PERPENDICULARITY DEVIATION AND SURFACE ROUGHNESS IN ABRASIVE WATER JET CUTTING OF CARBON STEEL

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ABSTRACT: Abrasive water jet is cutting tool capable to cut a wide range of materials. Investigation on perpendicularity deviation and surface roughness in abrasive water jet cutting of carbon steel is proposed in this paper. Full factorial design of experiment with three factors, abrasive flow rate, traverse rate and standoff distance, each in two levels is employed to investigate perpendicularity deviation and surface roughness. The analysis of means and analysis of variance are employed to determine effect of factors on perpendicularity deviation and surface roughness. Regression analysis was used to find correlation of perpendicularity deviation and surface roughness versus process factors.
KEY WORDS: abrasive water jet cutting, perpendicularity deviation, surface roughness, regression analysis

1. INTRODUCTION

Abrasive water jet cutting is like grinding, except that abrasive particles are moved through the material by water jet. In abrasive water jet cutting, pressures to 400 MPa are currently used. High pressure supply line directs the pressurized water from the pump via accumulator to the cutting head. Cutting head consists of nozzle, mixing chamber and focusing tube. Nozzle is made of sapphire, ruby or diamond. Orifice is with diameter of 0.15 to 0.35 mm. Focusing tube is made of hard metal. Focusing tube is with diameter of 0.54 to 1.1 mm and length of 50 to 100 mm. Water is pressed out of the orifice in form of jet. Result is a very thin, extremely high velocity water jet. Solid abrasive particles are added and mixed with the water jet in the mixing chamber of the cutting head. High speed of the water jet creates a partial vacuum in the mixing chamber so that abrasive particles are sucked in and flushed away by the water jet. Water jet and abrasive particles create abrasive water jet. Focusing tube focuses and directs the abrasive water jet to the workpiece. Schematic view of abrasive water jet cutting is shown in Figure 1 [1]. Mix of high pressure water jet with abrasives gives an effective cutting tool. Abrasive water jet can cut wide range of materials and thickness. Abrasive water jet makes it possible to cut random contours, very fine tabs and filigree structures. Tolerances of ±0.1 mm can be realized in metal cutting. There is no thermal effect on the workpiece. Abrasive water jet produces very little lateral force. Abrasive water jet cutting is characterized by a large number of factors that determine the performances of the process.

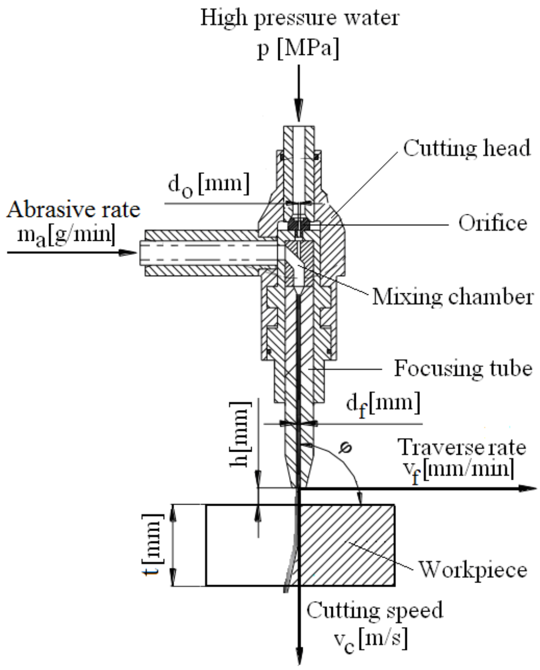

Figure 1. Abrasive water jet cutting

Factors of the abrasive water jet cutting can be classified (Figure 2) in categories as: workpiece (material type, thickness, chemical structure, hardness, toughness, grain size), high pressure pump (pump pressure, water flow rate, water purity, accumulator volume), abrasive (material type, hardness, particle diameter, particle shape, particle size distribution, humidity), cutting head (orifice diameter, nozzle material, focusing tube diameter, focusing tube length, focusing tube material), motion system (precision, accuracy, stiffness, working conditions) and process parameters (water pressure, traverse rate, abrasive mass flow rate, standoff distance, impact angle, traverse direction).

