Surface Texture in Abrasive Waterjet Cutting

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Abstract

When cutting thick material with an abrasive waterjet, the surface area can be characterized by two texture types. At the top of the cut, the surface texture is smooth. At the bottom, the slurry jet exiting the workpiece forms large striations in the surface.

An investigation was conducted to experimentally determine the influence of the abrasive waterjet cutting parameters on surface texture.

A mathematical model was developed characterizing the correlation between the surface roughness and the abrasive waterjet cutting variables.

Keywords: *Abrasive Waterjet, Surface Quality, Cutting, Scanning Election Microscopy*

Introduction

The abrasive waterjet cutting technique is one of the most recently introduced machining methods. In this cutting technique, a thin, high velocity waterjet accelerates abrasive particles that are directed through an abrasive waterjet nozzle at the material to be cut. Advantages of abrasive waterjet cutting include the ability to machine hard materials, minimal heat build-up and few deformation stresses within the machined part, exceptional surface quality and metal removal rate, and omnidirectional machining that is ideal for automation.

Three topographical components—waviness, roughness, and errors of form—compose a machined part's surface texture. The irregular nature of a surface's texture arises from several processing factors.

When cutting thick material with an abrasive waterjet, two texture types can characterize the material's surface area. The first texture is located at the beginning of the cut. A smooth, uniform surface texture occurs when waterjet particles impact the kerf wall at shallow angles. The slurry jet exiting the workpiece forms large surface striations at the bottom of the cut. Particles impacting the kerf wall at large angles create the large striations. The striations (waviness in surface texture) cause poor surface quality.

In parts manufacturing, accuracy of shape and dimension, and surface finish are the primary quality objectives. Surface roughness is the irregularity in the cut material's surface texture. Roughness becomes important when abrasive waterjet machining produces parts requiring high quality. In the surface finish evaluation, surface profile characterization is used to judge surface quality. The parameters of surface profile characterization are arithmetic average, *Ra*; root mean square, *Rq*; and peak-to-valley, *Rt*. In this study, the arithmetic average of the roughness was measured and used for further analysis.[1]

Reseachers reported the surface roughness formed when cutting different materials with abrasive waterjets.[1-3] Tan developed a model predicting the surface finish.[4] Results of the model's application were in agreement with data obtained experimentally for abrasive waterjet machining.

The study's objective was to examine the effects of abrasive waterjet variables such as waterjet pressure, abrasive grain size, abrasive flow rate, and jet traverse speed on surface roughness. The varied surface roughness across cut depth was also examined. A mathematical relation was developed, relating surface roughness to five named variables. The multiple nonlinear regressor form proved satisfactory for this analysis. The experimental results were used to obtain the best surface quality while cutting a 0.25 in. (6.35 mm) thick plate of 304 stainless steel. A scanning electron microscope was used to observe the cut surface's micro irregularities that could not be determined with a stylus tip.

Experiment Setup

The experimental setup of the Syracuse University Abrasive Waterjet Laboratory includes the following basic components: high-pressure pump, abrasive waterjet cutting head, abrasive delivery system, abrasive material and water catcher, and *x-y* positioning table controlled by CNC controller.

The Flow System's waterknife intensifier pump (Model 9XH) is designed for waterjet and abrasive waterjet cutting. The first intensifier pump of 55,000 psi (379 M Pa) is used for water cutting, while the second one of 36,000 psi (248 M Pa) is used for abrasive waterjet cutting. The abrasive waterjet cutting head consists of a sapphire orifice, abrasive waterjet nozzle, and mixing chamber. The abrasive waterjet nozzle is critical to the technical and economic performance of the abrasive waterjet cutting system. Abrasive waterjet nozzles made of tungsten carbide have an average life of four hours when garnet is the abrasive. Nozzle wear significantly affects cutting quality.

Figure 1 shows the function of the abrasive waterjet cutting system. The intensifier pump supplies high pressure water to the normally closed pneumatic valve (1), providing a carrier medium for the abrasive material. Controlled by the 3-way air control valve (2), the air valve provides rapid ON/OFF control of the waterjet at the sapphire nozzle. The abrasive material stored in the hopper (3) is introduced into the waterjet stream at the mixing chamber (4). The adjustable valve (5) controls the abrasive material flow rate. Once the waterjet stream and abrasive are combined, the abrasive waterjet exits through the tungsten carbide nozzle (6) toward the workpiece.

