

Effect of cooling methods on hole quality in drilling of aluminium 6061-6T

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Abstract. The influence of cooling method and drilling parameters on hole production has been investigated experimentally and analytically by measuring the hole quality. A three-level, three-parameter experiment was conducted using design-of-experiment methodology. The three levels of independent input parameters were: for cooling method—flood drilling, minimum quantity lubrication (MQL) drilling and cryogenic drilling; for feed rate—0.2, 0.3 and 0.4 mm/rev; and for cutting speed—60, 75 and 100 m/min. The selected work and tool materials were aluminium 6061-6T and high speed steel (HSS), respectively. The measured output parameters were the three most widely used quality characteristics of drilled holes – diameter error, circularity and surface roughness. The results were analysed applying three methods: Pareto ANOVA, Taguchi method and traditional analysis. The findings revealed that the cooling method has a significant effect on diameter error (contribution ratio 88.27%), moderate effect on surface roughness (contribution ratio 41.74%) and relatively small effect on circularity (contribution ratio 23.64%). The best results for the dimensional accuracy and surface roughness were achieved by MQL drilling. Cryogenic drilling produced the best circularity results; however, in terms of dimensional accuracy and surface roughness it was the worst.

1. Introduction

Drilling is one of the oldest and the most widely used of all machining processes, comprising about 25-33% of all metal-machining operations [1, 2]. It is employed to create or to enlarge a round hole in a workpiece by the relative motion of a cutting tool, called a drill or drill bit. Drilling is a very important process since in many cases a drilled hole is the best option for assembling mechanical components and structures. Similar to all cutting processes, in drilling heat is generated by the cutting action of the cutting tool (drill) that overcomes the shear strength of the work material causing thermal distortion of the workpiece and reduction of tool life. However, in drilling operations it is estimated that 10-35% of total heat generated is dissipated to the workpiece which is higher than the other two most frequently used machining processes, namely turning (1.1-20%) and milling (1.3-25%) [3]. Therefore, careful consideration must be given to the selection of cutting fluid and its application method in drilling operations. Traditionally, flood cooling has been employed as it enables coolant to penetrate to the cutting edge of the drill and also helps remove the swarf from the cutting zone. Unfortunately, the down side of this method is the high cost of the disposal of contaminated cutting fluid. For this reason it is imperative to discover a cooling method that is more sustainable but still as

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effective in cooling the cutting edge. In this research, two alternative cooling methods, namely MQL and cryogenic cooling, have been investigated to establish their effectiveness in drilling.

Numerous studies on drill hole quality have reported in the literature. For example, Kivak et al. [4] investigated the influence of three drilling parameters – tool coating, cutting speed and feed rate – on the surface roughness and thrust force in drilling of AISI 316 stainless steel under dry cutting conditions. They utilised Taguchi's orthogonal array for optimising the input parameters and the analysis of variance (ANOVA) method for determining the most significant control factors. It was concluded that the most significant factors affecting surface roughness and thrust force were tool coating and feed rate, respectively.

Sreenivasulu et al. [5] applied Taguchi's orthogonal array for conducting their experiments. They employed grey relational analysis for optimising the surface roughness and roundness error in drilling of Al 6061 alloy having considered five process parameters: cutting speed, feed rate, drill diameter, point angle and cutting fluid mixture ratio. Their research revealed that the point angle and drill diameter are the two most significant factors affecting surface roughness and roundness error.

Davim and Reis [6] adopted the Taguchi method and ANOVA for finding the effects of cutting speed and feed rate on cutting power, specific cutting pressure and delamination factor in drilling of a carbon fiber reinforced plastic (CFRP) material. They concluded that feed rate has the most significant effect out of the three output parameters considered.

Pandeand and Relekar [7] examined the reduction of burr formation in drilling through-holes applying a response surface methodology technique considering four process parameters: drill diameter, feed rate, length to diameter ratio of hole and workpiece hardness.

Tsao and Hocheng [8] evaluated the effects of three drilling parameters – feed rate, spindle speed and drill diameter – on thrust force and surface roughness in drilling of composite laminate applying Taguchi's orthogonal array. They discovered that feed rate and drill diameter are the most significant factors affecting the thrust force whereas feed rate and spindle speed contribute the most to the surface roughness.

Çiçek et al. [9] applied the Taguchi method to investigate the effects of cryogenic treatment of drill and cutting parameters (cutting speed and feed rate) on hole quality (surface roughness and roundness error) in drilling of AISI 304 stainless steel under dry drilling conditions. Three drill categories: conventional heat treatment, cryogenic treatment and cryo-tempering were considered. ANOVA was employed to determine the most significant control factors and it was reported that the feed rate and cutting speed were the most significant factors influencing surface roughness and roundness error.

Kurt et al. [10] applied the Taguchi method, ANOVA and a regression analyses for investigating the effects of four drilling parameters (cutting speed, feed rate, depth of drilling and drill coating) on the surface finish and diameter error of a hole in the dry drilling of an Al 2024 alloy. They found that the most significant factor affecting surface roughness was tool coating while the most significant factor affecting diameter error was feed rate.

Kumar and Packiaraj [11] utilised Taguchi's orthogonal array, ANOVA and regression analysis to investigate the effect of drilling parameters, namely cutting speed, feed rate and drill tool diameter, on surface roughness, tool wear, material removal rate and hole diameter error in drilling of oil hardening non-shrinking steel (OHNS) material using a HSS spiral drill.

Islam et al. [12] investigated the effect of canned cycles on three drilled hole quality characteristics: diameter error, circularity and surface roughness in drilling aluminium 6061 under wet cutting conditions. A traditional analysis, Pareto ANOVA and Taguchi's signal-to-noise (S/N) ratio were employed for the analysis and established that the canned cycle has a profound effect on drilled hole quality and that overall spot drilling canned cycle (G81) produces the best results.

Braga et al. [13] compared the performance of uncoated and diamond coated carbide drills using MQL and flood of abundant soluble oil in the drilling of aluminium–silicon alloys (7% silicon content) with solid carbide drills. They reported that MQL produced better quality (in terms of forces, tool wear and quality of holes including diameter error, circularity, surface roughness and taper) compared to that obtained from flood of abundant soluble oil.

Kalidas et al. [14] examined the performance of three different coatings (TiAlN/TiN multi-layer coated HSS drills, TiAlN-coated HSS drills and molybdenum disulfide-coated carbide using design-of-experiment methodology considering three input parameters: spindle speed, feed rate, and coolant type (flood and dry). Comparison was based on four criteria: maximum temperature rise in the workpiece, average hole radius, variation in hole radius along the depth, and surface roughness of the hole. They concluded that drill coatings did not have a substantial effect on the measured workpiece temperatures or the surface texture of the resulting hole. In dry drilling, with increasing feed rate the maximum temperature rise in the workpiece decreased whereas in flood drilling it increased.