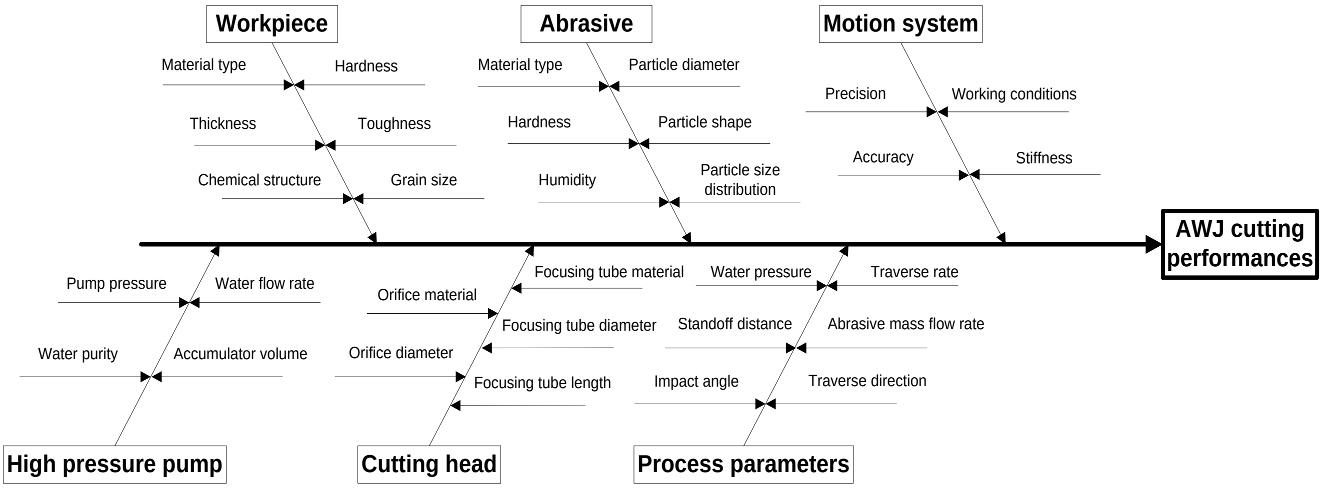

Figure 2. Factors of the abrasive water jet cutting

Performances of the abrasive water jet cutting can be classified (Figure 3) in categories as:

- Process performances (nozzle wear, focusing tube wear, temperature, noise, vibration),
- Quality performances (form deviations, dimension deviations, cut quality),
- Productivity performances (machining time, productivity), and
- Economy performances (manufacturing, power consumption).

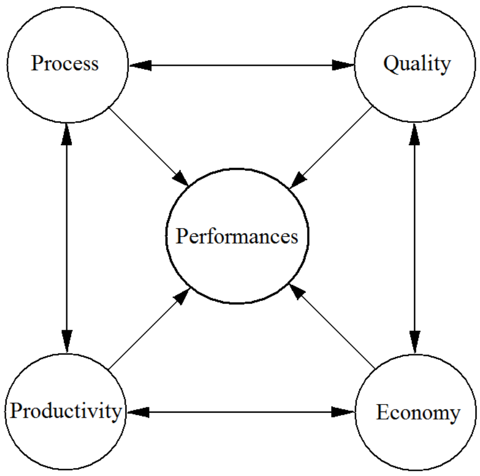

Figure 3. Performances of the abrasive water jet cutting

Performances of the cut quality are: kerf depth, kerf width, perpendicularity deviation, surface roughness, drag line lag, edge radius, burr, and jet affected zone. The most important cut quality performances are perpendicularity deviation and surface roughness.

Perpendicularity or angularity deviation of the cut surfaces (kerf taper) is distance between two parallel straight lines (tangents) between which the cut surface profile is inscribed within the set angle of 90°. Perpendicularity deviation of the cut surfaces includes not only the perpendicularity or angularity deviation of the cut surfaces, but also the flatness deviations.

