

Optimization and an experimental study on surface roughness of 6061 Aluminum alloy cut by abrasive water jet

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ABSTRACT

This study investigates the influence of abrasive water jet cutting (AWJC) parameters on surface roughness (Ra) and kerf morphology of 15 mm-thick AA6061 aluminum alloy. Ra was measured at depths of 2, 6, 10, and 14 mm, increasing from 1.68 μm at the entry to 3.05 μm at the exit, with variability decreasing at greater depths. Kerf morphology revealed the classical tri-zonal structure—smooth, transition, and striation-dominated zones—consistent with the Ra measurements. Taguchi L9 design and ANOVA identified traverse speed as the dominant factor influencing Ra (61.5%), followed by water pressure (34.3%), while stand-off distance (SoD) had only a minor influence ($\approx 1.3\%$) within the tested range (3–7 mm). A multiple linear regression model ($S = 0.145 \mu\text{m}$, $R^2 = 97.14\%$, adjusted $R^2 = 96.29\%$) accurately predicted Ra trends: higher traverse speed increased Ra by reducing jet–material interaction time, whereas higher water pressure reduced Ra by maintaining jet coherence and extending the smooth cutting zone. At the optimal parameters ($P = 3800 \text{ bar}$, $V = 50 \text{ mm/min}$, $\text{SoD} = 3 \text{ mm}$; A3B1C1), the model predicted $Ra \approx 1.84 \mu\text{m}$. An initial comparison with the experimental mean of 1.97 μm (Run 7) gave a 6.6% error, while a confirmation test yielded a mean of 1.88 μm , reducing the error to only 2.1%. These results validate both the regression model and the Taguchi-based optimization, confirming that surface finish in AWJC of thick AA6061

is primarily governed by traverse speed and water pressure. The depth-resolved analysis provides practical guidance for optimizing process parameters to enhance surface integrity in aluminum components.

1. Introduction

Non-traditional machining technologies are increasingly important in advanced industries such as nuclear engineering, aerospace, electronics, and automotive manufacturing [1]. Among these, abrasive water jet cutting (AWJC) has gained widespread application due to its ability to machine a broad range of materials using a high-pressure water jet mixed with abrasive particles [2,3]. AWJC offers high dimensional accuracy and superior surface quality, while enabling precise material removal without inducing heat-affected zones, making it suitable for both metals and composites [3]. These advantages including the ability to cut virtually any material, minimal cutting forces, no thermal distortion, high flexibility for complex geometries, and cost efficiency have led to its preference over conventional methods [4].

Surface quality is a critical requirement in many engineering applications, with surface roughness (Ra) commonly used as the primary indicator. Numerous studies have investigated the influence of AWJC process parameters such as water pressure, traverse speed, stand-off distance, and abrasive type on surface roughness [5]. Aluminum alloys, particularly AA6061, are widely used in aerospace and automotive industries due to their low density, high strength-to-weight ratio, good corrosion resistance, and excellent machinability, making them common subjects in machining and surface modification studies [6, 7].

Despite extensive research, most prior work has focused on relatively thin plates (typically <10 mm), with limited attention given to thicker materials. In practice, roughness defects become more pronounced at the exit zone of thick plates, directly impacting component performance. To address this gap, the present study investigates AWJC of 15 mm-thick AA6061, with particular emphasis on depth-dependent surface roughness at the 14 mm exit depth.

Process optimization was performed using Taguchi's method and ANOVA, and a linear regression model was developed and experimentally validated. By combining thickness-focused analysis, depth-resolved measurements, and regression validation, this work distinguishes itself from earlier studies and provides practical guidance for high-quality AWJC of thick aluminum components.

2. Literature Review

The abrasive water jet machining (AWJM) process inherently generates surface texture irregularities and increases surface activation. Numerous studies have investigated the effects of process parameters on surface roughness in aluminum alloys, employing various optimization techniques. AWJM can also be used as a surface texturing operation for thin aluminum alloy UNS A92024, where controlling parameters such as abrasive mass flow rate, stand-off distance, and traverse speed allows modification of surface roughness and wettability. This approach can create controlled surface textures without significant material thinning, preserving structural integrity and enabling precision surface modification in applications requiring both surface functionality and minimal material removal [7]. Investigations on AA7024 using linear regression and neural network models revealed that higher jet pressure reduces surface roughness, whereas increased feed rate and stand-off distance result in rougher surfaces [8].

A Taguchi-based Grey Relational Analysis (GRA) was employed to optimize the abrasive water jet machining (AWJM) parameters for Al-6061 alloy, focusing on stand-off distance (SoD), abrasive mass flow rate (AMFR), and Traverse speed (TS). The study evaluated their effects on multiple responses, including material removal rate (MRR), surface roughness (SR), and kerf width (KW). Using Taguchi's L9 orthogonal array and GRA, the optimal parameter combination that simultaneously minimized SR and KW while maximizing MRR was identified as SoD = 2 mm, AMFR = 250 g/min, and TS = 200 mm/min, demonstrating the effectiveness of this multi-response optimization approach

in AWJM processes [9]. Increasing traverse speed in abrasive water jet (AWJ) cutting of 6061-T6 aluminum alloy has been reported to increase surface roughness due to reduced interaction time between the abrasive jet and the workpiece. Higher traverse speeds limit the engagement of abrasive particles, resulting in less efficient cutting and more surface irregularities. Slower traverse speeds allow longer interaction, producing smoother surfaces and more uniform kerf geometry. Water pressure and stand-off distance also influence the surface quality in combination with traverse speed. These findings highlight the importance of optimizing process parameters to achieve the desired surface finish in AWJ-machined aluminum alloys [10]. Similarly, studies on AA7075 employed Grey Relational Analysis (GRA) in combination with Taguchi arrays to optimize multiple parameters, concluding that nozzle speed and abrasive flow rate are the dominant factors controlling surface quality [11]. Research on TiC-reinforced AA6063 composites using Taguchi methodology highlighted that abrasive flow rate, feed rate, and stand-off distance significantly affect surface roughness [12].