Heisel and Pfeifroth [15] investigated the influence of point angle and cutting speed on machining force and drill hole quality (delamination, fraying, burr formation) when drilling CFRP with cemented carbide drills. They found that the increase in cutting speed did not influence drill hole quality but increased feed forces and decreased drilling torques.

Xia [16] investigated the effect of cooling method (dry and cryogenic) and cutting parameters on drilling performance in drilling of CFRP in terms of thrust force, torque, cutting edge radius, outer corner flank wear, hole quality (including surface roughness, diameter error, roundness, delamination, burr formation, sub-surface quality) and reported better performance of cryogenic drilling in terms of hole quality (surface roughness, diameter error, burr formation and sub-surface quality) and tool wear.

Pirtini and Lazoglu [17] developed a mathematical model based on the mechanics of the drilling process for the prediction of cutting force and 3D hole profile and validated their model experimentally.

Furness et al. [18] examined the effect of feed rate and spindle speed on hole quality features such as diameter error, circularity, location error, angularity error and taper in drilling of hot rolled steel under dry conditions using a full factorial ANOVA. They concluded that feed rate and spindle speed have a relatively small effect on the measured hole quality features and, as a result, under certain conditions drilling production rates can be increased without considerably sacrificing hole quality.

Govindaraju et al. [19] compared the performance of conventional coolant and liquid nitrogen in drilling medium-carbon steel material. The selected input variables were cutting speed and feed whilst the measured output parameters were cutting temperature, thrust force and surface roughness. They reported better performance for liquid nitrogen with regards to cutting temperature with a 6% to 51% reduction. However, in terms of thrust force, liquid nitrogen produced mixed results with at lower feed rates the thrust force being increased by 6% to 32% in contrast to higher feed rates where the thrust force was decreased by 4% to 8%.

From the above discussion, the effect of cooling method on drill hole quality has been relatively lacking. Much of the research thus far has focused on optimising drilling parameters such as cutting speed, feed rate, depth of drilling and drill coating. The main objective of this research is to investigate the influence of cooling method on quality characteristics of drilled holes produced on a CNC machining centre and to optimise drilling parameters. The three cooling methods included in this study are flood drilling, MQL drilling and cryogenic drilling.

2. Scope

In current dimensioning and tolerancing practice [20, 21], dimensional specifications are expressed through: (i) size, (ii) form, (iii) orientation, (iv) location and (v) surface texture requirements. Drill hole quality can be evaluated by a number of parameters such as size variation (diameter error), form error (circularity and cylindricity), orientation error (perpendicularity of hole axis), location error (location of hole axis) and surface texture (surface roughness). The three most important quality characteristics for drilled holes are diameter error, circularity and surface roughness (as determined by arithmetic averages or R_a values). Therefore, they were selected for this study.

Diameter error is the variation in size which is defined by the difference between the measured and designed diameter where a positive error indicates overcutting of work material. It is an important quality characteristic of drilled holes, especially when cylindrical fit is involved. For drilled holes, circularity (also known as roundness or out-of-roundness) is another important quality characteristic

that is geometric in nature. Circularity represents variation in form, which is defined by two concentric circular boundaries within which each circular element of the surface must lie [21]. It is particularly important for rotating component parts where excessive circularity values may cause unacceptable vibration and heat. Surface roughness represents the random and repetitive deviations of a surface profile from the nominal surface which is used widely for representing the topography of a surface in short wavelengths. It is of great importance from the viewpoint of wear, corrosion, fatigue, noise, load-carrying capacity, heat transfer and many others.

The results were analysed applying three techniques – Pareto ANOVA, Taguchi's signal-to-noise (S/N) ratio analysis and traditional analysis. Pareto ANOVA is a simplified ANOVA method based on the Pareto principle. It does not require an ANOVA table and does not use F-tests. Therefore, it does not require detailed knowledge about the ANOVA method. Further details on Pareto ANOVA are available in Park [22].

The Taguchi method has been a popular choice in optimising process parameters in which experiments are conducted using the fractional factorial design-of-experiment (DOE) methodology. It applies S/N ratio as a quantitative analysis tool for optimizing the outcome of a process. The S/N ratio formula depends on the type of the variable. All three quality characteristics considered here fall under 'the smaller the better' category for which following formula [23] can be used.

$$S/N = -10 \log \frac{1}{n} \left(\sum_{i=1}^n y_i^2 \right) \quad (1)$$

where n is the number of observations and y is the observed data.

The higher the value of the S/N ratio, the better the result is, because it guarantees the highest quality with minimum variance. A thorough treatment of the Taguchi method can be found in Ross [23].

In traditional analysis, the average values of the responses are used. This tool is particularly suitable for monitoring a trend of change in the relationship of variables. However, it does not provide the complete picture as it normally does not include data on scatter of the responses.

It should be noted that drilling is not viewed as producing a good surface finish or accurate machined hole. Generally, enhancements have to be made to upgrade the dimensional accuracy of drilled holes, necessitating a secondary process. This involves the use of a variety of tools to improve the surface finish although an increase in the deviation in the geometric aspects of the machined hole may occur.

3. Experimental work

The experiments were planned using DOE methodology and a three-level, three-parameter experimental run based on full factorial design was conducted. A total of 27 through holes with a $\varnothing 11.7 \times 24$ mm design size were produced on a single $225 \times 70 \times 24$ mm aluminium block. Aluminium 6061-6T was chosen as the work material because of its extensive use in the industry. The chemical composition of the work material, compiled from Matweb [25], has been listed in Table 1. Holes were arranged in three rows, each of which contained nine holes. Three new, 11.7 mm diameter high-speed steel (HSS) twist drill bits, one for each row, were used to perform the drilling operation. Holes were drilled on a vertical CNC machining centre (Leadwell V-30 Machining Centre, Taiwan) with 5.5 kW spindle power and a maximum spindle speed of 4500 rpm. Peck drilling canned cycle (G83) with 8 mm peck distance was used to facilitate chip removal and application of cutting fluid near the cutting edge. Machining was performed applying three cooling methods – flood, MQL and cryogenic. For flood drilling, Castrol Clearedge EP690, a semi-synthetic soluble cutting fluid, was applied. For MQL operation, 2010 Coolube, a vegetable-based metal cutting lubricant, was sprayed in mist form by a Uni-Max cutting tool lubrication delivery system, manufactured by Unist, U.S.A. For cryogenic cooling liquid nitrogen was used. The details of input parameters (cooling methods, feed rate and

cutting speed) are given in Table. 2. The application of all three cooling methods were similar as the coolant was directed at the drilling operation through a nozzle. Additional safety precautions were observed when using liquid nitrogen, in particular that protective clothing was worn and adequate oxygen levels were maintained.