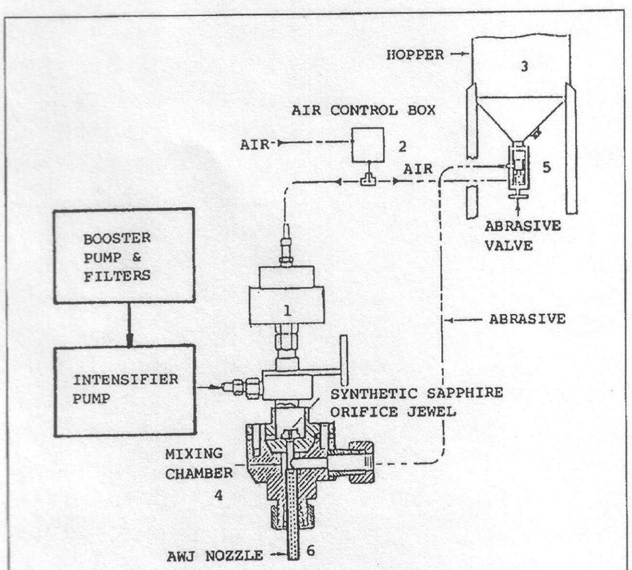

Figure 1
A General Concept of Abrasive Waterjet Cutting System

The variables involved in the abrasive waterjet cutting process are presented in *Figure 2*. The output of the process, such as surface texture, geometrical accuracy, metal removal rate, and actual depth of cut, depends on the interrelationships of the abrasive waterjet variables. Most of these variables could be used as control values. However, the limitations of today's available abrasive waterjet cutting systems reduce on-line control variables to the following four:[5]

1. Jet Traverse Speed,
2. Direction of Motion,
3. Angle of Impingement, and
4. Nozzle Standoff Distance.

Variables could be changed and used as the control values between individual operations:

1. Waterjet Pressure,
2. Abrasive Flow Rate,
3. Abrasive Grain Size,
4. Abrasive Waterjet Nozzle Diameter,
5. Waterjet Nozzle Diameter, and
6. Abrasive Material.

One objective in this study is to analyze and optimize the effect of selected abrasive waterjet variables on surface roughness.

To obtain the independent, interactive, and higher order effects of different process variables on surface roughness, experiments were planned using central composite design. The adequacy of the model was tested using analysis of variance.

Four independent variables were selected to analyze their influence on the surface roughness. The variables include waterjet pressure, abrasive flow rate, abrasive grain size, and jet traverse speed. The experimental design was a 2^4 factorial with seven center points, which required 23 test runs. The test runs were repeated twice. A measurement level for surface roughness across the thickness of cut was used as a fifth variable. The number of measurements was 23x2x3 = 138. Selected variables and their levels are presented in *Table 1*.

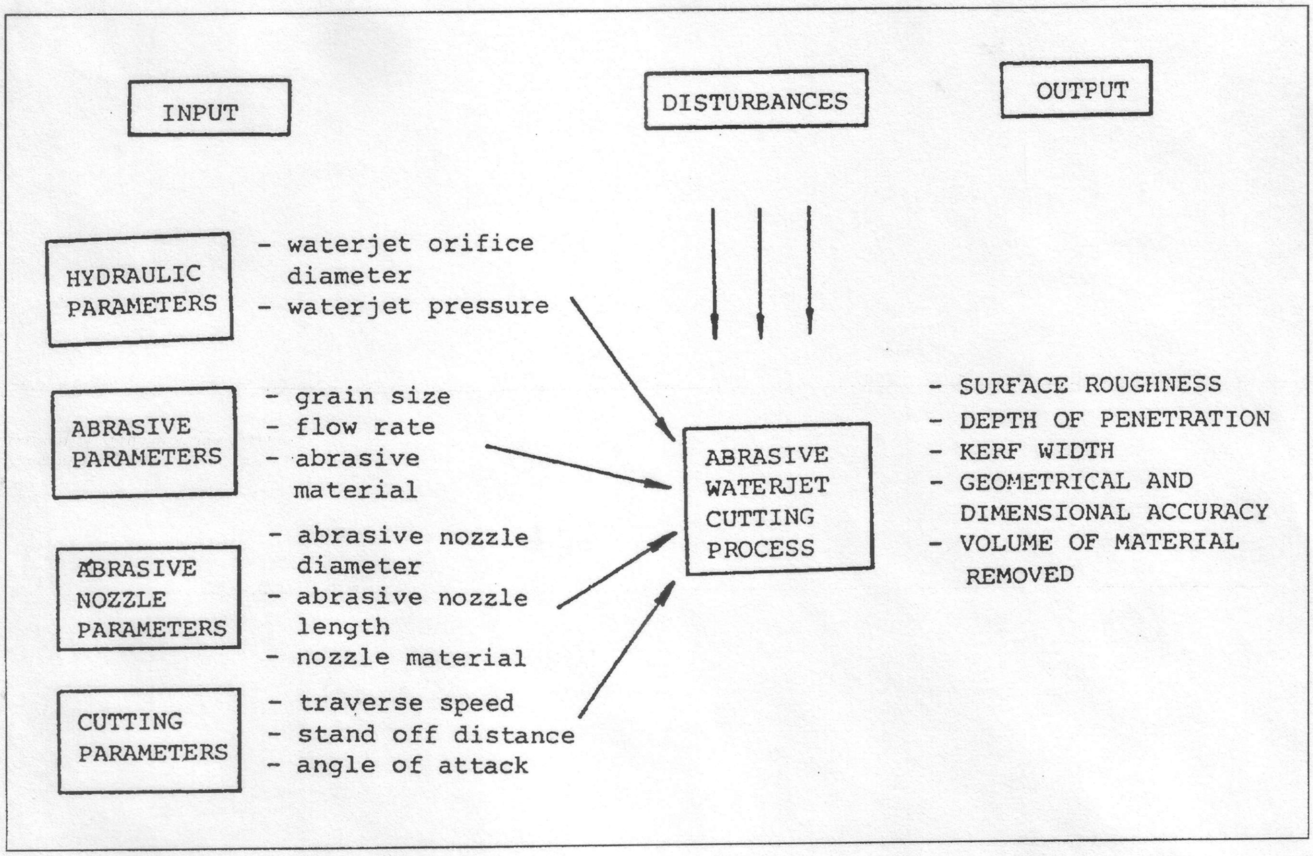

Figure 2
Schematic Presentation of Input and Output Parameters in Abrasive Waterjet Cutting