The machinability of LM26 aluminum metal matrix composites reinforced with graphite and fly ash was studied using abrasive water jet machining (AWJM). Lower traverse speeds and stand-off distances, combined with higher abrasive flow rates, improved surface quality, offering insights for optimizing AWJM parameters [13]. Another researcher employed a hybrid Taguchi-based Gray Relational Analysis and Principal Component Analysis approach to optimize AWJM of Al 6061-T6 alloy. The study investigated surface roughness, material removal rate, and kerf taper angle, and found that optimal combinations of traverse speed, stand-off distance, and abrasive flow rate significantly enhanced surface quality and machining efficiency [14]. Additionally, an L27 Taguchi design study emphasized that abrasive particle grain size is the most influential parameter affecting surface roughness [15]. An experimental study investigated the effects of traverse speed, water pressure, and stand-off distance on surface roughness and taper angle in abrasive water jet machining of 7075 aluminum composite. Response Surface Methodology (RSM) was used

to model the relationships between process parameters and machining outcomes. Increasing water pressure and traverse speed was found to increase surface roughness and taper angle. Reducing stand-off distance improved surface quality and cut precision. The RSM models provided predictions that closely matched experimental results, enabling identification of optimal process parameters [16]. Cutting depth has also been shown to strongly influence surface quality. Increasing depth significantly affects surface roughness and waviness, producing distinct “smooth” and “rough” zones along the kerf [17].

More recent work reported that as depth increases, the jet’s cutting capability diminishes, generating larger kerf taper and higher roughness due to energy dissipation and particle scattering [18].

While these studies provide valuable insights, most focus on single-depth analysis or different aluminum alloys. In contrast, the present study investigates AA6061 across multiple depth levels (2, 6, 10, and 14 mm), with particular attention to the exit zone (14 mm), where surface roughness is typically most critical. Furthermore, the study validates the optimal parameters using a regression model with minimal prediction error, offering a more comprehensive assessment than earlier research that relied primarily on Taguchi optimization alone.

3. Experimental Methodology

In this study, 15 mm thick Aluminum Alloy 6061 plates were used as the base material. The chemical composition of the material is presented in Table 1. Constant and variable process parameters are summarized in Tables 2 and 3, respectively. Garnet abrasive with a mesh size of 80 (average particle size $\approx 150\text{--}180\text{ }\mu\text{m}$) was employed during cutting. The orifice was made of sapphire, and the focusing nozzle was tungsten carbide. Experiments were conducted on a CNC-based abrasive water jet cutting machine, model CL510 (Waterjet Corporation S.R.L., 2017), capable of a maximum water pressure of 4000 bar (Fig. 1). Figure 1 shows the overall machine setup, including the workpiece

mounted on the cutting table and the nozzle assembly directing the water–abrasive jet onto the material. During cutting, the workpiece was securely fixed, and high-pressure water mixed with abrasive particles was delivered through the nozzle to achieve controlled material removal and accurate kerf formation. This setup allowed precise control of key process parameters, including traverse speed, stand-off distance, and abrasive flow rate, to evaluate their effects on surface roughness and cut quality. All experiments were performed using single-pass cutting. The specimens were rectangular AA6061 blocks with dimensions of 100 mm × 40 mm × 15 mm. Figure 2 illustrates the planned cutting paths, where red lines indicate the precise trajectories followed by the nozzle. These paths were designed to ensure uniform material removal across the workpiece and to achieve reproducible results in all trials.

Table 1. Weight percentages of the base materials (wt. %).

Components	Al	Si	Mg	Fe	Cu	Cr	Mn	Zn	Sn	Ti
AA 6061	97.22	0.94	0.84	0.46	0.23	0.13	0.08	0.05	0.02	0.02

Table 2. Constant values for input parameters.

Constant Data	Opening Diameter(mm)	Concentration Tube Diameter(mm)	Abrasive flowrate (g/min)	Jet Angle (°)
Value	1.00	1.06	320	90

Table 3. Variable input parameter values.

Variable parameters	Water Pressure, P(bar)	Traverse speed, V(mm/min)	Stand-off distance, SoD (mm)
Value	2500, 3200 and 3800	50,100, and 150	3, 5, and 7

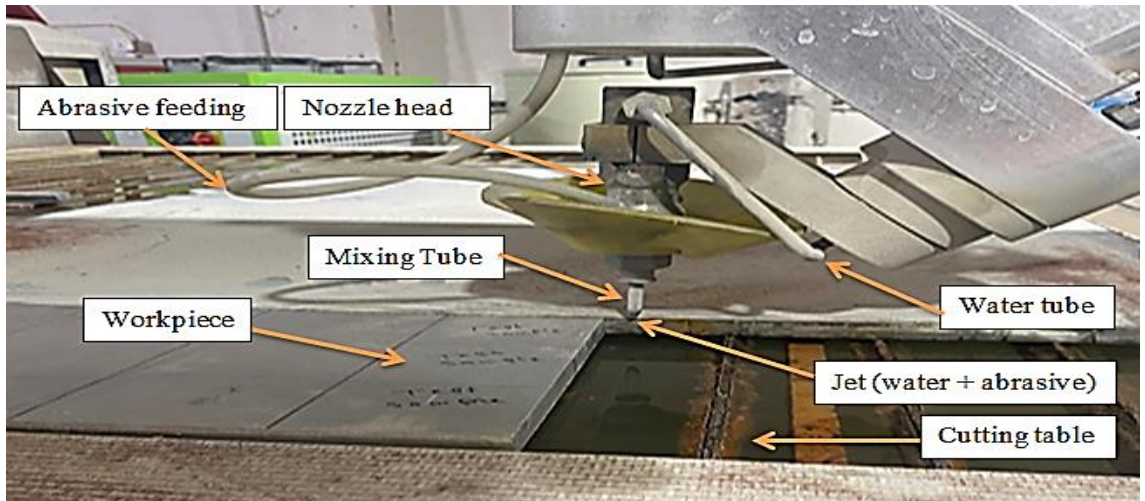


Fig.1. Abrasive water jet cutting setup showing the water and abrasive supply, mixing tube, nozzle head, and workpiece on the cutting table.