Table 1. Chemical composition of the work material [25].

Aluminium, Al	95.8 - 98.6 %
Chromium, Cr	0.04 - 0.35 %
Copper, Cu	0.15 - 0.40 %
Iron, Fe	<= 0.70 %
Magnesium, Mg	0.80 - 1.2 %
Manganese, Mn	<= 0.15 %
Other, each	<= 0.05 %
Other, total	<= 0.15 %
Silicon, Si	0.40 - 0.80 %
Titanium, Ti	<= 0.15 %
Zinc, Zn	<= 0.25 %

Table 2. Input variables.

Input Parameters	Symbol	Unit	Level 0	Level 1	Level 2
Cooling method	A		Flood	MQL	Cryogenic
Feed Rate	B	mm/rev	0.2	0.3	0.4
Cutting Speed	C	m/min	60	75	100

The precision measurement data for diameter error and circularity was obtained using a general purpose coordinate measuring machine (Discovery Model D-8 manufactured by Sheffield, UK). It has 0.1 micron position resolution with axial repeatability of measurement of ± 2.5 micron within its full travel area. The diameters of the holes were calculated using the standard built-in software package of the CMM. Eight points were probed to determine the diameter in the horizontal plane with the diameter of each hole being checked at 1 mm height increments. The circularity data was obtained from the CMM applying a similar probing scheme.

The surface roughness parameter arithmetic average (R_a) for each hole was determined by a surface-measuring instrument, the Surftest SJ-201P, manufactured by Mitutoyo, Japan. For each hole, three surface roughness measurements were taken parallel to the hole axis at three axial positions excluding entry and exit positions.

4. Results and analysis

The measurement results for diameter error, circularity and surface roughness, and their respective S/N ratios calculated by applying Equation 1, are given in Table 3. Analysis of the results, performed using Pareto ANOVA, the Taguchi method, and traditional analysis, are presented in subsequent subsections.

Table 3. Experimental results for diameter error, circularity, surface roughness and corresponding S/N ratios.

Expt. number	Measured Parameters			Calculated S/N Ratio for		
	Diameter error (mm)	Circularity (mm)	Surface roughness (μm)	Diameter error (mm)	Circularity (mm)	Surface roughness (μm)
1	0.012	0.069	2.603	35.981	22.347	-8.311
2	0.011	0.056	3.577	38.030	24.203	-11.178
3	0.012	0.073	2.113	36.273	22.477	-6.518
4	0.007	0.037	3.450	41.145	27.933	-10.765
5	0.023	0.028	2.977	28.109	30.340	-9.489
6	0.016	0.060	3.003	34.563	24.049	-9.762
7	0.011	0.041	4.013	34.350	27.437	-12.110
8	0.008	0.027	3.223	40.341	30.805	-10.357
9	0.011	0.023	2.573	38.259	31.949	-8.291
10	0.018	0.095	3.873	33.454	20.341	-11.783
11	0.012	0.051	2.290	37.506	25.784	-7.395
12	0.006	0.045	2.450	43.490	26.761	-7.787
13	0.016	0.062	2.437	35.153	23.911	-7.757
14	0.013	0.059	2.643	36.583	24.274	-8.446
15	0.008	0.020	1.983	39.845	32.738	-6.084
16	0.019	0.029	2.817	34.112	30.206	-9.079
17	0.012	0.048	2.733	36.775	26.050	-8.767
18	0.007	0.023	1.643	41.844	32.029	-4.452
19	0.071	0.042	2.603	22.907	26.388	-8.370
20	0.087	0.026	3.250	20.950	30.325	-10.337
21	0.053	0.024	4.433	24.927	31.560	-13.031
22	0.077	0.027	3.977	22.201	30.634	-12.135
23	0.048	0.044	3.380	25.441	26.213	-10.611
24	0.055	0.019	4.863	24.255	33.998	-13.880
25	0.074	0.025	3.127	22.440	31.520	-10.276
26	0.074	0.023	3.567	21.970	32.130	-11.228
27	0.046	0.030	2.867	25.454	29.248	-9.300

4.1. Diameter error

Pareto ANOVA analysis (Table 4) shows that parameter A (cooling method) has the most significant effect on diameter error with a contribution ratio of $P = 88.27\%$, followed by C (cutting speed), $P = 3.78\%$, and B (feed rate), $P = 0.32\%$, with the least influence. The A×C interaction (cooling method and cutting speed) also plays a role in the cutting process ($P = 2.25\%$). It is worth noting that the total contribution of the main effects is approximately 92% compared with 8% total contribution of the interaction effects, thus making it easier to optimize the diameter error through selection of input parameters, especially the cooling method.

The results obtained from the Pareto ANOVA analysis in Table 4 were verified by the response table and the response graph for the mean S/N ratio, as shown in Table 5 and Figure 1, respectively. The results show that parameter A (cooling method) has the most significant effect on diameter error (see Max-Min column in Table 5), which supports the results obtained from the Pareto ANOVA analysis in Table 4.

Table 4. Pareto ANOVA analysis for diameter error.

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	327.05	293.52	294.91	291.73	281.74	305.02	296.98	290.09	288.03
1	338.76	287.30	288.13	285.33	285.70	283.84	299.21	300.54	286.05
2	210.55	295.54	293.31	299.30	308.91	287.51	280.18	285.73	302.27
Sum of squares of difference (S)	30149.49	110.84	75.41	293.25	1292.19	768.65	649.45	347.82	469.98
Contribution ratio (%)	88.27	0.32	0.22	0.86	3.78	2.25	1.90	1.02	1.38

Cumulative contribution	88.27	92.05	94.30	96.20	97.58	98.60	99.45	99.78	100.00
Check on significant interaction	A×C two-way table								
Optimum combination of significant factor level	A1B2C2								

Table 5. Response table for mean S/N ratio for diameter error, and significant interaction mean S/N ratio

Input Parameters	Symbol	Level 0	Level 1	Level 2	Max - Min
Cooling type	A	36.34	37.64	23.39	<u>14.25</u>
Feed rate	B	32.61	31.92	32.84	0.92
Cutting speed	C	31.30	31.74	34.32	3.02
Interaction A×C	A×C	33.89	31.54	31.95	2.35

In selecting the optimum combination of parameters, both the Pareto ANOVA analysis (Table 4) and the response for the mean S/N ratio (Table 5 and Figure 1) confirm that the medium feed rate, B2 produces the lowest diameter error. Due to A×C interaction a two-way table was developed (not included due to space constraints) which showed that A1C2 achieved the lowest diameter error.