Table 1
Factors of 2^5 Factorial Design

Factors	Level 1	Level 2	Level 3
Jet Traverse Speed (in/min) or (mm/min)	2 (50.79)	4 (101.59)	6 (152.39)
Abrasive Flow Rate (lb/min) or (kg/min)	1.0 (0.453)	1.5 (0.679)	2.0 (0.906)
Water Pressure (kpsi) or (MPa)	30 (207)	34 (234)	38 (262)
Abrasive Grain Size (Mesh)	80	115	170
Level of Measurement (in.) or (mm)	0.0625 (1.58)	0.125 (3.17)	0.1875 (4.76)

To restrict the study's size the following variables were kept constant:

1. Diameter of Waterjet Orifice = 0.013 in. (0.33 mm),
2. Diameter of Abrasive Nozzle = 0.047 in. (1.19 mm),
3. Length of Abrasive Nozzle = 2.0 in. (50.79 mm),
4. Nozzle/Workpiece Standoff = 0.0625 in. (1.58 mm),
5. Angle of Attack = 90 degree.

Garnet, supplied by the Barton Mines Corporation, was used as the abrasive material. Mesh No. 80, mesh No. 115, and mesh No. 170 replaced the company's size designations for the garnet particles, #80HP, #120HP, and #220HP, respectively. The sieve analysis performed by the Barton Mines Corporation, is given in *Figure 3*. From *Figure 3* it is apparent that the abrasive particle size distribution is in a large range. In further analysis the average diameter of the abrasive particles will be used.

To avoid adverse influence of nozzle wear on surface roughness, new nozzles were used with each cut.

The surface roughness was measured at three levels across the thickness of the cut: 0.0625 in. (1.58 mm), 0.125 in. (3.17 mm), and 0.1875 in. (4.76 mm), using the Mitutoyo Surftest 401.

The surface texture of an abrasive waterjet cut sample is shown in *Figure 4*.

As evidenced from a previously performed investigation, it is evident that the striation lines will appear when the cutting efficiency decreases.[1] Their appearance is caused by increasing the jet traverse speed, lowering the water pressure, or selecting an inappropriate abrasive flow rate or abrasive grain size. The main purpose of this study is to develop the mathematical model that will describe the relationship between the abrasive waterjet cutting variables and the surface roughness. This model could then be used for selecting the abrasive waterjet cutting conditions to obtain the required surface roughness across the entire cut.