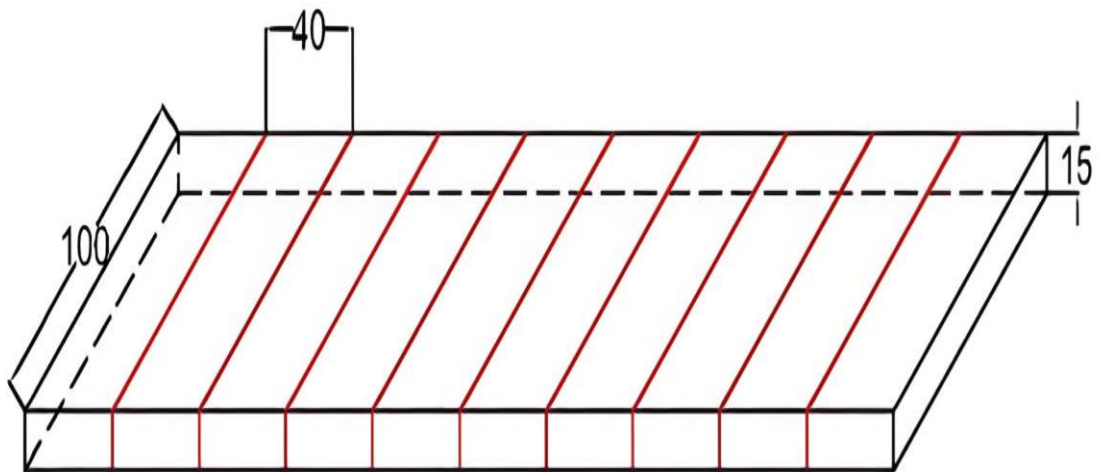


Fig.2. Schematic representation of the AA6061 aluminum alloy specimen (100 × 40 × 15 mm) prepared for abrasive water jet machining. The red lines indicate the cutting paths applied during experimentation.

The machined AA6061 specimens obtained under different Taguchi L9 trial conditions are shown in Fig. 3, where each sample (1–9) corresponds to a specific combination of water pressure, traverse speed, and stand-off distance (SoD). The arrows indicate the cutting direction. The AWJC experiments were designed using an L9 Taguchi array with three factors: water pressure (2500–3800 bar), traverse speed (50–150 mm/min), and stand-off distance (SoD) (3–7 mm) each at three levels (Table 4). Surface roughness (Ra) was measured using a Taylor Hobson Talysurf 10 stylus profilometer in the Mechanical Department laboratory, Erbil, Iraq. Three measurements per trial were taken at different locations, and the average Ra value was reported.



Fig.3. Machined AA6061 specimens (15 mm thick) labeled 1–9 after abrasive water jet cutting based on the Taguchi L9 design, representing different combinations of water pressure, traverse speed, and stand-off distance. Arrows indicate the cutting direction.

Table 4. Input control factors with levels used in the experiments.

Factors	Parameters	Levels			Observed Value
		Level 1	Level 2	Level 3	
A	Water Pressure, (P) (bar)	2500	3200	3800	Surface Roughness (Ra) (μm)
B	Traverse Speed, (V) (mm/min)	50	100	150	
C	Stand- off Distance, (SoD) (mm)	3	5	7	

4. Results

4.1 Surface Roughness Variation with Depth of cut

The mean surface roughness (Ra) values at depths of 2, 6, 10, and 14 mm are presented in Table 5. A clear increasing trend is observed with depth across all nine Taguchi runs, indicating that surface finish deteriorates as the cut becomes deeper. For example, in Run 1, Ra increases from 1.58 μm at 2 mm to 2.82 μm at 14 mm, while in Run 3, the increase is more pronounced, rising from 2.48 μm to 4.50 μm . Conversely, Run 7 consistently exhibits the lowest Ra values (0.70–1.97 μm), highlighting more favorable cutting conditions. These variations across runs demonstrate the significant influence of process parameters—particularly water pressure, traverse speed, and stand-off distance —on surface roughness and process stability. The full dataset of replicated measurements is provided in Appendix A (Table A.).

Table 5. Mean surface roughness Ra (μm) at different depths of cut for all Taguchi runs.

Surface roughness Ra (μm)				
Run	2 mm	6 mm	10 mm	14 mm
1	1.58	2.05	2.80	2.82
2	1.74	2.28	2.90	3.38
3	2.48	2.98	3.80	4.50
4	1.18	1.80	2.30	2.49
5	1.48	2.28	2.60	3.00
6	2.28	3.08	3.40	3.74

7	0.70	1.28	1.60	1.97
8	1.38	1.98	2.30	2.31
9	2.28	2.78	3.10	3.23

4.2 Kerf morphology

The kerf morphology of AA6061 specimens after abrasive water jet cutting (AWJC) is shown in Fig. 4. Fig. 4a presents nine specimens (1–9), where variations in waviness and striations across different parameter settings are evident, with most specimens exhibiting the typical three-zone structure along the 15 mm depth. Fig. 4b highlights Sample 3, where the smooth cutting zone ($\approx 0\text{--}4$ mm) appears flat and uniform, the transition zone ($\approx 4\text{--}9$ mm) shows faint waviness and irregular surface patterns, and the rough/striation zone ($\approx 9\text{--}15$ mm) displays inclined waviness and pronounced grooves. This progression corresponds to the gradual loss of jet energy with depth and to the increase in Ra values, which reached up to $4.50\text{ }\mu\text{m}$ in Run 3 at 14 mm. Fig. 4c shows Sample 7, which illustrates a relatively flat and uniform kerf wall with no distinct zoning, indicating improved surface quality under its parameter combination. Across all nine specimens, the tri-zonal morphology was most pronounced in Samples 2, 3, 5, and 6, whereas Samples 1, 4, and 7 exhibited comparatively uniform kerf walls. Samples 8 and 9 displayed localized linear features at the lower kerf, attributed to jet scattering and instability.

4.3 Statistical summary of surface roughness (Ra)

The statistical summary of surface roughness (Ra) across different depths of cut is presented in Table 6. Each value represents the mean of $n = 27$ measurements (three repetitions per run across nine runs), together with standard deviation (SD), coefficient of variation (%CV), and the 95% confidence interval (CI). The results confirm a depth-dependent trend: Ra increases from a mean of $1.68\text{ }\mu\text{m}$ at 2 mm to $3.05\text{ }\mu\text{m}$ at 14 mm, corresponding to an overall increase of approximately 82%.

Repeatability analysis shows that variability decreases slightly with depth, with %CV reducing from 34.7% at 2 mm to about 23.7% at 10 mm, before increasing again to 25.4% at 14 mm. The relatively high %CV at shallow depths suggests that Ra at 2 mm is more sensitive to process fluctuations, whereas deeper cuts exhibit more consistent, though higher, roughness values. The 95% CIs further demonstrate the precision of these estimates: at 2 mm, the true mean Ra is expected to lie between 1.23 μm and 2.13 μm , while at 14 mm it ranges from 2.45 μm to 3.65 μm . Importantly, the non-overlapping intervals across depths provide strong statistical evidence that the increases in Ra with depth are significant and not due to random variation.

