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Effects of Canned Cycles and Cutting Parameters on Hole Quality in Cryogenic Drilling of Aluminum 6061-6T

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***Abstract*—**The influence of canned cycles and cutting parameters on hole quality in cryogenic drilling has been investigated experimentally and analytically. A three-level, three-parameter experiment was conducted by using the design-of-experiment methodology. The three levels of independent input parameters were the following: for canned cycles—a chip-breaking canned cycle (G73), a spot drilling canned cycle (G81), and a deep hole canned cycle (G83); for feed rates—0.2, 0.3, and 0.4 mm/rev; and for cutting speeds—60, 75, and 100 m/min. The selected work and tool materials were aluminum 6061-6T and high-speed steel (HSS), respectively. For cryogenic cooling, liquid nitrogen (LN_2) was used and was applied externally. The measured output parameters were the three widely used quality characteristics of drilled holes—diameter error, circularity, and surface roughness. Pareto ANOVA was applied for analyzing the results. The findings revealed that the canned cycle has a significant effect on diameter error (contribution ratio 44.09%) and small effects on circularity and surface finish (contribution ratio 7.25% and 6.60%, respectively). The best results for the dimensional accuracy and surface roughness were achieved by G81. G73 produced the best circularity results; however, for dimensional accuracy, it was the worst level.

***Keywords*—**Circularity, diameter error, drilling canned cycle, Pareto ANOVA, surface roughness.

I. Introduction

In the material cutting process, large amounts of heat are generated due to plastic deformation at the shear plane and to overcome friction at the tool-chip and tool-work interfaces. The heat generated elevates the temperature of the tools, workpieces, and chips, and the heightened temperature strongly influences tool wear, tool life, the dimensional accuracy and surface integrity of a machine surface, and the chip formation mechanism. Historically, cutting fluids have been applied extensively in machining operations to reduce the adverse effects of excessive heat. The most common practice is flood machining in which a large quantity of cutting fluid is applied to the cutting tool and workpiece interface. However, the excessive amount of cutting fluid used in flood machining is an area of concern with respect to workers' health and wider environmental issues that are central to high disposal costs for such fluid. Consequently, alternative methods such as machining with Minimum Quantity Lubrication (MQL) and cryogenic machining have been proposed.

In recent years, cryogenic machining has attracted the interest of the machining community for its potential environmental and economic benefits. Liquid nitrogen (LN_2) is the most commonly used cryogenic coolant because it is nontoxic, clean, and safe, and it has no disposal cost. In addition to its environmental benefits, cryogenic machining improves machining performance in terms of tool wear/tool life [1]-[3], dimensional accuracy [4], [5], and surface quality [6]-[8]. It has been reported that cryogenic machining can enhance the functional performance of machined components through improving its major surface integrity characteristics [9].

A number of papers have been published investigating the performance of cryogenic machining. A detailed treatment of the topic can be found in [10]-[12]. Most of the published literature refers to cryogenic turning; only a limited number of studies have been carried out on cryogenic drilling [13]-[19], although drilling is the most widely used of all machining processes (comprising about one third of all material-machining operations) [20]. This research is an attempt to close this gap by examining the performance of cryogenic drilling operations to improve three-hole quality characteristics.

Several factors influence drill hole quality; the most obvious ones are the cutting parameters—feed rate and cutting speed. Cryogenic cooling is characterized by rapid cooling through the localized application of cutting fluid; this is greatly influenced by the drilling canned cycle that may have significant effects on drill hole quality. The objective of this research is to explore this possibility in detail.

II. Drilling Canned Cycle

Canned cycles are an integral part of modern CNC machining. It is a convenient way of performing a series of operations initiated by a single code, thus reducing the number of blocks in a program and the memory space required for storing the program, and saving program development time and reducing the potential for programmers' errors. In CNC drilling, canned cycles are widely used, and the most frequently used drilling canned cycles are the following: a spot drilling canned cycle (G81), a deep hole canned cycle (G83),

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and a chip-breaking canned cycle (G73). Depictions of these operations are illustrated in Fig. 1.

G81 is the simplest and most commonly used drilling cycle. In G81, the drill moves to the reference plane (R) position at a rapid traverse speed. The drill then plunges to a point Z-depth position with the specified feed rate and then rapidly retracts to point R with a rapid traverse speed.