Surface roughness describes the surface textures of the machined parts. There are several parameters to describe surface roughness, such as: arithmetic average roughness (Ra), root-mean-square roughness (Rq) and maximum peak-to-valley roughness (Ry or Rmax) etc. Arithmetic average roughness (Ra) is defined as the arithmetic value of the profile deviations from centre line along the sampling length.

Terms related to water jet cutting - geometrical product specification and quality, according ISO/TC 44 N 1770, are shown in Figure 4. [2]

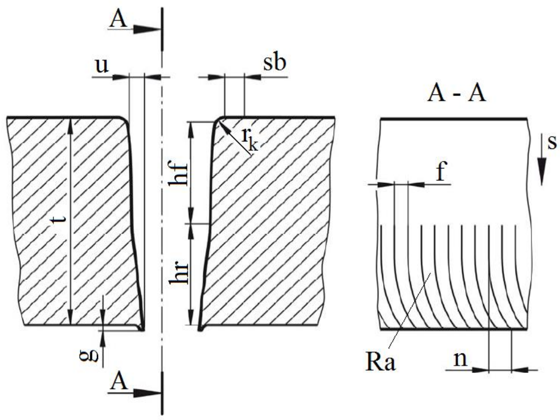

Figure 4. Terms related to water jet cutting.
Ra - surface roughness, f - pitch of drag line, g - burr, hf - fine cut, hr - remaining surface, n - drag, r_k - edge radius, s - jet direction, sb - jet affected zone, t - workpiece thickness, u - perpendicularity deviation

There are some studies regarding perpendicularity deviation (kerf taper) and surface roughness in abrasive water jet cutting. Alberdi A. et al. (2013) [3], have worked on composite cutting with abrasive water jet. A study of the effect of the abrasive water jet process parameters on the quality of cut taper and surface roughness was carried out. Ramulu and Arola (1994) [4] was conducted an experimental investigation to determine the influence of cutting factors on the surface roughness and kerf taper of an abrasive water jet machined graphite/epoxy laminate. Babu et al. (2006) [5] presented a study on the use of single mesh size abrasives in AWJ cutting of aluminum 6063 T6. Design of experiment with four factors (single mesh size abrasives, water pressure, traverse rate and abrasive flow rate) and three levels are employed to investigate depth of cut, kerf width, kerf taper and surface roughness. Maros Z. (2012) [6] has worked on taper cut at abrasive water jet cutting of AlMgSi0.5 aluminum alloy. Cutting tests were carried out for investigation of kerf taper. The water pressure, the abrasive mass flow rate and the traverse rate were changed in different levels.

2. DESIGN OF EXPERIMENT

The equipment used for machining the samples was abrasive water jet cutting machine Hydro Jet Eco 0615, with pump pressure of 150 MPa, power of 7.5 kW and water flow rate of 2.4 l/min. Cutting head is with orifice diameter of 0.35 mm and a focusing tube diameter of 1.02 mm. Focusing tube length is 76 mm. All experiments were conducted with water pressure of 150 MPa. Abrasive material was Garnet with 80 mesh size (≈ 177 μm). Workpiece material used in experimental tests was carbon steel EN S235 with thickness of 6.5 mm. The chemical properties of EN S235 are given in Table 1 and mechanical properties of EN S235 are given in Table 2.

Table 1. Chemical properties of EN S235

C (%)	Cr (%)	Ni (%)	Mo (%)	Mn (%)	Al (%)
0.13	0.08	0.10	0.013	0.58	0.033
Cu (%)	Si (%)	P (%)	S (%)	N (%)	V (%)
0.32	0.25	0.013	0.008	0.01	0.001

Table 2. Mechanical properties of EN S235

Yield $Rp_{0.2}$ (MPa)	Tensile Rm (MPa)	Elongation (%)
240	360-440	25

Design of experiment was conducted using full factorial design. Control factors are: abrasive flow rate (m_a), traverse rate (v_f) and standoff distance (h). Investigated performances are perpendicularity deviation (u) and surface roughness (R_a). Control factors and their levels are shown in Table 3 [7].