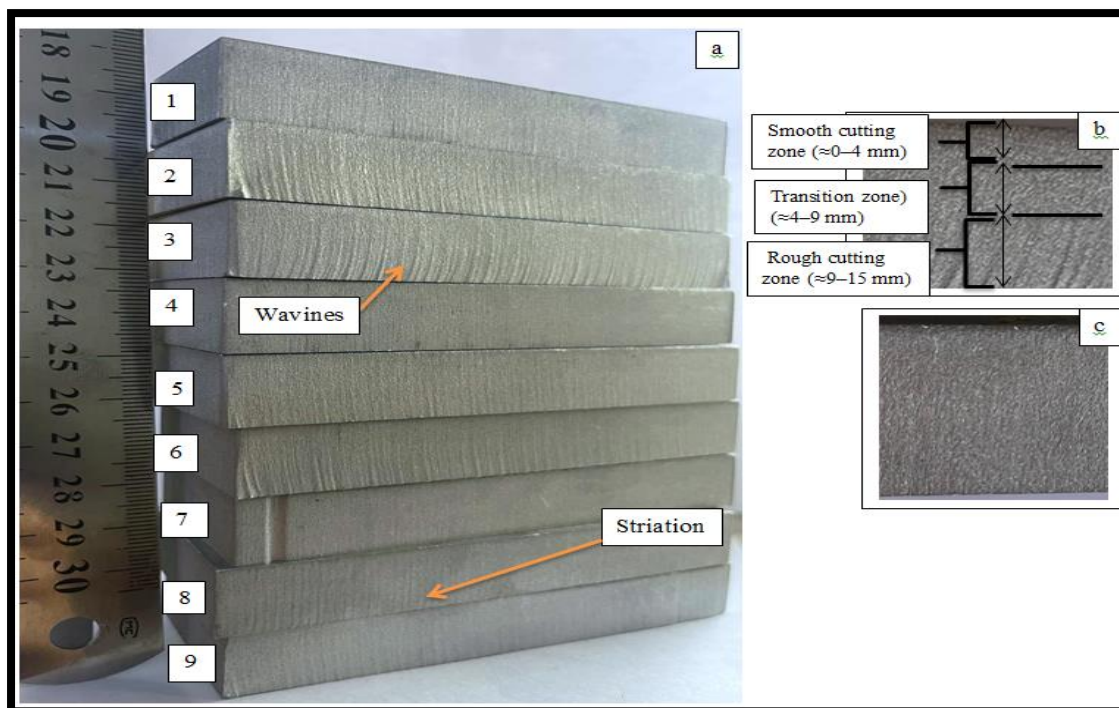


Fig.4. Kerf morphology of AA6061 specimens after abrasive water jet cutting (AWJC). (a) Nine specimens (1–9) showing variations in waviness and striations across cutting conditions. (b) Sample 3 illustrating the three characteristic zones: smooth ($\approx 0-4$ mm), transition ($\approx 4-9$ mm), and rough/striation ($\approx 9-15$ mm). (c) Sample 7 exhibiting a relatively flat and uniform kerf wall without distinct zoning.

Table 6: Statistical summary of surface roughness (Ra) across different depths of cut. The 95% confidence intervals (CI) are expressed as Mean $\pm$ margin of error (μm).

Depth (mm)	Mean Ra (μm)	SD	%CV	95% CI
2 mm	1.68	0.58	34.72	1.68 ± 0.45
6 mm	2.28	0.59	25.74	2.28 ± 0.45
10 mm	2.76	0.65	23.74	2.76 ± 0.5
14 mm	3.05	0.77	25.41	3.05 ± 0.6

4.4 Repeatability Analysis

Table 7 presents the repeatability and uncertainty analysis of Ra measurements at different depths of cut. The repeatability (s_r) shows a gradual increase with depth, rising from 0.020 μm at 2 mm to 0.060 μm at 14 mm, which reflects the higher scatter of surface roughness values in the striation-dominated lower cutting zone. Similarly, the standard uncertainty (u) and expanded uncertainty (U , 95% CI) also increase with depth, ranging from 0.012 μm and ± 0.024 μm at 2 mm to 0.035 μm and ± 0.070 μm at 14 mm, respectively. The pooled estimates ($s_r = 0.041$ μm , $u = 0.024$ μm , $U = \pm 0.048$ μm) remain very small when compared with the measured Ra values reported in Table 5, confirming that the measurements are precise and statistically reliable. This validates that the depth-dependent increase in Ra is a genuine process effect of AWJC, rather than a result of measurement error.

Table 7. Analysis of measurement system repeatability and uncertainty for surface roughness (Ra).

Depth of Cut (mm)	Precision (s_r) (μm)	Standard Uncertainty (u) (μm)	Expanded Uncertainty (U , 95% CI) (μm)
2	0.020	0.012	± 0.024
6	0.031	0.018	± 0.036
10	0.046	0.027	± 0.054
14	0.060	0.035	± 0.070
Pooled	0.041	0.024	± 0.048

Note: s_r = repeatability standard deviation (precision of repeated Ra measurements), u = standard uncertainty (1σ estimate of measurement uncertainty), and U = expanded uncertainty at 95% confidence ($U = 2u$).

4.5 Taguchi Design

MINITAB 15 was used to calculate response tables and evaluate the main effects of water pressure, nozzle traverse speed, and stand-off distance on surface roughness using Signal-to-Noise (S/N) ratios. ANOVA was then performed to assess the statistical significance of each factor. The experimental results for the Taguchi L9 array are presented in Table 8. Table 9 presents the Taguchi L9 orthogonal array with the experimental parameters and the measured surface roughness (Ra) values at a 14 mm depth. The Ra values vary considerably, ranging from a minimum of 1.97 μm (Run 7: P = 3800 bar, V = 50 mm/min, SoD = 7 mm) to a maximum of 4.50 μm (Run 3: P = 2500 bar, V = 150 mm/min, SoD = 7 mm). This pattern confirms that higher water pressure combined with lower traverse speed produced smoother surfaces, whereas low water pressure with higher traverse speed resulted in the poorest surface finish. This confirms that traverse speed increases Ra by reducing jet–material interaction time, while water pressure decreases Ra by enhancing jet coherence. The repeatability of the measurements is demonstrated by the small differences among the three trials within each run, indicating a stable and reliable experimental process. The mean Ra and corresponding S/N ratios also reinforce these trends: the best surface quality was obtained in Run 7 (Mean Ra = 1.97 μm , S/N = –5.90 dB), while the worst was in Run 3 (Mean Ra = 4.50 μm , S/N = –13.07 dB). Overall, the results highlight that traverse speed and water pressure are the dominant parameters controlling surface roughness, while stand-off distance had only a minor influence within the tested range (3–7 mm).