Overall the best combination for achieving the lowest diameter error was A1B2C2, i.e., medium level of cooling (MQL), high feed rate (0.4 mm/rev) and high cutting speed (100 m/min).

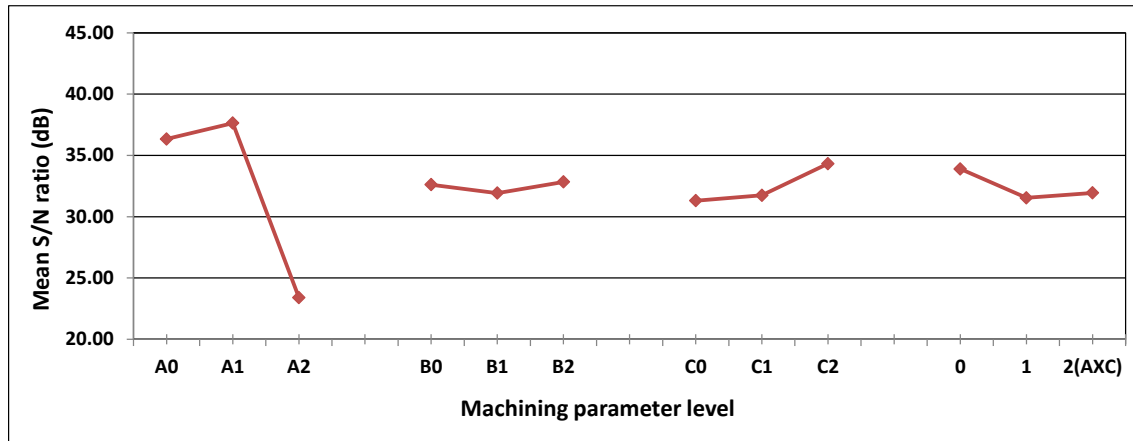


Figure 1. Response graph for mean S/N ratio for diameter error.

Further analysis using the traditional method (Figure 2) were conducted as an additional verification of the Pareto ANOVA (Table 4) and the Taguchi S/N response (Table 5 and Figure 1). Variation of diameter error under three input parameters is shown in Figure 3. As illustrated in Figure 2 and 3, the cooling method has the highest influence on diameter error with cryogenic cooling producing the worst result on average and in all cases. The effects of flood and MQL drilling on diameter error are approximately the same. Flood drilling produced marginally better results for low cutting speeds, whereas MQL produced marginally better results for high cutting speeds. It is worth noting that flood and MQL drilling produced the same average diameter error (Figure 2), whereas with regard to S/N ratio, MQL drilling was superior, which indicates that, compared to flood drilling, MQL drilling produces less variation.

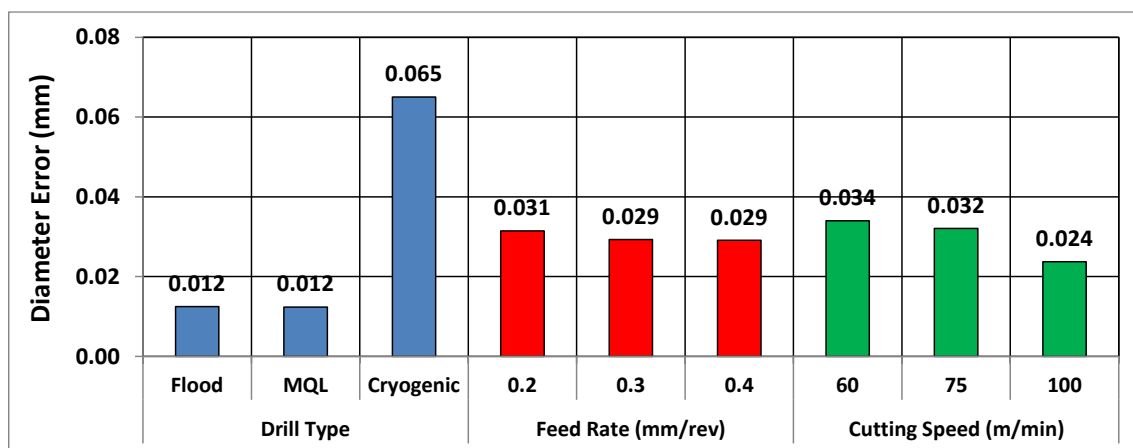


Figure 2. Average variation of diameter error under three input parameters.

4.2. Circularity

The Pareto ANOVA analysis (Table 6) shows that parameter B (feed rate) has the most significant effect on circularity, with a contribution of $P = 33.26\%$, followed by A (cooling method; $P = 23.64\%$) and C (cutting speed; $P = 11.46\%$). The interaction A×C (cooling type and feed rate) also plays a role in the cutting process, with $P = 11.64\%$. The total contribution of the main effects was approximately

68%, compared to the total 32% contribution of the interaction effects, thus making it relatively difficult to optimize the circularity error through selection of input parameters.

The results obtained from the Pareto ANOVA analysis in Table 6 were verified by the response table (Table 7) and response graph (Figure 4) for the mean S/N ratio. The results show that parameter B (feed rate) has the most significant effect on circularity, which confirms the results obtained from the Pareto ANOVA analysis in Table 6. A two-way table was used to analyse the optimum A×C interaction, showing that A2C2 achieved the best circularity. Thus, the optimum combination to achieve the best circularity is A2B2C2; i.e., high cooling type (cryogenic), high feed rate (0.4 mm/rev) and high cutting speed (100 m/min).