Table 3. Control factors and levels

Code	Control factors	Levels		
		-1	0	+1
A	Abrasive flow rate, m_a (g/min)	300	500	700
B	Traverse rate, v_f (mm/min)	50	100	150
C	Standoff distance, h (mm)	1	3	5

Three control factors with two levels are arranged in design of experiment with 12 tests (8 tests are for base design and 4 tests for centre point).

3. ANALYSIS OF RESULTS

Influence of factors on perpendicularity deviation and surface roughness was analyzed using the analysis of means and analysis of variance. To analyze the effect of factors on perpendicularity deviation Normal plot, Pareto chart and Main effect plots were generated by using Minitab software. In Figure 5 Normal plot of the standardized effects is shown and in Figure 6 Pareto chart for perpendicularity deviation is shown.

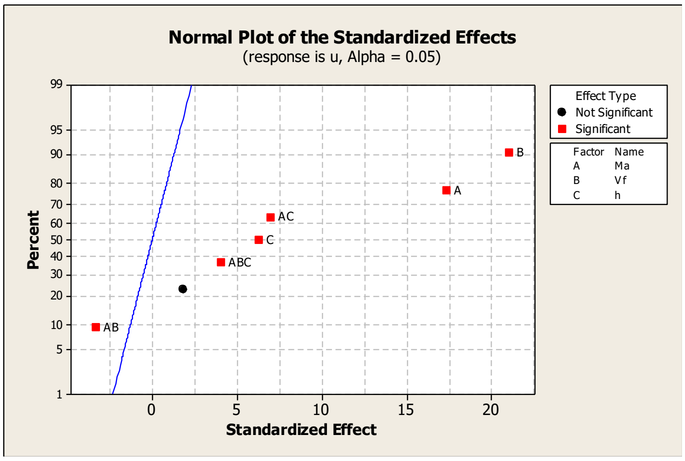

Figure 5. Normal plot for perpendicularity deviation

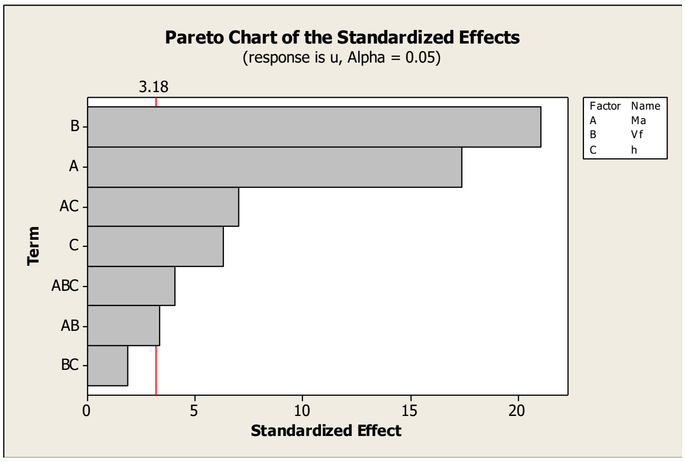

Figure 6. Pareto chart for perpendicularity deviation

From Figures 5 and 6, it is seen the effect type of factors and interactions (significant or not significant) on perpendicularity deviation. Control factors (abrasive flow rate, traverse rate and standoff distance) are significant factors on perpendicularity deviation. Interactions abrasive flow rate-traverse rate, abrasive flow rate-standoff distance and abrasive flow rate-traverse rate-standoff distance are significant on perpendicularity deviation. Interaction traverse rate-standoff distance is not significant. Main effects plot and Interaction plot for perpendicularity deviation (u) are presented in Figures 7 and 8. From Figure 7 it is seen that as the abrasive mass flow rate, traverse rate and standoff distance increase, the perpendicularity deviation increases. In Figure 8 the parallel lines indicate interactions that are not significant.