Table 8. Taguchi L9 Orthogonal Array showing factor levels for each experimental run

Run	Water Pressure, P (bar)	Traverse Speed, V (mm/min)	Stand-off distance (SoD) , (mm)
1	2500	50	3
2	2500	100	5
3	2500	150	7

4	3200	50	5
5	3200	100	7
6	3200	150	3
7	3800	50	7
8	3800	100	3
9	3800	150	5

Table 9. Taguchi L9 orthogonal array with experimental parameters and measured surface roughness (Ra).

Run	Water Pressure, P (bar)	Traverse Speed, V (mm/min)	Stand-off distance (SoD), (mm)	Ra (μm) – Trial 1	Ra (μm) – Trial 2	Ra (μm) – Trial 3	Mean Ra (μm)	S/N Ratio (dB)
1	2500	50	3	2.56	2.93	2.96	2.817	-9.013
2	2500	100	5	3.38	3.38	3.37	3.377	-10.57
3	2500	150	7	4.48	4.4	4.63	4.503	-13.073
4	3200	50	5	2.49	2.48	2.49	2.487	-7.912
5	3200	100	7	2.89	3.25	2.87	3.003	-9.567
6	3200	150	3	3.58	3.74	3.89	3.737	-11.455
7	3800	50	7	1.92	1.89	2.1	1.97	-5.899
8	3800	100	3	2.54	2.28	2.11	2.31	-7.298
9	3800	150	5	3.24	3.24	3.21	3.23	-10.184

4.6 Main Effects for S/N (smaller-the-better)

S/N ratios were calculated using the “Smaller-is-Better” method:

$$S/N = -10 \cdot \log_{10} \left[\left(\frac{1}{n} \right) \sum_{i=1}^n (Y_i)^2 \right] \quad (1)$$

Where: Y_i is the measured Ra for the i th trial, and n is the number of measurements. A larger negative S/N value indicates a higher and more variable response, which is undesirable. Fig 5 presents the main effects plot for

signal-to-noise (S/N) ratios using this criterion to determine the most effective machining parameters for minimizing surface roughness. The vertical axis represents the mean S/N ratio calculated for each factor level across all experimental runs, while the horizontal axis shows the factor levels. Each line illustrates how the mean S/N ratio changes with the level of a single factor (water pressure, traverse speed, and stand-off distance (SoD)). A steeper slope indicates a stronger influence on surface roughness.

The main effects plot for S/N ratios (Fig. 5) and the corresponding response table (Table 10) clearly demonstrate the relative influence of the control factors on surface roughness. Water pressure (P) shows a strong positive effect, with the S/N ratio improving steadily as pressure increases from 2500 to 3800 bar. Traverse speed (V) exerts the most dominant influence, as indicated by the steepest slope in Fig. 5 and the highest Delta value (3.962) in Table 10; increasing traverse speed from 50 to 150 mm/min sharply decreases the S/N ratio, signifying a strong deterioration of surface finish. Stand-off distance has only a marginal effect, with a Delta of 0.300, and its S/N values remain nearly constant across the three levels. These results confirm that traverse speed is the most critical factor (Rank 1), followed by water pressure (Rank 2), while stand-off distance (Rank 3) plays a negligible role in affecting Ra. Accordingly, the optimal factor combination for minimizing surface roughness is identified as high water pressure (3800 bar, Level 3), low traverse speed (50 mm/min, Level 1), and small stand-off distance (3 mm, Level 1), corresponding to the Taguchi condition A3B1C1.

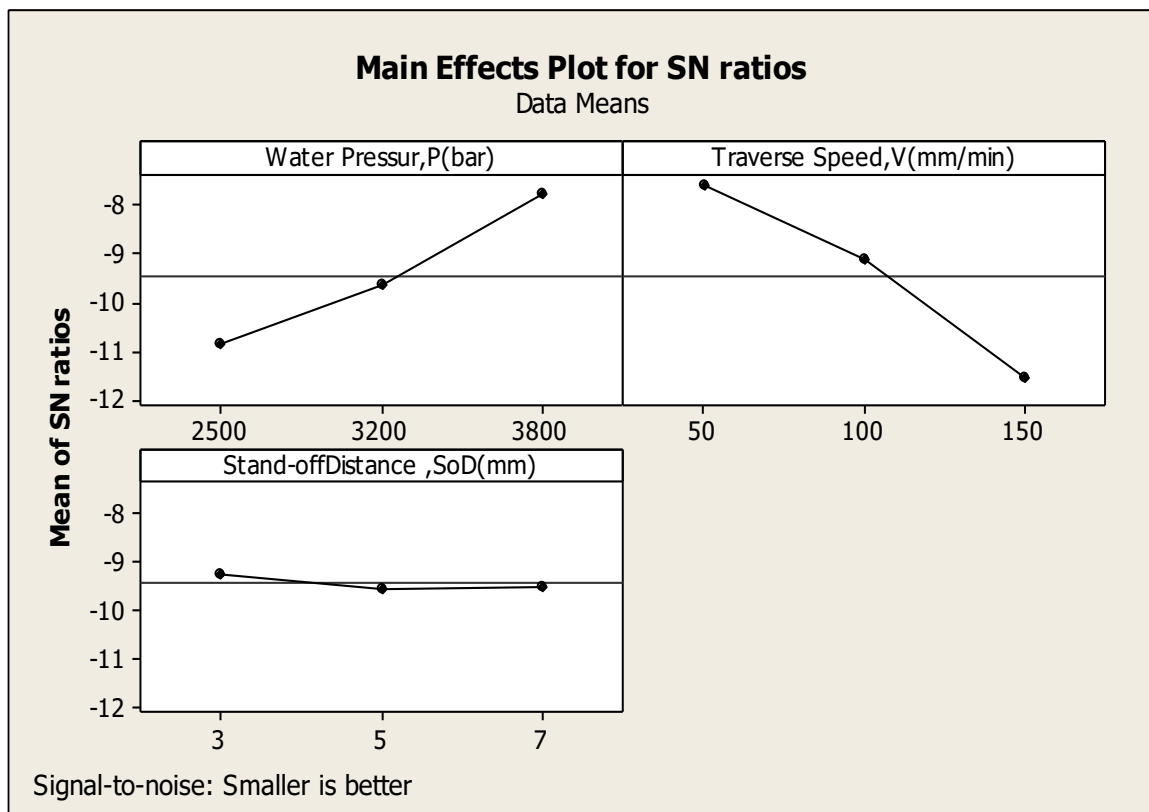


Fig.5. Main effects plot of S/N ratios for surface roughness (Ra) with respect to pressure (P), traverse speed (V), and stand-off distance (SoD) .