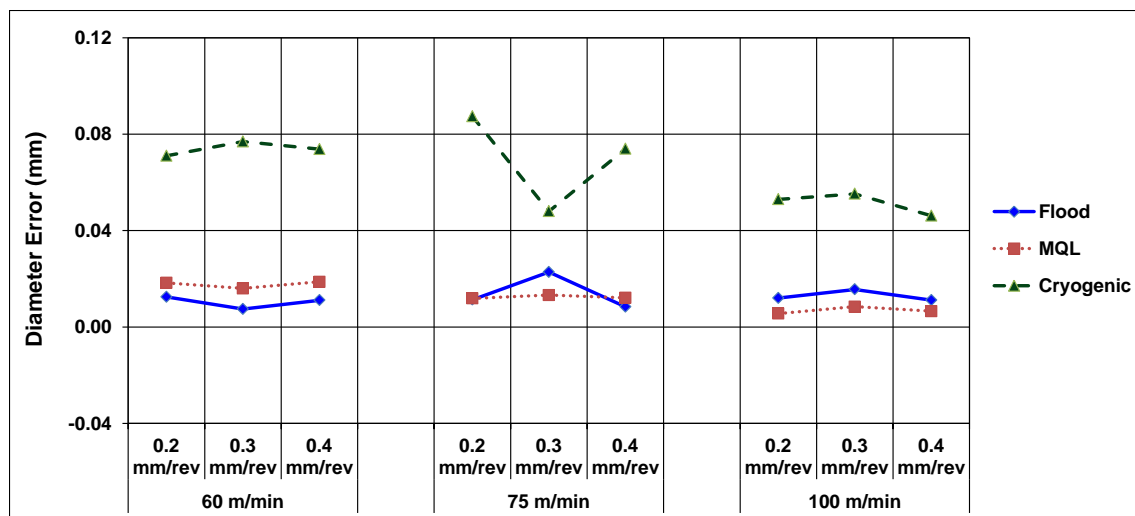
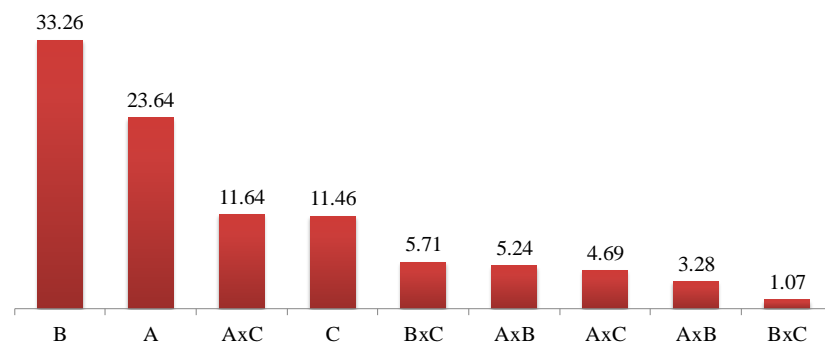


Figure 3. Variation of diameter error under three input parameters.

Table 6. Pareto ANOVA analysis for circularity.

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	241.54	230.18	248.16	242.85	240.72	257.91	248.63	248.85	243.13
1	242.09	254.09	248.10	258.88	250.12	254.61	265.42	256.02	260.26
2	272.02	271.37	259.38	253.92	264.81	243.12	241.60	250.79	252.26
Sum of squares of difference (S)	1824.63	2566.76	253.29	404.29	884.54	361.62	898.47	82.52	440.73
Contribution ratio (%)	23.64	33.26	3.28	5.24	11.46	4.69	11.64	1.07	5.71



Cumulative contribution	33.26	56.91	68.55	80.01	85.72	90.96	95.65	98.93	100.00
Check on significant interaction	A×C two-way table								
Optimum combination of significant factor level	A2B2C2								

Further analysis using the traditional method (Figure 5) was conducted as an additional verification of the Pareto ANOVA (Table 6) and the Taguchi S/N response (Table 7 and Figure 4). As illustrated in Figures 5, the best circularity was achieved at high cooling level (cryogenic), high feed rate (0.4 mm/rev) and high cutting speed feed rate (100 m/min). The results therefore confirm those obtained from the Pareto ANOVA and Taguchi S/N. The variation of circularity under the three input parameters shown in Figure 6 does not reveal any conclusive trend, although cryogenic drilling produced the best results in most cases.

Table 7. Response table for mean S/N ratio for surface roughness, and significant interaction mean S/N ratio

Input Parameters	Symbol	Level 0	Level 1	Level 2	Max - Min
Cooling type	A	26.84	26.90	30.22	3.39
Feed rate	B	25.58	28.23	30.15	<u>4.58</u>
Cutting speed	C	26.75	27.79	29.42	2.68
Interaction A×C	A×C	27.63	29.49	26.84	2.65

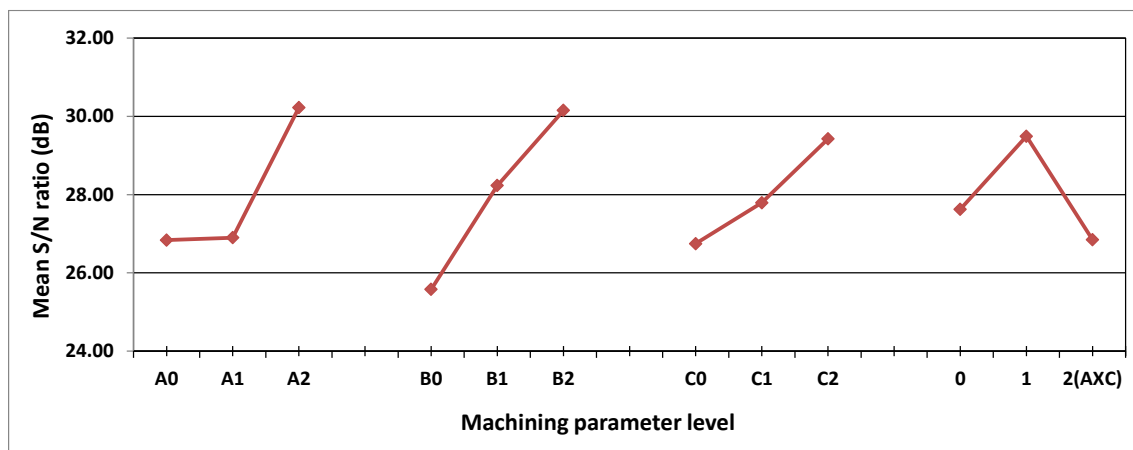


Figure 4. Response graph for mean S/N ratio for circularity.

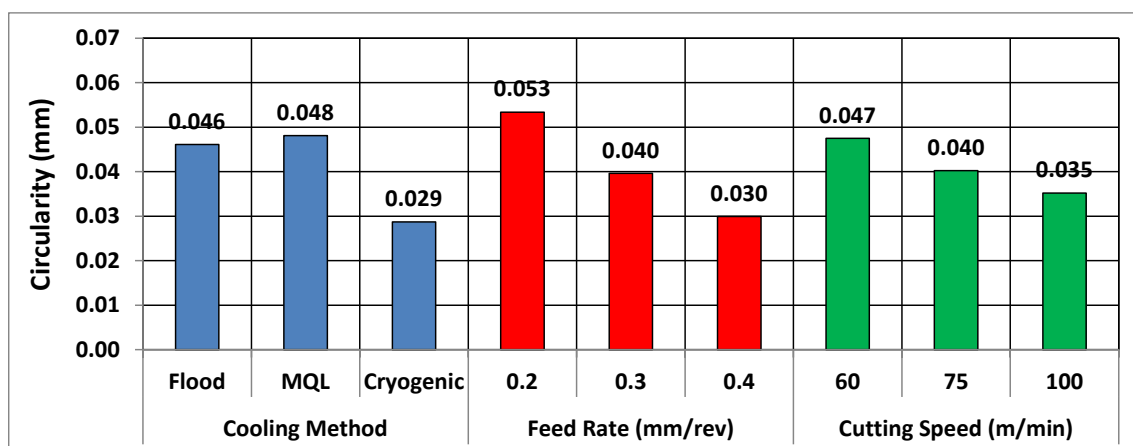


Figure 5. Average variation of circularity under three input parameters.