G83 is intended for deep hole drilling, which allows the chips to be cleared at certain intervals. In this case, a drill also moves from point R to point Z with a specified feed rate; however, it moves incrementally. After drilling an incremental distance (Q), the drill is fully retracted from the hole to point R. This facilitates the chip breaking and clears the chips out of the hole, improves the cooling of the drill, reduces the chance of drill breakage, and improves hole quality.

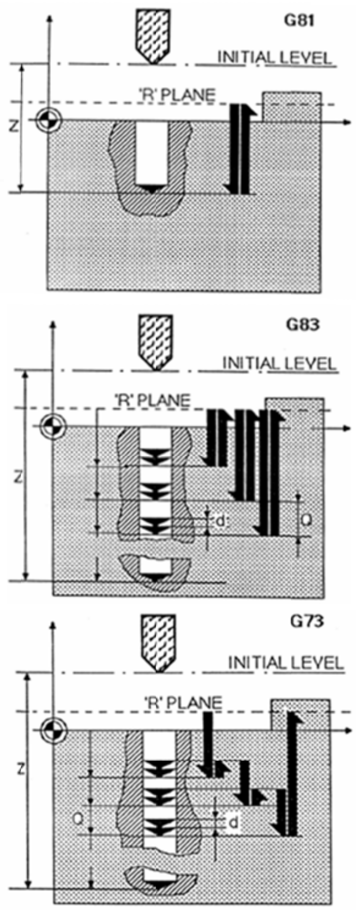


Fig. 1 Drilling canned cycles

G73 is used for drilling a material that has the tendency to produce stringy chips. Like G83 drilling in this case, the drill moves incrementally from point R to point Z with a specified feed rate; however, after drilling an incremental distance (Q), the drill is not totally retracted from the hole but retracted only by a small distance (d). Because the drill is not completely retracted, the cooling of the drill is not as good as it is with G83.

III. Scope

Drill hole quality can be evaluated by such parameters as size error (diameter error), form error (circularity/cylindricity), orientation error (perpendicularity of hole axis), location error (location of hole axis), and surface texture (surface roughness). This study investigates three important quality characteristics for drilled holes on aluminum, namely, diameter error, circularity, and surface roughness.

Diameter error is the variation in size defined by the difference between the measured and designed diameter, where a positive error indicates the overcutting of work material. Circularity, also known as roundness, represents a variation in form and is defined by two concentric circular boundaries in which each circular element of the surface must lie. Surface roughness represents the random and repetitive deviations of a surface profile from the nominal surface and is used widely for representing the topography of a surface in short wavelengths.

The results were analyzed by applying the Pareto analysis of variance (ANOVA), which a simplified ANOVA method based on the Pareto principle. It does not require an ANOVA table and does not use F-tests. Consequently, it does not require detailed knowledge about the ANOVA method. It is an excellent tool for determining the contribution of each input parameter and its interactions with the output parameters. Details treatment of the Pareto ANOVA analysis toll can be found in [21].

TABLE I
Chemical Composition of the Work Material [22]

Aluminum, 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 %

IV. Experimental Work

This study was performed on the drilling of aluminum 6061-6T, which is readily available and widely used in the industry. The chemical composition of the work material, compiled from MatWeb [22], is listed in Table I. The experiments were planned using the design-of-experiment (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 aluminum block. Holes were arranged in three rows, each of which contained nine holes. Three new, 11.7 mm diameter HSS twist drill bits, one for each row, were used to perform the drilling operation. Holes were drilled on a vertical CNC machining center (Leadwell V-30 Machining Centre, Taiwan) with 5.5 kW spindle power and a maximum spindle speed of 4,500 rpm. Liquid nitrogen (LN_2) was used as coolant, which was directed at the drilling operation through a nozzle. The details of input parameters (canned cycles, feed rate, and cutting speed) are given in Table II.

TABLE II
INPUT VARIABLES

Input Parameters	Symbol	Unit	Level 0	Level 1	Level 2
Canned cycle	A		G73	G81	G83
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 were obtained by a general purpose coordinate measuring machine (CMM) (Discovery Model D-8 manufactured by Sheffield, U.K.). 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 were obtained from the CMM applying a similar probing scheme. The surface roughness parameter arithmetic average (Ra) for each hole was measured by a surface-measuring instrument (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. The drilling thrust force was measured by a rotating cutting force dynamometer (type 9125A, manufactured by Kistler, Switzerland). A K-type thermocouple was attached to the workpiece to monitor the workpiece temperature throughout the experiment.