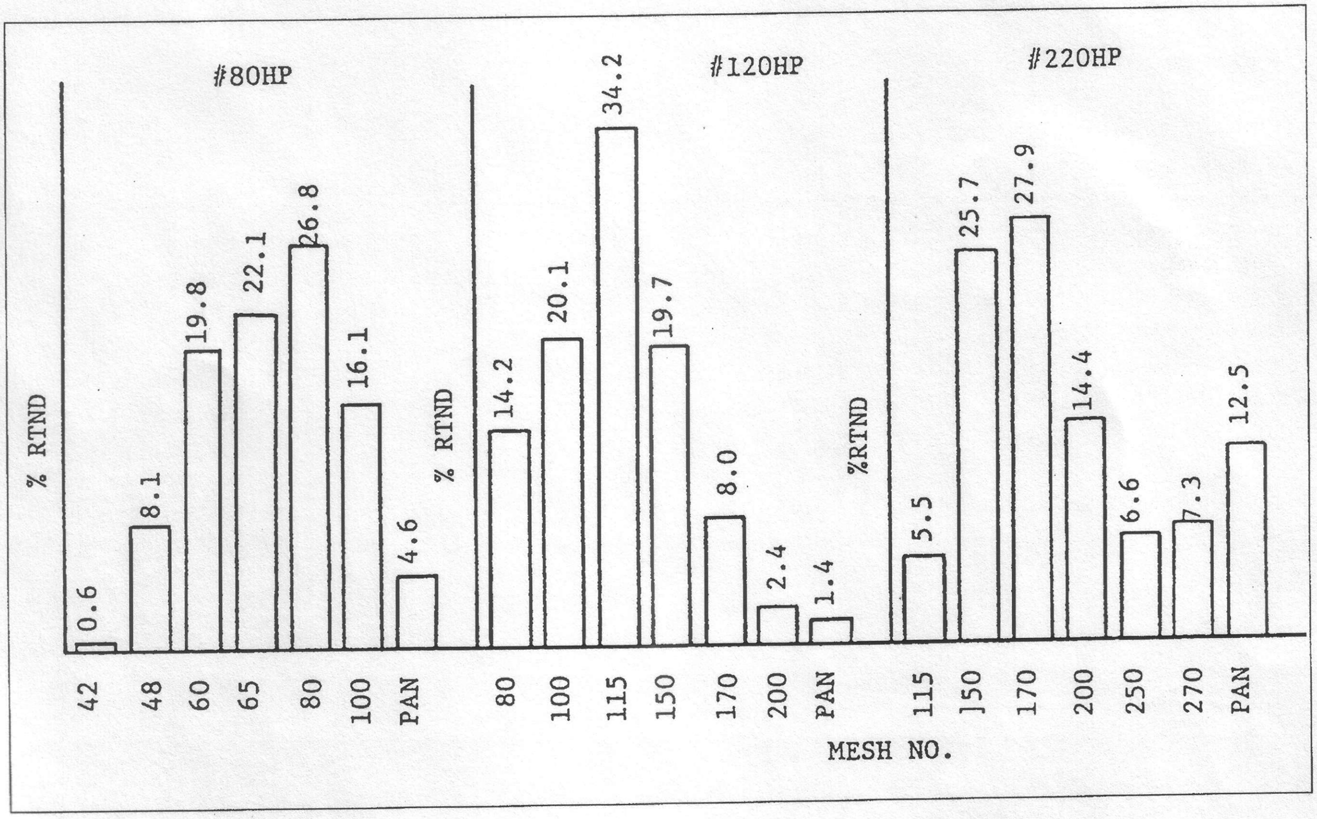

Figure 3
Abrasive Particle Size Distributions

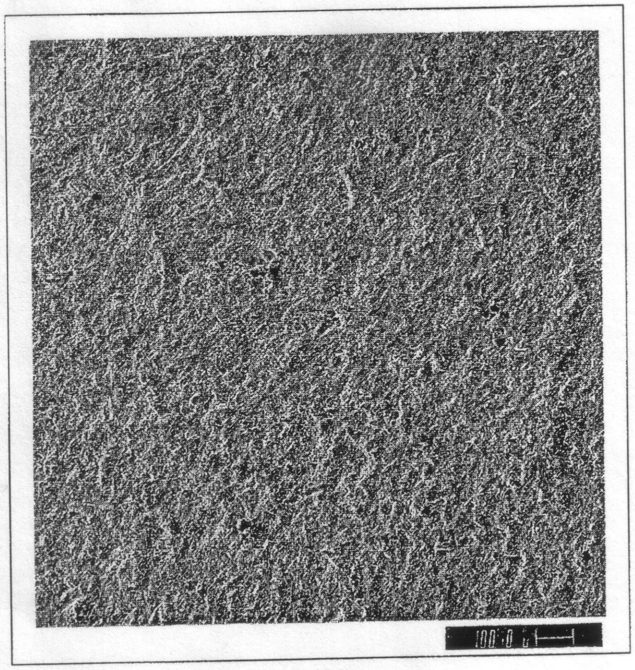

Figure 4
**A Typical Surface Texture of Abrasive Waterjet Cut Sample of 304 Stainless Steel (50 x magnification)
Abrasive Grain Size Mesh No. 80, Jet Traverse Speed—2.0 in/min (50.79 mm/min),
Abrasive Flow Rate— 1.0 lb/min (0.453 kg/min),
and Waterjet Pressure—30 Kpsi**

Results and Discussions

An empirical equation quantifies the relationship between surface roughness and abrasive waterjet cutting variables employed. The influence of waterjet pressure, abrasive flow rate, abrasive grain size, jet traverse speed, and measurement level on the surface roughness is determined through a 2^5 central composite factorial design. This design uses the variables of *Ra* in the response. A set of cutting conditions was arranged by central composite factorial design (*Table 2*).

After conducting the experiments, surface roughness was evaluated. The second order model was fitted, using a SASRSREG computer program, as follows:

$$R_a = C_0 + \sum_{i=1}^{n} C_i X_i + \sum_{i=1}^{n} C_{ii} X_{ii}^2 + \sum_{i=1}^{n} C_{ij} X_i X_j \quad (1).$$

After model parameter estimation, the regression equation for *Ra* is

$$\begin{aligned} Ra = {} & 305.96 - 56.54\,V - 81.55\,F + 0.62\,P - 11.98\,D - \\ & -0.82\,G + 4.79\,V^2 - 0.34\,FV - 0.15\,PV + 1.56\,PF + \\ & +208.5\,DV - 93.00\,DF - 12.75\,DP + 550.96\,D^2 + \\ & +0.12\,GV + 0.22\,GF - 0.01\,GP + 1.96\,GD \end{aligned} \quad (2)$$

where

Ra is the surface roughness (μ*in*),
F is the abrasive flow rate (*lb/min*),
P is the water pressure (*kpsi*),
G is the abrasive grain size (*mesh*),
D is the level of measurement across the cut (*in*),
V is the traverse speed (*in/min*), and
Ci are the regression coefficients.

The correlation coefficient is $r = 0.95$. To test the correlation of equation (1), the *F*-test was used. This model is significant at 0.001 level.

In *Table 2* the predicted values of surface roughness are compared with the measured value. The proposed mathematical model fits the measured data with high accuracy.