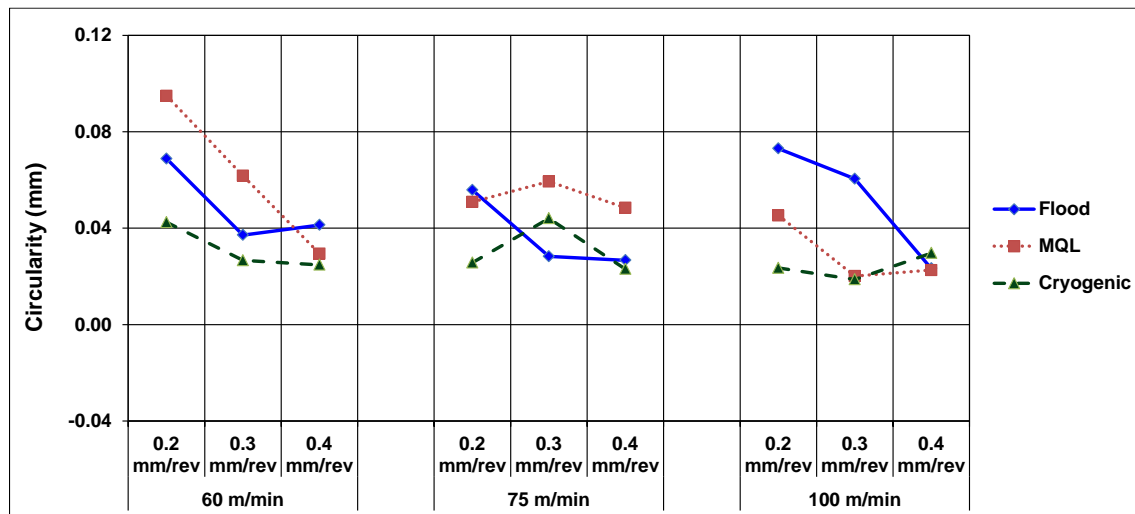


Figure 6. Variation of circularity under three input parameters.

4.3. Surface roughness

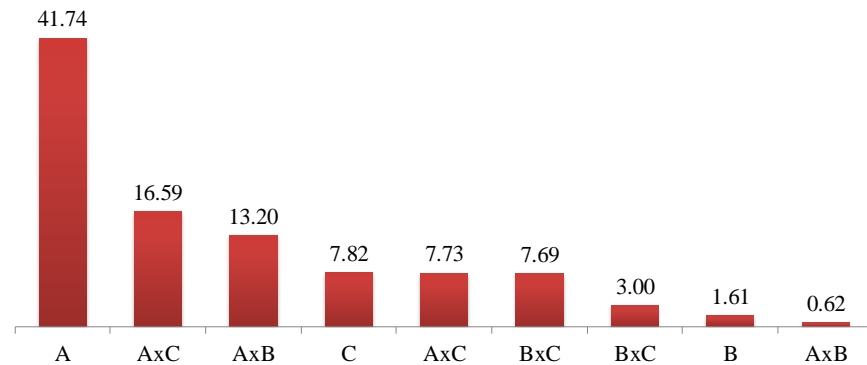
The Pareto ANOVA analysis (Table 8) indicated that parameter A (cooling method) had the most significant effect on surface roughness ($P = 41.74\%$), followed by C (cutting speed, $P = 7.84\%$) and B (feed rate, $P = 1.61\%$). The A×C interaction (cooling type and cutting speed) also played a role in the cutting process with $P = 16.59\%$. The total contribution of the main effects was approximately 51%, compared to the total 49% contribution of the interaction effects, thus making it difficult to optimize the circularity error through selection of input parameters.

The results obtained from the Pareto ANOVA analysis in Table 8 were verified by the response table (Table 9) and response graph (Figure 7) for the mean S/N ratio. The results show that parameter A (cooling method) had the most significant effect on surface roughness which confirms the results obtained from the Pareto ANOVA analysis in Table 8. A two-way table was used to analyse the optimum A×C interaction, showing that A1C2 achieved the best surface roughness. Thus, the optimum combination to achieve the best surface roughness is A1B2C2; i.e., medium cooling type (MQL), high feed rate (0.4 mm/rev) and high cutting speed (100 m/min).

Further analyses using the traditional method (Figure 8) was conducted as an additional verification of the Pareto ANOVA (Table 8) and Taguchi's S/N (Table 9 and Figure 7). As illustrated in Figures 8, the best surface roughness was achieved at medium cooling level (MQL), high feed rate (0.4 mm/rev) and low cutting speed feed rate (60 m/min). The results therefore confirm those obtained from the Pareto ANOVA and Taguchi S/N in terms of cooling method and feed rate. However, for cutting speed the results are different as, considering S/N ratio (Figure 7), high cutting speed was the best, whereas with regard to average surface roughness (Figure 8) low cutting speed was the best. This indicates that the variations in surface roughness were different at different cutting conditions which can be seen in Figure 9. Figure 9 also demonstrates that at high cutting speed, MQL was the best cooling method, whereas cryogenic was the worst.

Table 8. Pareto ANOVA analysis for surface roughness.