Table 10. Response table for S/N ratios (Smaller-is-Better)			
Level	Water Pressure, P (bar)	Traverse Speed, V (mm/min)	Stand-off distance, SoD (mm)
1	-10.885	-7.608	-9.255
2	-9.645	-9.145	-9.555
3	-7.794	-11.570	-9.513
Delta	3.092	3.962	0.300
Rank	2	1	3

Where: Delta is the difference between the maximum and minimum S/N ratio for each factor, while Rank is the relative influence of each factor on the response (Smaller-is-Better) S/N method.

4.7 ANOVA Studies

The ANOVA results for S/N ratios (Smaller-is-Better) of surface roughness are presented in Table 11. Traverse speed (V) was the most influential factor, contributing 61.5% of the total variation, followed by water pressure (P) at 34.3%. Stand-off distance (SoD) had only a minor effect, contributing 1.3%, while the experimental error accounted for 2.9%. The F-values and P-values indicate that both traverse speed ($F = 215.37$, $P < 0.001$) and water pressure ($F = 120.20$, $P < 0.001$) are highly significant, whereas stand-off distance ($F = 4.54$, $P = 0.024$) is marginally significant. Overall, these results confirm that optimizing traverse speed and water pressure is crucial for minimizing surface roughness, while stand-off distance has negligible impact within the tested range.

Table 11. ANOVA of signal-to-noise (S/N) ratios (Smaller-is-Better) showing the statistical significance and contributions of water pressure, traverse speed, and stand-off distance (SoD) to surface roughness (Ra).

Sources	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Contribution (%)
Water Pressure, P (bar)	2	5.0876	5.0876	2.5438	120.20	0.000	34.3
Traverse Speed, V (mm/min)	2	9.1158	9.1158	4.5579	215.37	0.000	61.5
Stand-off distance (SoD), (mm)	2	0.1920	0.1920	0.0960	4.54	0.024	1.3
Error	20	0.4233	0.4233	0.0212	—	—	2.9
Total	26	14.8186	—	—	—	—	100

Notes: DF = degrees of freedom; SS = sum of squares; MS = mean square. F-value = ratio of factor variance to error variance; P-value indicates statistical significance. Contribution (%) = relative contribution of each factor to surface roughness variation

4.8 Regression Analysis:

A multiple linear regression model was developed to quantify the effects of water pressure (P), traverse speed (V), and stand-off distance (SoD) on surface roughness (Ra). The resulting regression equation is:

$$\text{Ra} = 3.97 - 0.000814 P + 0.0140 V + 0.0511 \text{ SoD} \quad (2)$$

Where: P = Water pressure (bar), V = Traverse speed (mm/min), SoD = Stand-off distance (mm)

The regression model exhibits a standard error of $S = 0.145 \mu\text{m}$, with $R^2 = 97.14\%$ and adjusted $R^2 = 96.29\%$, demonstrating that it explains almost all of the variation in Ra. The coefficients show that surface roughness increases with higher traverse speed and stand-off distance, whereas increasing water pressure reduces Ra. At the optimal Taguchi parameters (P = 3800 bar, V = 50 mm/min, SoD = 3 mm; A3B1C1), the model predicts a surface roughness of $Ra \approx 1.84 \mu\text{m}$. Comparison with the experimental mean Ra of $1.97 \mu\text{m}$ obtained in Run 7 shows a difference of $0.13 \mu\text{m}$, corresponding to a prediction error of 6.6%. This indicates good agreement and confirms the reliability of the regression model, while further validation was carried out through a dedicated confirmation test (Section 4.9).

4.9 Confirmation test

Table 12 presents the confirmation test results for surface roughness (Ra) under the optimum parameter combination (A3B1C1). The predicted Ra value was $1.84 \mu\text{m}$, while the experimental trials yielded values of 1.86, 1.88, and $1.90 \mu\text{m}$, with a mean of $1.88 \mu\text{m}$. Compared with the prediction; this

corresponds to an error of only 2.1%, which is lower than the 6.6% error observed in the direct comparison with Run 7. This confirms the regression model more robustly and demonstrates the consistency of the Taguchi optimization.

Table 12. Confirmation test results for surface roughness (Ra) under the optimum parameter combination (A3B1C1).

Level	Predicted Ra (μm)	Experimental Ra (μm)	Mean Ra (μm)	Error (%)	95% CI (μm)
A3B1C1	1.84	1.86, 1.88, 1.90	1.88	2.1	1.83 – 1.93

5. Discussion

Surface roughness (Ra) is a critical indicator of part quality in abrasive water jet cutting (AWJC), particularly for thick materials. Measurements at multiple depths (2, 6, 10, and 14 mm) confirmed that Ra progressively increased toward the exit zone due to jet energy dissipation, kerf widening, and abrasive particle scattering. The 14 mm depth was therefore selected for optimization, as it consistently produced the poorest surface quality and represented the most critical region of the cut. Focusing on this depth ensures that the optimized parameters improve the most challenging zone, while maintaining acceptable finish at shallower depths.

Kerf morphology supported these results. The specimens exhibited the classical smooth, transition, and striation zones, which correlated with the depth-resolved Ra values. The smooth zone resulted from a coherent, high-energy jet, the transition zone reflected the onset of energy decay and scattering, and the striation zone was dominated by waviness and grooves caused by jet deflection and turbulence. Variations across samples highlighted the role of process parameters: increasing traverse speed reduced jet–material interaction time, which increased Ra and promoted surface waviness. In contrast, higher water pressure maintained jet coherence, extended the smooth cutting zone, and reduced Ra. These findings are consistent with prior reports [3–6, 9, 10, 19,

20], which also identified depth-dependent deterioration of kerf surfaces and emphasized the dominant role of traverse speed in promoting striation formation.

