, W. "Improving Fatigue Strength of Metals using Abrasive Waterjet Peening." *Machining Science and Technology.* Vol. 10, 2006, pp. 197 – 218.

[6] Chillman, A., Ramulu, M., and Hashish, M. "Waterjet and Water-Air Jet Surface Processing of a Titanium Alloy: A Parametric Evaluation." *ASME: Journal of Manufacturing Science and Engineering*. Vol. 132, 2010.

[7] Chillman, A., Ramulu, M., Hashish, M., and Cantrell, A. "High Pressure Waterjets – An Innovative Means of Alpha Case Removal for Superplastically Formed Titanium Alloys." *Key Engineering Materials*. Vol. 433, 2010, pp. 103-111.

[8] Hashish, M., et al, "Method and Apparatus for Fluidjet Formation", US patent number 6280302, August 2001.

[9] Soyama, H., Saito, K., Saka, M. "Improvements on Fatigue Strength of Aluminum Alloy by Cavitation Shotless Peening." *Journal of Engineering Materials and Technology, ASME.* Vol. 124, 2002, pp. 135 – 139.

[10] Kunaporn, S. "An Experimental and Numerical Analysis of Waterjet Peening of 7075-T6 Aluminum Alloy." Ph.D. Dissertation. University of Washington, 2002.

[11] Kunaporn, S., Ramulu, M., Jenkins, MG, Hashish, M. "Residual stress induced by waterjet peening: A finite element analysis." *Journal of Pressure Vessel Technology*. Vol. 126, No. 3, 2004, pp. 333 – 340.

[12] Ramulu, M., Kunaporn, S., Jenkins, M., Hashish, M., and Hopkins, J. "Fatigue Performance of High-Pressure Waterjet-Peened Aluminum Alloy." *ASME Journal of Pressure Vessel Technology.* Vol. 124, No. 1, 2002, pp. 118 – 123.

7. NOMENCLATURE

C_D	Coefficient of Discharge
d_n	Orifice Diameter
$\dot{\mathbf{E}}_{\mathbf{NET}}$	Net Waterjet Power
$\mathbf{E}_{\mathbf{dA}}$	Energy Density Transferred to Workpiece
P_A	Applied Air Pressure; Water-Air Jet
P_S	Supply Pressure
Q_A	Air Flow Rate; Water-Air Jet
R_a	Average Roughness
SOD	Standoff Distance
t_e	Exposure Time per Unit Area
u	Traverse Rate
ρ_w	Density; Water
σ_R	Residual Stress
σ_Y	Yield Strength