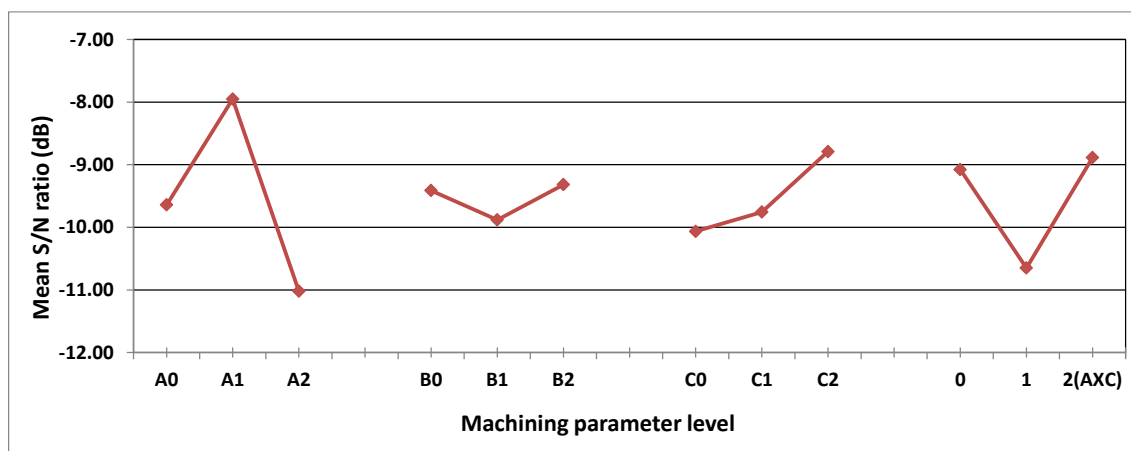
Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	-86.78	-84.71	-84.93	-79.10	-90.59	-81.69	-92.01	-88.54	-79.05
1	-71.55	-88.93	-87.79	-84.05	-87.81	-95.85	-80.13	-81.61	-90.10
2	-99.17	-83.86	-84.78	-94.35	-79.11	-79.96	-85.37	-87.35	-88.34
Sum of squares of difference (S)	1148.29	44.23	17.18	363.20	215.24	456.31	212.56	82.44	211.51
Contribution ratio (%)	41.74	1.61	0.62	13.20	7.82	16.59	7.73	3.00	7.69



Cumulative contribution	41.74	58.33	71.53	79.36	87.08	94.77	97.77	99.38	100.00
Check on significant interaction	AxC two-way table								
Optimum combination of significant factor level	A1B2C2								

Table 9. Response table for mean S/N ratio for surface roughness, and significant interaction mean S/N ratio

Input Parameters	Symbol	Level 0	Level 1	Level 2	Max - Min
Cooling type	A	-9.64	-7.95	-11.02	<u>3.07</u>
Feed rate	B	-9.41	-9.88	-9.32	0.56
Cutting speed	C	-10.07	-9.76	-8.79	1.28
Interaction AxC	AxC	-9.08	-10.65	-8.88	1.77

**Figure 7.** Response graph for mean S/N ratio for surface roughness.

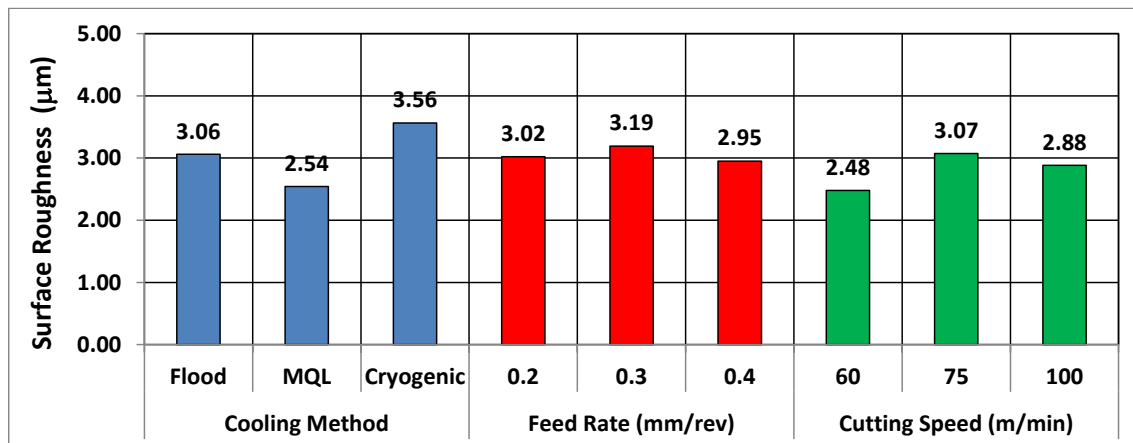


Figure 8. Average variation of surface roughness under three input parameters.

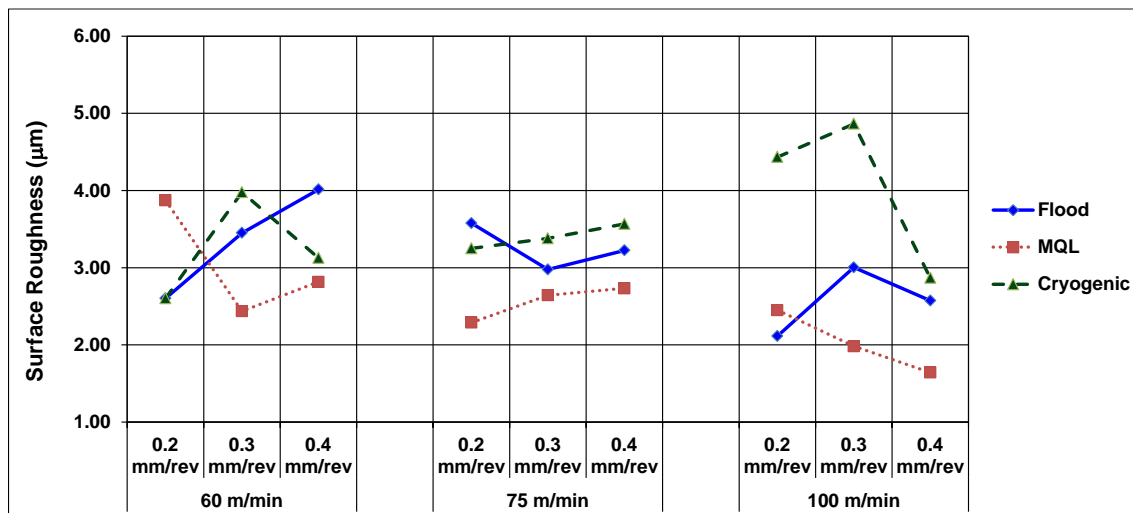


Figure 9. Variation of surface roughness under three input parameters.

5. Discussion

The findings indicate that the cooling method has a significant effect on diameter error (contribution ratio 88.27%), moderate effect on surface roughness (contribution ratio 41.74%), and a relatively small effect on circularity (contribution ratio 23.64%). A small interaction between cooling method and cutting speed ($A \times C$) was present for all three output parameters: diameter error (contribution ratio 2.25%), circularity (contribution ratio 11.64%) and surface roughness (contribution ratio 16.59%).

Further analysis of hole size variation for the three cooling methods is presented in Table 10. In all three cases the holes were oversized, which is common in drilling operations. Galloway [24] concluded that it is caused by the variation in relative lip heights of the drill and proposed the following formula for calculating hole oversize (HO).

$$HO = H \cdot \tan(P) \quad (2)$$

where H is the relative lip height and P is the half point angle.