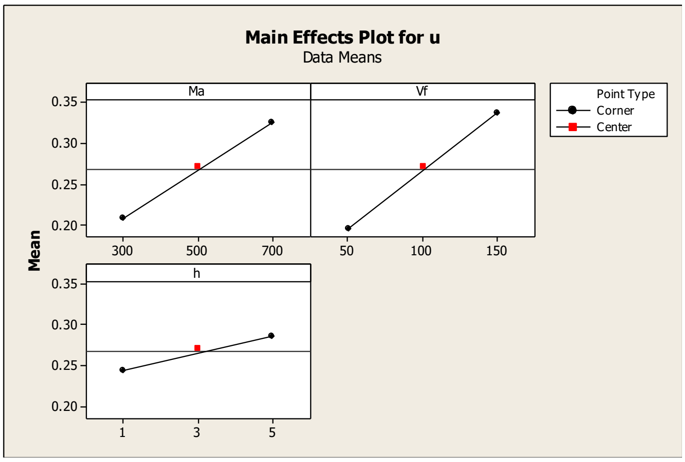

Figure 7. Main effects plot for perpendicularity deviation

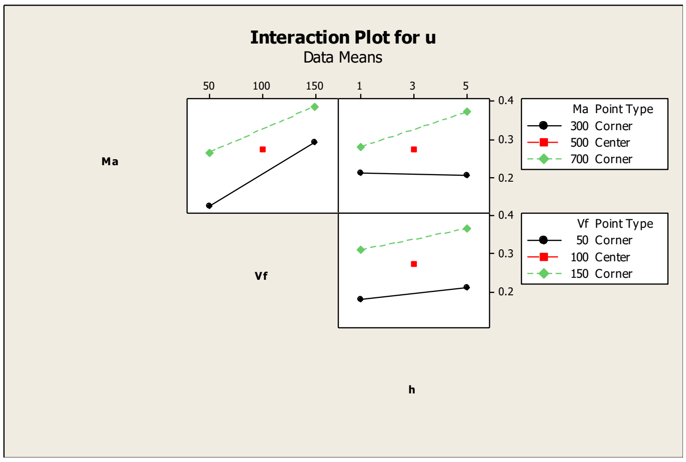

Figure 8. Interaction plot for perpendicularity deviation

Analysis of variance (ANOVA) was carried out to find the relative effect of factors on performance. In ANOVA, the ratio between the variance of the factor and the error variance is called Fisher's ratio (F). It is used to determine whether the factor has a significant effect on the performance by comparing with the F table value at the α significance level. Greater the F-ratio, more significant is the factor. Analysis of variance for perpendicularity deviation (u) is shown in Table 4. Standard F table value at 95% confidence level is $F_{0.05,1,3}$=10.13.

Table 4. Analysis of variance for perpendicularity deviation

Source	DF	SS	MS	F	p	%
Main effects	3	0.07184	0.02395	261.23	0.000	90.28
A	1	0.02761	0.02761	301.23	0.000	34.70
B	1	0.04061	0.04061	443.05	0.000	51.04
C	1	0.00361	0.00361	39.41	0.008	4.54
2-Way Inter.	3	0.00584	0.00195	21.23	0.016	7.34
AB	1	0.00101	0.00101	11.05	0.045	1.27
AC	1	0.00451	0.00451	49.23	0.006	5.67
BC	1	0.00031	0.00031	3.41	0.162	0.39
3-Way Inter.	1	0.00151	0.00151	16.50	0.027	1.90
ABC	1	0.00151	0.00151	16.50	0.027	1.90
Curvature	1	0.00010	0.00010	1.14	0.365	0.13
Error	3	0.00027	0.00009	-	-	0.34
Total	11	0.07957	-	-	-	100

DF-degree of freedom, SS-sum of square, MS-mean square, F-ratio, p–value, and %-percent contribution

From Table 4, it is seen that factors: abrasive flow rate, traverse rate and standoff distance have a strong (clearly statistically significant) effect on the perpendicularity deviation with contribution of 90.28%. Traverse rate is the most significant factor affecting the perpendicularity deviation with contribution of 51.04%, abrasive flow rate affecting with contribution of 34.70%, and standoff distance affecting with contribution of 4.54%. Interaction abrasive flow rate-traverse rate affects the perpendicularity deviation with contribution of 1.27%, interaction abrasive flow rate-standoff distance affects with contribution of 5.67%, and interaction abrasive flow rate-traverse rate-standoff distance affects with contribution of 1.90%.