V. RESULTS AND ANALYSIS

A. Diameter Error

The Pareto ANOVA for diameter errors summarized in Fig. 2 shows that parameter A (canned cycle) has the most significant effect on diameter error, with a contribution ratio of P = 44.09%, followed by C (cutting speed), P = 24.62%, and B (feed rate), P = 13.63%. The interaction effects are small. The total contribution of the main effects is approximately 82% compared with the 18% total contribution of the interaction effects, thus making it easier to optimize the diameter error through the selection of input parameters, especially the canned cycle.

The Pareto ANOVA (Fig. 2) shows that parameter A (canned cycle) has the most significant effect on dimeter error. Considering the interaction between canned cycle and cutting speed (A×C), a two-way table was developed for selecting the optimum combinations of parameters A and C. The two-way tables are not included in this paper due to space constraints. The two-way table of A×C interaction showed that A2C2 yields the lowest diameter error. The optimum level of the remaining parameter feed rate (B) was chosen as B0 from the Pareto ANOVA (Fig. 2). Overall, the best combination for achieving the lowest diameter error was A2B0C2, i.e., high level of canned cycle (G83), low fed rate (0.2 mm/rev), and high cutting speed (100 m/min).

The variation of average diameter error under three input parameters is shown in Fig. 3. It shows that the canned cycle has the greatest influence on diameter error (largest difference between maximum and minimum values). G83 produced a slightly better diameter error than G81. Compared to G83 and G81, G73 produced diameter errors that were two times larger. Fig. 3 also shows that with the increase of feed rate, the diameter error increase, whereas with the increase of cutting speed, the diameter error initially increases and then decreases to the minimum at a high cutting speed.

B. Circularity

The Pareto ANOVA for circularity summarized in Fig. 4 illustrates that the most significant parameter affecting the circularity was the interaction between feed rate and cutting speed (B×C), (P = 26.30%), followed by cutting speed (C) (P = 24.20%) and feed rate (B) (P = 19.50%). The effect of a canned cycle (A) was small (P = 7.25%). 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 the selection of input parameters.

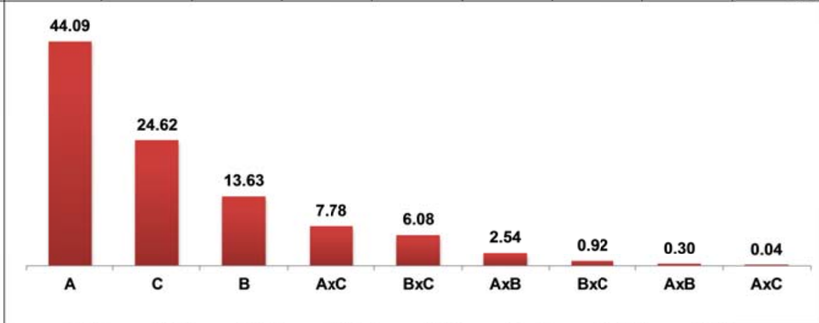
The Pareto ANOVA (Fig. 4) shows that the interaction between feed rate and cutting speed (B×C) has the most significant effect on circularity. Therefore, a two-way table was developed for selecting the optimum combinations of parameters B and C. The two-way table of B×C interaction showed that B1C1 yields the lowest circularity. The optimum level of the remaining parameter canned cycle (A) was chosen as A0 from the Pareto ANOVA (Fig. 4). Overall, the best combination for achieving the lowest circularity was A0B1C1, i.e., low level of canned cycle (G73), medium feed rate (0.3 mm/rev), and medium cutting speed (75 m/min).

The variation in average circularity under three input parameters is shown in Fig. 5. It shows that compared to feed rate and cutting speed, the canned cycle has relatively small influence on circularity. G73 produced the best circularity, followed by G81 and G83. Compared to G73, G83 produced circularity that was two times larger. Fig. 5 also shows that the best circularity can be achieved at a medium feed rate and a medium cutting speed, whereas a high feed rate and a low cutting speed produce the worst circularity.