The measurement level for the surface roughness indicates the surface quality obtained by abrasive waterjet cutting. Surface quality decreases drastically from top to the bottom. The deterioration of surface quality depends on several process variables. A mathematical model was developed to select the optimal variable combination influencing the surface roughness. Using a developed response surface model, effects of different abrasive waterjet cutting variables on the surface roughness were studied.

Influence of Waterjet Pressure

The influence of waterjet pressure and other selected variables on the surface roughness is analyzed in conjunction with the thickness of the cut.

Figure 5 shows the effect of waterjet pressure on the surface roughness across the entire thickness of the cut. An increase in waterjet pressure causes an increase in surface quality, i.e. a decrease in surface roughness. As seen in *Figure 5*, the effect of waterjet pressure on surface roughness at the cut's beginning is negligible. However, the influence of waterjet pressure on surface roughness increases as the depth of the cut increases.

The increase in particle velocity at the abrasive nozzle exit and partical fragmentation inside the abrasive nozzle caused the positive effect on surface roughness. However, high waterjet pressure can generate negative effects; the abrasive particles can lose cutting ability when they become too fragmented. Also, the abrasive nozzle and elements of the intensifier pump wear faster. These adverse effects could be criteria for determining the optimal waterjet pressure.[6]

Table 2
Central Composite Design

	Factors				Response Ra (µin) D=0.0625 in.			D = 0.125 in.			D = 0.1875 in.		
Run	V (in/min)	F (lb/min)	P (kpsi)	G (mesh No.)	Measured I	Measured II	Predicted	Measured I	Measured II	Predicted	Measured I	Measured II	Predicted
1	6	2.0	38	80	104	110	110	187	169	162	217	265	218
2	2	2.0	38	80	98	108	119	117	106	118	133	142	122
3	6	2.0	30	80	103	95	103	119	149	161	216	180	224
4	2	2.0	30	80	96	104	107	124	117	113	149	127	123
5	6	1.0	38	80	137	118	122	153	173	180	265	206	242
6	2	1.0	38	80	112	110	130	129	140	135	161	142	145
7	6	1.0	30	80	143	106	128	249	166	192	283	265	260
8	2	1.0	30	80	129	117	130	155	141	142	177	148	158
9	6	2.0	38	170	88	106	104	151	131	164	214	255	229
10	2	2.0	38	170	70	80	80	86	90	88	92	104	100
11	6	2.0	30	170	110	84	105	169	218	172	265	259	243
12	2	2.0	30	170	70	76	76	82	100	90	106	108	109
13	6	1.0	38	170	102	94	101	163	175	167	259	226	237
14	2	1.0	38	170	76	86	75	102	88	89	125	114	107
15	6	1.0	30	170	98	88	114	173	173	187	285	283	264
16	2	1.0	30	170	68	90	84	92	98	104	122	129	129
17	4	1.5	34	115	95	101	86	125	108	122	145	187	163
18	4	1.5	34	115	98	102	86	126	110	122	154	169	163
19	4	1.5	34	115	100	98	86	130	121	122	149	158	163
20	4	1.5	34	115	97	95	86	131	116	122	139	170	163
21	4	1.5	34	115	94	99	86	127	126	122	142	157	163
22	4	1.5	34	115	93	98	86	119	121	122	158	174	163
23	4	1.5	34	115	91	95	86	115	123	122	146	167	163

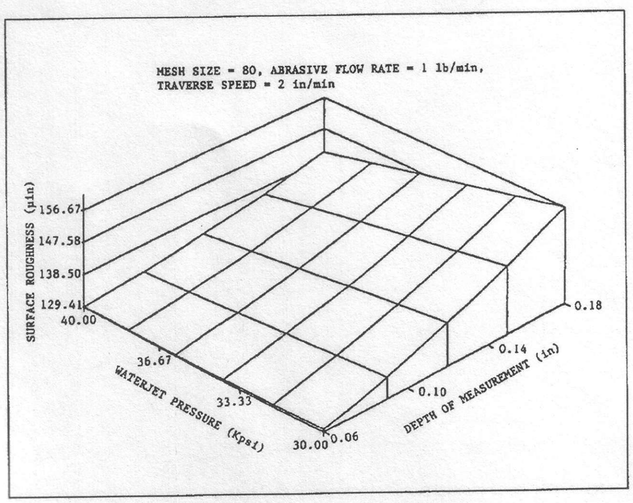

Figure 5
Effect of Waterjet Pressure and Depth of Measurement on Surface Roughness

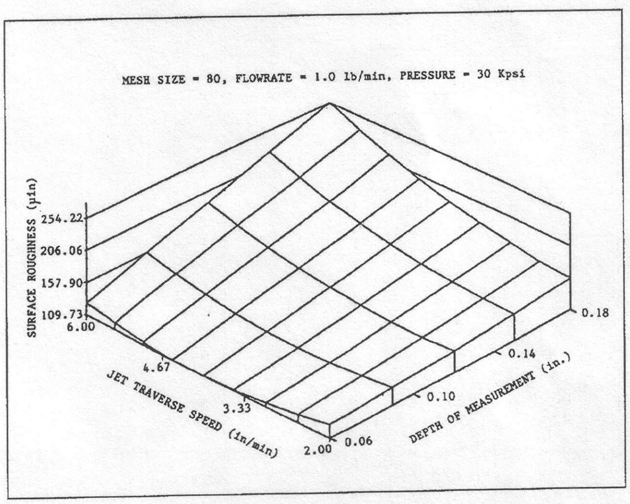

Figure 6
Effect of Jet Traverse Speed and Depth of Measurement on Surface Roughness

Influence of Jet Traverse Speed

The relationship between the surface roughness across the cut's thickness and the jet traverse speed is given in *Figure 6*. An increase in jet traverse speed will cause an increase in surface roughness. The smallest change in the surface roughness occurs under the lowest jet traverse speed. The jet traverse speed has little influence on the surface roughness at the cut's top. The diagram in *Figure 6* helps to determine the critical jet traverse speed corresponding to a shift in the cutting mechanism from cutting wear mode to deformation wear mode.