To analyze the effect of factors on surface roughness Normal plot, Pareto chart and Main effect plots were generated. In Figure 9 Normal plot of the standardized effects is shown and in Figure 10 Pareto chart for surface roughness is shown.

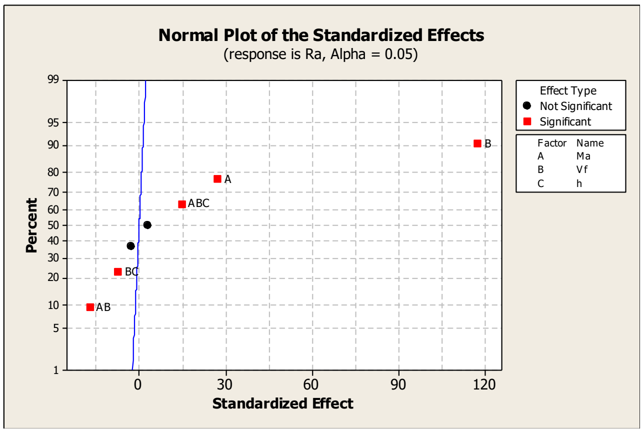

Figure 9. Normal plot for surface roughness

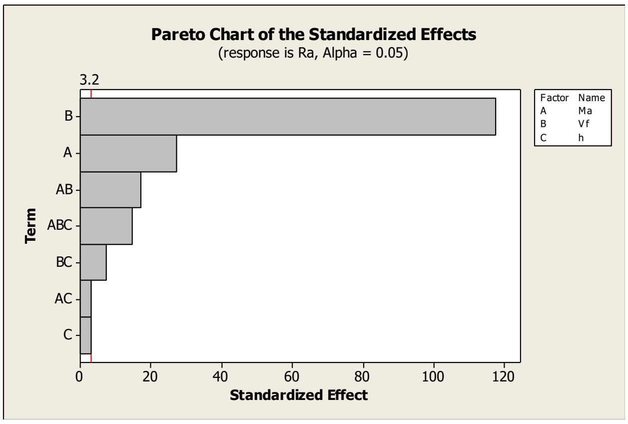

Figure 10. Pareto chart for surface roughness

From Figures 9 and 10 it is seen effect type of factors and interactions (significant and not significant). Abrasive flow rate and traverse rate are significant factors on surface roughness. Standoff distance is not significant factor. Interactions abrasive flow rate-traverse rate, traverse rate-standoff distance and abrasive flow rate-traverse rate-standoff distance are significant on surface roughness. Other interactions are not significant.

Main effects plot and Interaction plot for surface roughness (Ra) are presented in Figures 11 and 12.