Drill hole oversize also depends on the work material [26]. Other possible reasons include runout of the drill when attached to the machine, thermal distortion, a non-symmetric point angle and runout of the chisel edge. For an 11.7 mm diameter hole produced by CNC drilling the anticipated oversizing is 80 microns [27]. All three cooling methods produced holes within the expected range; however, compared to MQL and flood drilling, cryogenic drilling produced five times larger size (diameter) errors.

The precision of a manufacturing processes is often expressed by the international tolerance (IT) grade [28]. The IT grades of traditional machining processes used for making holes varies between IT05 (for fine cylindrical grinding) and IT13 (for drilling) [29]. The smaller the grade of IT number, the higher is the precision of the process. The following formula [29, 30] based on the tolerance standards for cylindrical fits was used for calculating IT grade in which process capability tolerance was replaced by six times the standard deviation of measured hole size variation data.

$$PC = \left(0.45\sqrt[3]{X} + 0.001X\right) 10^{\frac{IT-16}{5}} \quad (3)$$

where PC is the process capability tolerance (mm), X is the manufactured dimension (mm) and IT is the IT grade number.

The calculated IT values show that cryogenic cooling performed poorly in terms of diameter error. The expected IT grade for a drilling operation is between IT10 and IT13 [29]. Flood and MQL drilling diameter errors are within the expected range, however cryogenic drill is not.

Table 10. Comparison of size variation

Cooling Method	Unit	Flood	MQL	Cryogenic
Design size	mm	11.700	11.700	11.700
Measured mean size	mm	11.712	11.712	11.765
Size error	μm	12.5	12.3	65.0
6 x Standard deviation	μm	299.2	175.2	395.1
IT grade		13.310	12.148	13.914

Changes in average diameter error and circularity along the axis for different cooling methods are illustrated in Figures 10 and 11, respectively. Examination of Figure 10 reveals the influence of pecking distance on diameter error in cryogenic cooling. This is thought to be caused by the difference in thermal expansion of the drill and workpiece with respect to coolant exposure time. The pecking distance was arbitrary taken as a third of the depth of the drilled hole. Reducing the pecking distance would reduce this effect due to improved exposure of liquid nitrogen to the drill bit. The pecking distance is seen not to have any effect on circularity (Figure 11) which suggests that a better application of liquid nitrogen results in evenly distributed temperature over the drill bit and workpiece.

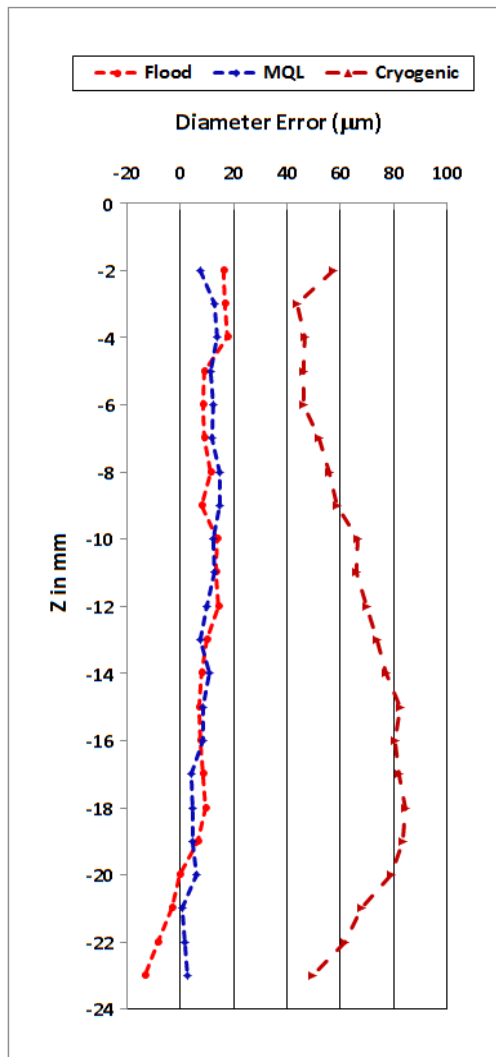


Figure 10. Change of diameter error along hole axis.

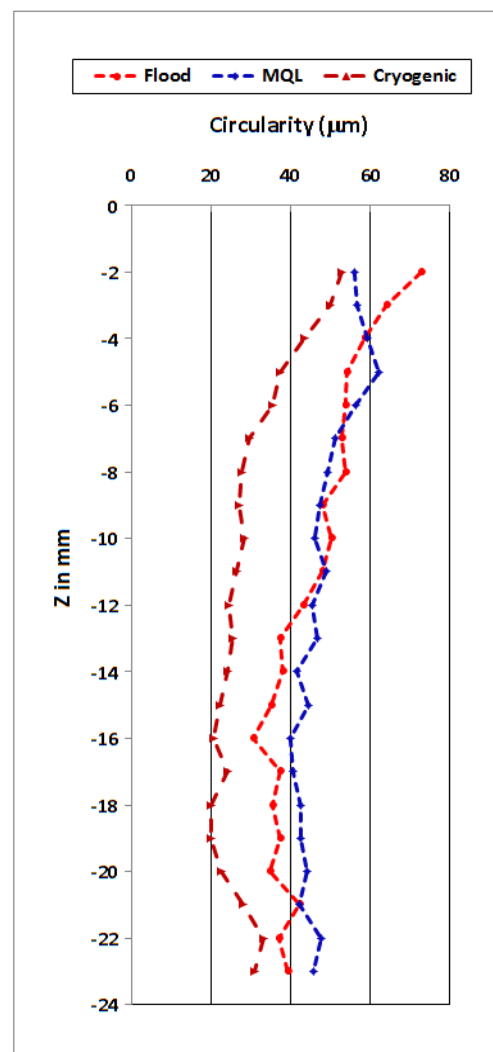


Figure 11. Change of circularity along hole axis.

6. Conclusions

Based on the results of the present experimental and analytical investigations, the following conclusions can be drawn:

- Cooling method significantly influences diameter error (contribution ratio 88.27%). MQL provides marginally better diameter error than flood drilling; however, compared to MQL and flood drilling, cryogenic drilling produced five times larger diameter errors.
- Cooling method has moderate effect on surface roughness (contribution ratio 41.74%). MQL provides the best surface finish followed by flood and cryogenic drilling. Compared to MQL and flood drilling, cryogenic drilling produced considerably worse surface finish.
- Cooling method has relatively small effect on circularity (contribution ratio 23.64%). The best results for the circularity were achieved by cryogenic drilling. Compared to cryogenic drilling, MQL and flood drilling produced substantially worse circularity.

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