Influence of Abrasive Flow Rate

Figure 7 shows the effect of abrasive flow rate on surface roughness. As seen in *Figure 7*, an increase in the abrasive flow rate will increase the surface quality. Under the analyzed conditions, this influence depends on the cut's depth. The influence of abrasive flow rate on surface quality increases as the cut's depth increases. Garnet of mesh No. 170 with an increase in the abrasive flow rate can cause a decrease in the surface quality. The higher abrasive flow rate increases interference between particles and reduces the particle exit velocity causing the decrease in surface quality.[1,6]

Influence of Abrasive Grain Size

The relationship between surface roughness across the cut's thickness and abrasive grain size are given in *Figure 8*. By increasing the mesh number and decreasing the diameter of abrasive particles, the surface quality increases. However, if the cut's depth increases while the particle's diameter decreases, the surface quality will decrease more rapidly. The cutting rate reduces drastically due to the lower particle inertia. In order to achieve a higher velocity of the abrasive and water mixture, the water pressure must be increased. To ensure uniform inlet flow of the finer abrasive material, a slurry should be used.

Scanning Electron Microscopy

A scanning electron microscope was used to analyze the micro irregularities on a waterjet cut surface of 304 stainless steel.

Figure 9 shows the surface cut by three different abrasive grain sizes (mesh No. 80, mesh No. 115, and mesh No. 170), keeping other cutting conditions constant. A scanning microscope examination was performed at three levels across the cut's thickness (at the beginning, middle, and end). The scanning microphotographs (*Figure 9*) reveal that the abrasive wear tracks on the top are straight vertical lines. At the cut's bottom the abrasive wear tracks are inclined. The edge of the top is plastically deformed under the impingement of abrasive particles. Below this zone, single garnet particles have plowed wear tracks in an abrasive wear mode. The jet traverse speed has the largest influence on the inclination of the abrasive wear tracks.

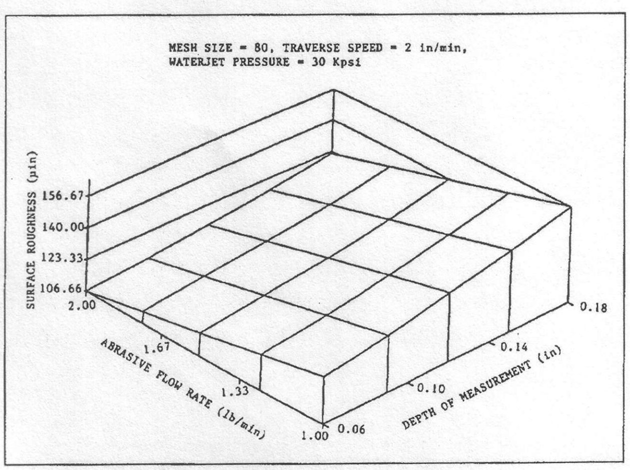

Figure 7
Effect of Abrasive Flow Rate and Depth of Measurement on Surface Roughness

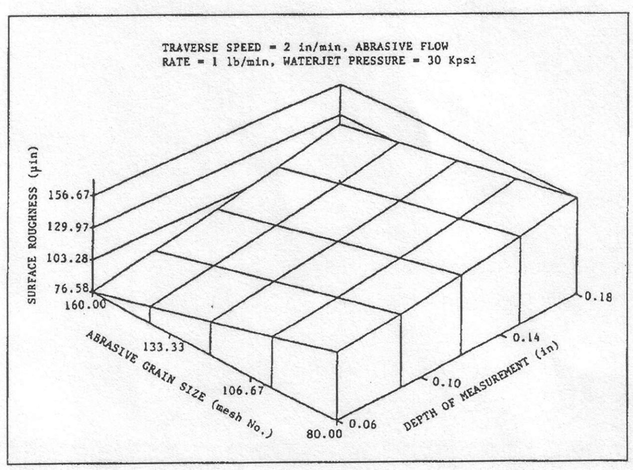

Figure 8
Effect of Abrasive Grain Size and Depth of Measurement on Surface Roughness