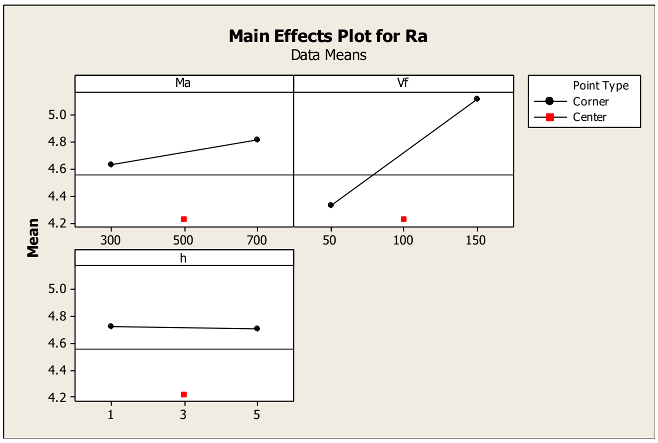

Figure 11. Main effects plot for surface roughness

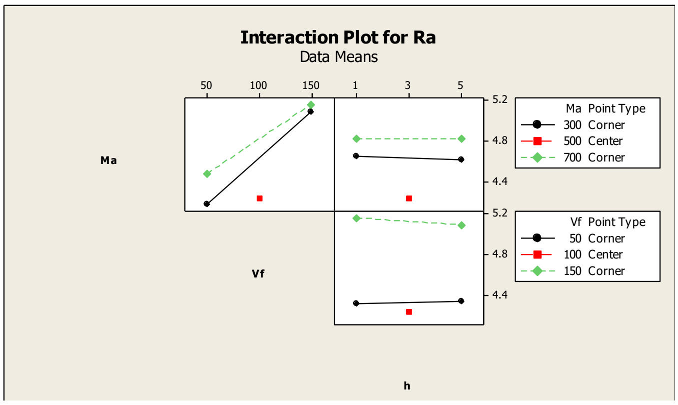

Figure 12. Interaction plot for surface roughness

From Figure 11, it is seen that as the abrasive mass flow rate and traverse rate increase the surface roughness increases. Change of the standoff distance has not effect on the surface roughness.

The results of analysis of variance for surface roughness (Ra) are shown in Table 5.

Table 5. Analysis of variance for Ra

Source	DF	SS	MS	F	p	%
Main effects	3	1.33330	0.44443	4848	0.000	65.39
A	1	0.06845	0.06845	746	0.000	3.36
B	1	1.26405	1.26405	13789	0.000	61.99
C	1	0.00080	0.00080	8.73	0.060	0.04
2-Way Inter.	3	0.03225	0.01075	117	0.001	1.58
AB	1	0.02645	0.02645	288	0.000	1.30
AC	1	0.00080	0.00080	8.73	0.060	0.04
BC	1	0.00500	0.00500	54.55	0.005	0.24
3-Way Inter.	1	0.02000	0.02000	218	0.001	0.98
ABC	1	0.02000	0.02000	218	0.001	0.98
Curvature	1	0.65340	0.65340	7128	0.000	32.04
Error	3	0.00028	0.00009	-	-	0.01
Total	11	2.03922	-	-	-	100

DF-degree of freedom, SS-sum of square, MS-mean square, F-ratio, p–value, and %-percent contribution

Standard F table value at 95% confidence level is $F_{0.05,1,3}$=10.13. From Table 5, it is seen that factors: abrasive flow rate and traverse rate have a strong (clearly statistically significant) effect on the surface roughness. Traverse rate is the most significant factor affecting the surface roughness with contribution of 61.99%. Abrasive flow rate affected the surface roughness with contribution of 3.36%. Standoff distance is not significant factor and affected the surface roughness with contribution of 0.04%. Interaction abrasive flow rate-traverse rate affected the surface roughness with contribution of 1.30%. Interaction of traverse rate-standoff distance affected the surface roughness with contribution of 0.24%. Interaction of abrasive flow rate-traverse rate-standoff distance affected the surface roughness with contribution of 0.98%.

4. REGRESSION ANALYSIS

Regression analysis is a powerful tool for mathematical modelling real process. Regression analysis includes the experimental data, mathematical methods and statistical analysis. Regression analysis was used to find correlation of perpendicularity deviation and surface roughness versus process factors.

The quasi-linear mathematical model has form:

$$y = y_e - \varepsilon = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j \qquad (1)$$

where y is the estimated response, y_e is the measured response, ε is the experimental error, *k* is number of factors, β_0 is the free term, β_i is the linear effect, β_{ij} is the interaction effect, and x_i are the factors.