The Taguchi analysis confirmed that traverse speed had the strongest influence on R_a , followed by water pressure, while stand-off distance had minimal effect. Physically, this is because higher traverse speeds reduce jet–material interaction, leading to rougher surfaces, whereas higher water pressure improves particle momentum and cutting efficiency, yielding smoother surfaces. Within the tested SoD range (3–7 mm), jet coherence was largely preserved, which explains why SoD contributed only a minor influence ($\approx 1.3\%$) on surface roughness. This observation aligns with several previous studies [2, 5, 6, 9, 11, 15], which also reported SoD to be less significant. In contrast, other researchers [4, 8, 10] observed stronger SoD effects at larger distances, where jet divergence reduces energy and alters impact angles. These differences confirm that the effect of SoD is range-dependent and influenced by nozzle design and material properties

The multiple linear regression model further reinforced these findings. It predicted $R_a \approx 1.84 \mu\text{m}$ at the optimal Taguchi parameters (A3B1C1: 3800 bar, 50 mm/min, 3 mm SoD). An initial comparison with the experimental mean of $1.97 \mu\text{m}$ from Run 7 produced an error of $\sim 6.6\%$. However, a separate confirmation test yielded a mean R_a of $1.88 \mu\text{m}$, reducing the prediction error to only 2.1%. This strong agreement confirms both the reliability of the regression model and the robustness of the Taguchi optimization. Similar levels of predictive accuracy have been reported in the literature [16, 22], where errors below 5% were achieved for AWJC optimization studies.

Overall, these results demonstrate that R_a and kerf morphology in AWJC of AA6061 are strongly depth- and parameter-dependent. High water pressure and low traverse speed are essential to suppress waviness and striations, while

stand-off distance plays only a secondary role within the tested range. The agreement with most prior studies, alongside differences observed in those employing larger SoD ranges, underscores the importance of parameter selection when optimizing AWJC for thick aluminum alloys.

6. Conclusion

1. Surface roughness (Ra) increased progressively with depth, rising from 1.68 μm at 2 mm to 3.05 μm at 14 mm. This depth-dependent deterioration is a genuine effect of the AWJC process, caused by jet energy loss and the transition from smooth cutting at the entry to striation-dominated morphology at the exit.
2. AWJC of 15 mm AA6061 revealed the classical smooth, transition, and striation zones, which are directly linked to depth-resolved Ra. Optimizing high water pressure and low traverse speed is essential to minimize waviness and striations.
3. Taguchi L9 optimization and ANOVA confirmed traverse speed as the dominant factor influencing Ra, followed by water pressure, while stand-off distance contributed only marginally. Higher traverse speeds increased Ra by reducing jet–material interaction time, whereas higher water pressure reduced Ra by enhancing jet energy and cutting efficiency.
4. The optimal AWJC conditions (3800 bar, 50 mm/min, 3 mm SoD) produced a mean Ra of 1.97 μm , closely matching the regression model prediction of 1.84 μm .
5. The multiple linear regression model ($S = 0.145 \mu\text{m}$, $R^2 = 97.14\%$, adjusted $R^2 = 96.29\%$) predicted $Ra \approx 1.84 \mu\text{m}$ under the optimal Taguchi parameters (A3B1C1). An initial comparison with the experimental mean of 1.97 μm from Run 7 produced a prediction error of 6.6%, while a dedicated confirmation test yielded a mean Ra of 1.88 μm , reducing the error to only 2.1%. This strong agreement validates

both the regression model and the effectiveness of the optimized parameters.

6. Overall, controlling traverse speed and water pressure is essential for improving surface finish in AWJC of AA6061, while stand-off distance has only a minor effect within the tested range. Combined with depth-resolved analysis, these findings provide practical guidance for optimizing AWJC parameters in machining thick aluminum components.

Conflicts of Interest

The authors declare no conflict of interest.

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باشترینکردن و توژیینه وهیه کی ئەزموونی لە سەر زبری پراوه به جەتی ئاوی گەردیلە دار AA6061 رووی ئالۆوی ئەلەمنیۆم

پوخته:

لەسەر زبری پوو و مۆرفۆلۆژیای (AWJC) ئەم توژیینه وهیه لیكۆلینه وه له کاریگەری پارامیترەکانی برینی جەتی ئاوی گەردیلە دار له قوولاییه کانی 2, 6, 10, 14 ملم پیاوانه کرا که له (Ra). زبری پووکار به ئەستووری 15 ملم دەکات AA6061 کیرفی ئالۆوی ئەلەمنیۆم له دەرچوون نیشان دەدات، لەگەڵ کەمبوونه وهی گۆرانکاری $3.05\mu\text{m}$ له کاتی چوونه ژووره وه بۆ $1.68\mu\text{m}$ زیادبوونی به رهوپیچچوون له قوولایی زیاتردا. مۆرفۆلۆژیای کیرف پیکهاتهیه کی سێ ناوچهیی جیاوازی ئاشکرا کرد: ناوچهیه کی سەر وهی نهرم، گواستنوه به شهپۆلی مامناوه ند، و ناوچهیه کی خواره وهی زāl به سەر هیلکاری، که په یوه ندیه کی نزیکیان له گەڵ زبری پپوراودا ههیه. زبری دهستنیشان به هاکانی خیراییتپه پرینیان وهک فاکتهری بالاده ست که کاریگه ری له سەر Taguchi L%61.5 و 9 ANOVA دیزاینی کرد دواتر په ستانی ئاو 34.3 %، له کاتیکدا مه ودا ی وه ستان کاریگه ریه کی که می هه بوو 1.3 % له مه ودا ی تاقیکراوی (7-3) ملم. مۆدیلیکی = 29.96 % به وردی پشبینی په وتی زبری کرد خیرایی تیپه رین به رزتر $R^2 = 14.97\%$ رپکخرا S, R^2 = 0.145 هیللی فره یی پاشه کشه ی کهم دهکاته وه به پاراستنی یه کگرتوویی Ra زیاد دهکات به که مکرده وهی کاتی کارلیکی جیت-ماده، له کاتیکدا په ستانی ئاوی به رزتر Ra جیت و درێژکرده وهی ناوچه ی برینی نهرم. له پارامیتره کانی گونجاودا- په ستانی به رزی 3800 بار، خیرایی که می تیپه رین، 50 Ra (پاکردنی 7) μm مۆدیلکه پشبینی به راوردیکی سهره تایلی له گەڵ مامناوه ندی تاقیکاری A3B1C 11.97 مه ودا ی بچووکی ده ستانی 3 ملم هه له که که مکرده وه بۆ ته نها 2.1 % که ئەم، $1.88\mu\text{m}$ له کاتیکدا تاقیکردنه وهی پشتراستکردنه وه مامناوه ندی هه له ی 6.6 % به خشی ئەنجامانه هه ردوو مۆدیلی پاشه کشه و باشکردنی بنه مادیار به تاگوچی پشتراست دهکهنه وه، پشتراستی دهکهنه وه که ته واکردنی پووکار له به شیوه یه کی سهره کی به خیرایی تیپه رین و په ستانی ئاو به رپوه ده چیت. شیکارییه