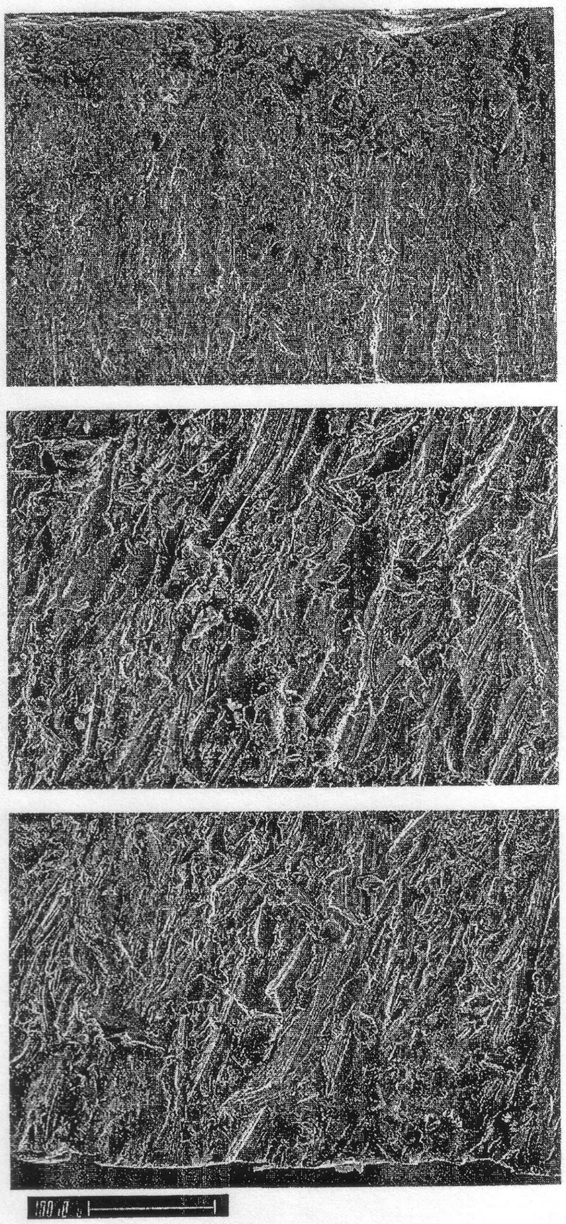

Figure 9
Scanning Microphotographs, 200 x Magnification
Abrasive Grain Size—Mesh No. 80

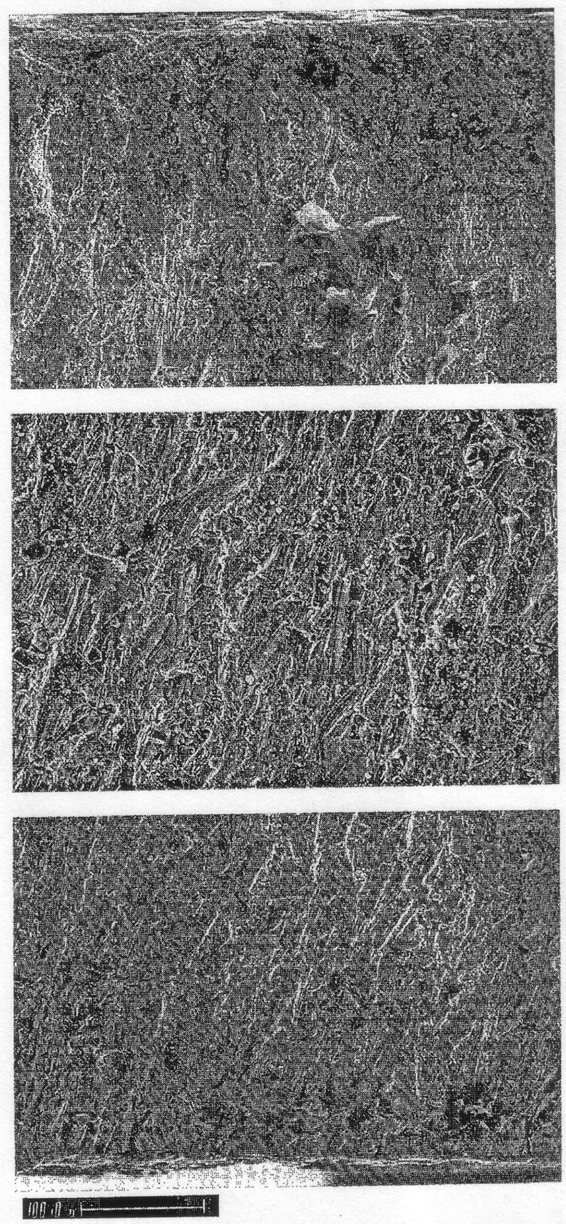

Figure 9b.
Abrasive Grain Size—Mesh No. 115

The width of the abrasive wear tracks is in direct correlation with the size of the abrasive particles. The width of the abrasive wear tracks is not uniform for a given size of abrasive particle, indicating nonuniformity of particle size. The largest width of the abrasive wear tracks is for the garnet particle size mesh No. 80.

Conclusions

The analysis presented in this study can be summarized as follows:

- The surface being cut by an abrasive waterjet is characterized by two types of texture. The first texture is located at the beginning of the cut and is characterized by the smooth surface.