Quasi-linear regression equation of perpendicularity deviation (u) versus abrasive flow rate (m_a), traverse rate (v_f) and standoff distance (h), with coefficient of determination of R^2=99.65%, is:

$$u = -0.106562 + 0.000434375 m_a + 0.00283125 v_f + 0.0090625 h - 0.0000031875 m_a v_f - 0.000009375 m_a h - 0.00028125 v_f h + 0.0000006875 m_a v_f h \qquad (2)$$

Quasi-linear regression equation of surface roughness (Ra) versus abrasive flow rate (m_a), traverse rate (v_f) and standoff distance (h), with coefficient of determination of R^2=99.99%, is:

$$R_a = 3.01125 + 0.0017125 m_a + 0.015325 v + 0.1325 h - 0.00001325 m_a v - 0.000225 m_a h - 0.0015 vh + 0.0000025 m_a vh \qquad (3)$$

Surface plots of perpendicularity deviation (u) and surface roughness (Ra) versus abrasive flow rate

(m_a) and traverse rate (v_f), according equations (2) and (3), are shown in Figures 13 and 14.

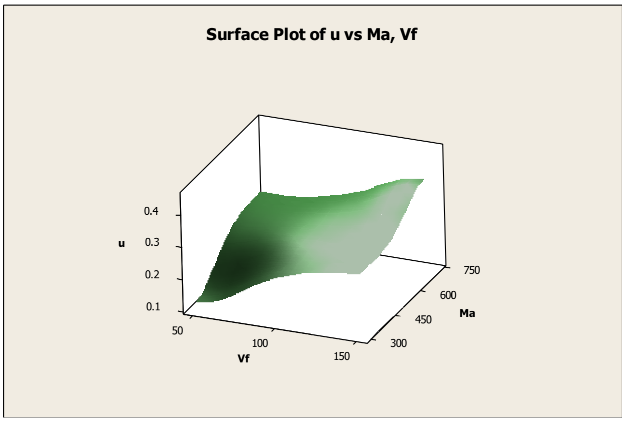

Figure 13. Surface plot of u versus abrasive m_a and v_f

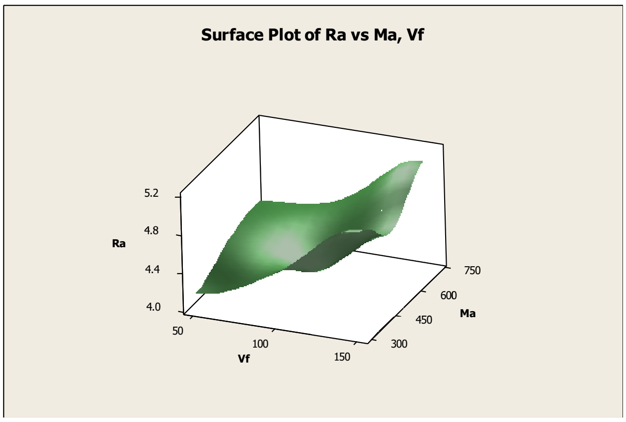

Figure 14. Surface plot of R_a versus m_a and v_f

5. CONCLUSION

Perpendicularity deviation and surface roughness of the cut are the most significant quality characteristics in analysing the quality of surfaces obtained by abrasive water jet cutting. Experimental investigation of perpendicularity deviation when cutting carbon steel EN S235 with abrasive water jet showed that the process factors abrasive flow rate, traverse rate and standoff distance have a clearly statistically significant effect on perpendicularity deviation with contribution of 90.28%. Traverse rate is the most significant factor with contribution of 51.04%, followed by the abrasive flow rate with contribution of 34.70%. Experimental investigation of the surface roughness showed that the process factors abrasive flow rate and traverse rate have a clearly statistically significant effect with contribution of 65.35%. Traverse rate is the most significant factor with contribution of 61.99%, followed by the abrasive flow rate with contribution of 3.36%. Regression analysis gives a good correlation of the perpendicularity deviation and surface roughness versus abrasive flow rate, traverse rate and standoff distance with coefficient of determination of R^2=99.65% and R^2=99.99% respectively.

6. ACKNOWLEDGEMENT

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