قوولِّييه AA6061 نهستووری AWJC چاره سه رکراوه کان پینمایی پراکتیکی بو باشکردنی پارامیته ره کانی پرؤسه که بو بهرزکردنه وهی یه کپارچه یی رووکار له پیکهاته کانی نهله منیؤمدا دابین دهکات

تحسين ودراسة تجريبية لخشونة سطح سبيكة ألومنيوم 6061 مقطوعة بنفث الماء الكاشط

ملخص :

على خشونة السطح ومورفولوجيا الشق لسبيكة ألومنيوم (AWJC) تبحث هذه الدراسة في تأثير معاملات القطع بنفث الماء الكاشط عند μm على أعماق 2 و 6 و 10 و 14 مم، مما يدل على زيادة من 1.68 (Ra) تم قياس خشونة السطح. بسمك 15 ملم AA6061 عند المخرج مع تناقص التباين عند الأعماق الأكبر. كشف مورفولوجيا الشق عن بنية ثلاثية المناطق مميزة: $05 \mu\text{m}$: المدخل إلى منطقة علوية ناعمة، ومنطقة انتقالية ذات موجات معتدلة، ومنطقة سفلية تهيم عليها التشقق وتتوافق هذه البنية بشكل وثيق مع قيم يليه ضغط Ra، سرعة العبور كعامل مهيم يؤثر على (61.5%) ANOVA وتحليل التباين Taguchi L9 حدد تصميم. المقاسة Ra $R^2 = 96.29\%$ ضمن النطاق المختبر (3-7 مم). نموذج انحدار خطي متعدد. 1.3% الماء 34.3% بينما كان تأثير مسافة التباعد ضئيلاً بتقليل زمن تفاعل النفث مع المادة Ra إذ أدت زيادة سرعة الحركة إلى زيادة Ra تنبأ بدقة باتجاهات $S = 0.145 \mu\text{m}$ ، $R^2 = 97.14$ معدل. بالحفاظ على تماسك النفث وتوسيع منطقة القطع السلسلة. عند المعلمات المثلى Ra بينما يزيدان بينما أدى ارتفاع ضغط الماء إلى خفض $Ra \approx 1.84 \mu\text{m}$ تنبأ النموذج (A3B1C1) ضغط ماء مرتفع 3800 بار، وسرعة اجتياز منخفضة 50 مم/دقيقة ومسافة تباعد 3 مم التشغيل (7 خطأ بنسبة 6.6%)، بينما أظهر اختبار التأكيد متوسطاً قدره μm أظهرت المقارنة الأولية مع المتوسط التجريبي البالغ 1.97 مما قلل الخطأ إلى 2.1% فقط. تثبتت هذه النتائج صحة كل من نموذج الانحدار والتحسين القائم على تاغوتشي، مؤكدة أن تشطيب $1.88 \mu\text{m}$ يخضع بشكل أساسي لسرعة الحركة وضغط الماء. يوفر التحليل المُحلل بالعمق إرشادات عملية لتحسين AWJC بسمك AA6061 السطح في معاملات العملية لتعزيز سلامة السطح في مكونات الألومنيوم يخضع

Appendix A

Ra measurements were repeated three times at each depth of cut for every Taguchi run (nine runs in total). Table A. shows these raw repeated values along with their mean per run. Among these, the 14 mm depth was used for optimization in the Taguchi analysis.

Table A. Raw repeated measurements of surface roughness (Ra (μm)) at depths of 2, 6, 10, and 14 mm for all Taguchi runs, with mean values per run.

Run	2 mm	6 mm	10 mm	14 mm
1	1.50, 1.60, 1.63	2.00, 2.10, 2.05	2.70, 2.80, 2.90	2.56, 2.93, 2.96
	Mean = 1.58	Mean = 2.05	Mean = 2.80	Mean = 2.82
2	1.70, 1.72, 1.80	2.20, 2.30, 2.35	2.80, 2.90, 3.00	3.38, 3.38, 3.37
	Mean = 1.74	Mean = 2.28	Mean = 2.90	Mean = 3.38
3	2.40, 2.50, 2.55	2.90, 3.00, 3.05	3.70, 3.80, 3.90	4.48, 4.40, 4.63
	Mean = 2.48	Mean = 2.98	Mean = 3.80	Mean = 4.50
4	1.10, 1.20, 1.25	1.70, 1.80, 1.90	2.20, 2.30, 2.40	2.49, 2.48, 2.49
	Mean = 1.18	Mean = 1.80	Mean = 2.30	Mean = 2.49
5	1.40, 1.50, 1.55	2.20, 2.30, 2.35	2.50, 2.60, 2.70	2.89, 3.25, 2.87
	Mean = 1.48	Mean = 2.28	Mean = 2.60	Mean = 3.00
6	2.20, 2.30, 2.35	3.00, 3.10, 3.15	3.30, 3.40, 3.50	3.58, 3.74, 3.89
	Mean = 2.28	Mean = 3.08	Mean = 3.40	Mean = 3.74
7	0.65, 0.70, 0.75	1.20, 1.30, 1.35	1.50, 1.60, 1.70	1.92, 1.89, 2.10
	Mean = 0.70	Mean = 1.28	Mean = 1.60	Mean = 1.97
8	1.30, 1.40, 1.45	1.90, 2.00, 2.05	2.20, 2.30, 2.40	2.54, 2.28, 2.11
	Mean = 1.38	Mean = 1.98	Mean = 2.30	Mean = 2.31
9	2.20, 2.30, 2.35	2.70, 2.80, 2.85	3.00, 3.10, 3.20	3.24, 3.24, 3.21
	Mean = 2.28	Mean = 2.78	Mean = 3.10	Mean = 3.23