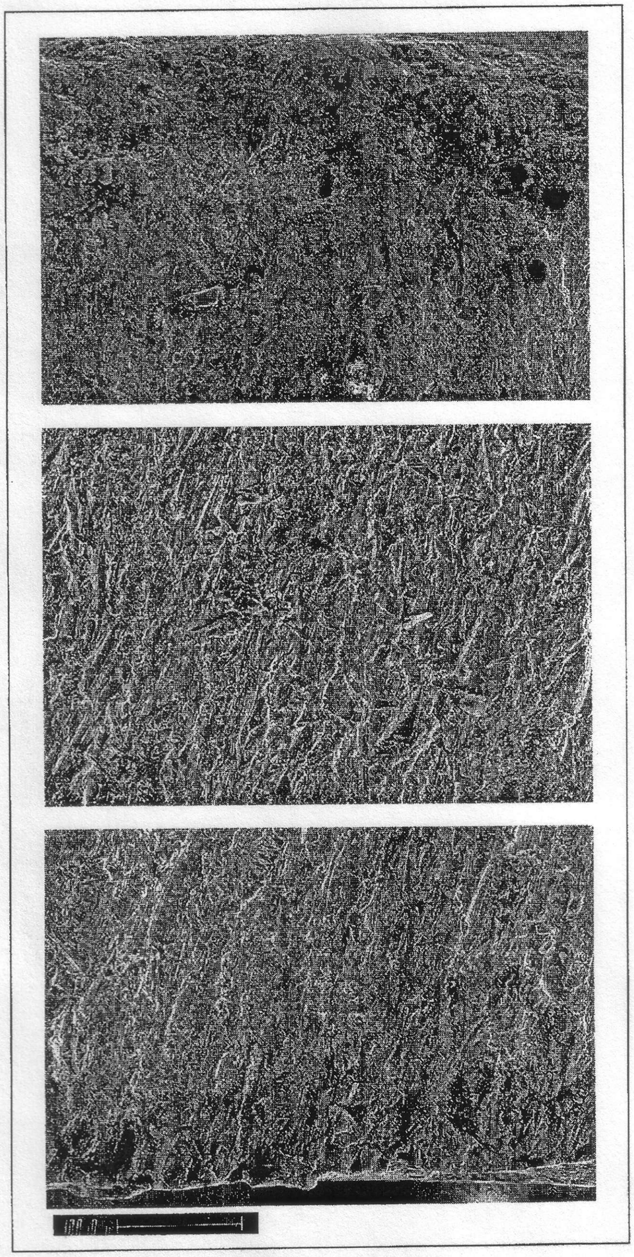

Figure 9c.
Scanning Microphotographs, 200 x Magnification
Abrasive Grain Size—Mesh No. 170

The second texture is located at the bottom of the cut and is characterized by large striations formed by the slurry jet exiting the waterjet's workpiece.

—A second order mathematical model was developed to characterize the correlation between surface roughness across the entire cut's depth and the abrasive waterjet cutting variables; namely water pressure, abrasive flow rate, abrasive grain size, and jet traverse speed.

—A scanning electron microscopy analysis shows that abrasive wear, caused by the individual garnet particles, is one mechanism presented during the metal removal by the abrasive waterjet.

Based on the obtained results, cutting by the abrasive waterjet is suitable for thin sheets if the surface finish is a critical parameter. This cutting technique can create distortion free parts of complex shape, which is a difficult achievement in sheet stamping.

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References

1. R. Kovacevic, H.H. Liaw, F.J. Barrows, "Surface Roughness and its Relationship to Cutting Parameters in Abrasive Waterjet Cutting," *Proceedings of the Third International Grinding Conference*, Lake Geneva, WI, October 4-6, 1988.
2. D.C. Hunt, C.D. Burnham, T.J. Kim, "Surface Finish Characterization in Machining Advanced Ceramics by Abrasive Waterjet," *Proceedings of the Fourth US Water Jet Conference*, Berkeley, CA, August 26-28, 1987, pp. 169-74.
3. K.F. Neusen, P.K. Rohatgi, C. Vaidyanathan, D. Alberts, "Abrasive Waterjet Cutting of Metal Matrix Composites," *Proceedings of the Fourth US Water Jet Conference*, Berkeley, CA, August 26-28, 1987, pp. 175-82.
4. D.K.M. Tan, "A Model for the Surface Finish in Abrasive Waterjet Cutting," *Proceedings of the Eighth International Symposium on Jet Cutting Technology*, Durham, England, September 9-11, 1986, pp. 309-13.
5. M. Mazurkiewich, P. Karlic, "Material Dynamic Response During Hydroabrasive Jet Machining (HAJM)," *Proceedings of the Fourth US Water Jet Conference*, Berkeley, CA, August 26-28, 1987, pp. 159-67.
6. M. Hashish, "Aspects of Abrasive Waterjet Performance Optimization," *Proceedings of the Eighth International Symposium on Jet Cutting Technology*, Durham, England, September 9-11, 1986, pp. 297-308.

Author Biography

Dr. Kovacevic was an Associate Professor of mechanical engineering, University of Titograd, Yugoslavia, prior to joining Syracuse University in January 1987. He has received awards from the Alexander von Humboldt Foundation, W. Germany; Carl Duisberg Foundation, W. Germany; and the Fulbright Foundation, USA. He earned his PhD at the University of Titograd, Yugoslavia, in 1978. He has published 20 refereed journal papers and 35 proceedings papers, and has authored and coauthored four books.