C. Surface Roughness

The Pareto ANOVA for surface roughness summarized in Fig. 6 demonstrates that the most significant parameter affecting the surface roughness was the interaction between feed rate and cutting speed (B×C), (P = 21.30% and 17.53%), followed by cutting speed (C) (P = 16.70%). The effects of a canned cycle (A) and a feed rate (B) were small, P = 6.60% and 6.06%, respectively. The total contribution of the main effects was approximately 70%, compared to the total 30% contribution of the interaction effects, thus making it very difficult to optimize the surface roughness through the selection of input parameters.

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	488.73	227.32	313.45	311.23	340.95	361.82	325.55	315.77	301.91
1	253.00	365.27	334.86	359.95	418.86	350.86	320.91	303.09	278.95
2	221.41	370.55	314.82	291.95	203.32	250.45	316.68	344.27	382.27
Sum of squares of difference (S)	128024.34	39573.31	862.03	7369.79	71473.44	22603.85	117.93	2669.02	17659.87
Contribution ratio (%)	44.09	13.63	0.30	2.54	24.62	7.78	0.04	0.92	6.08



Cumulative contribution	44.09	68.71	82.34	90.12	96.21	98.74	99.66	99.96	100.00
Check on significant interaction	AXC two-way table								
Optimum combination of significant factor level	A2B0C2								

Fig. 2 Pareto AVONA for diameter error

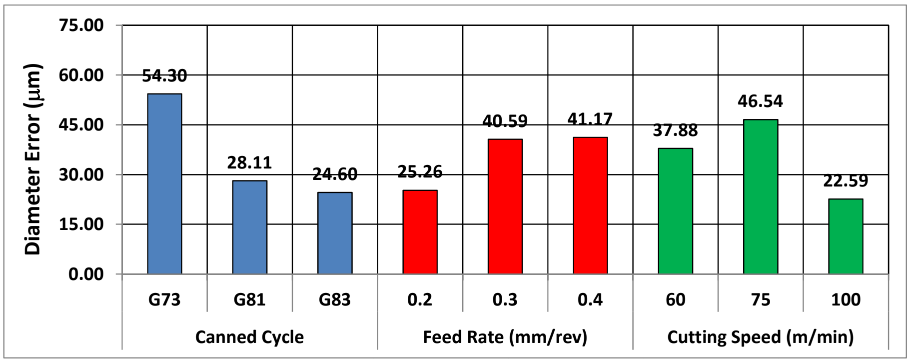
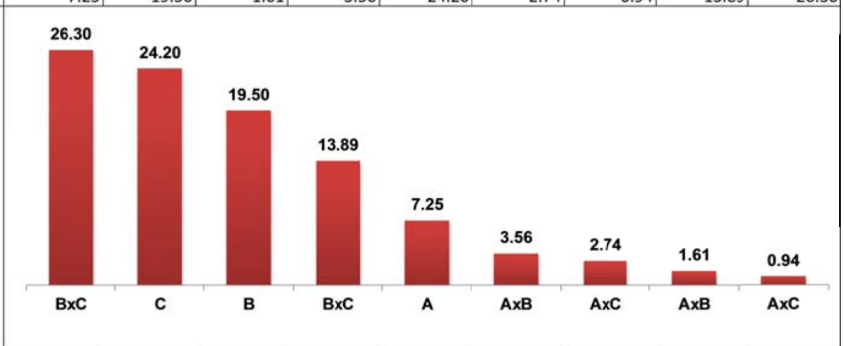


Fig. 3 Average variation diameter error under three input parameters

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	229.82	264.64	295.32	393.36	541.27	263.91	295.41	285.50	274.05
1	340.68	214.41	386.82	352.23	190.27	382.05	367.64	224.95	548.41
2	430.86	522.32	319.23	255.77	269.82	355.41	338.32	490.91	178.91
Sum of squares of difference (S)	60842.78	163730.71	13512.43	29926.94	203216.05	23037.95	7917.52	116590.47	220856.58
Contribution ratio (%)	7.25	19.50	1.61	3.56	24.20	2.74	0.94	13.89	26.30



Cumulative contribution	26.30	50.51	70.01	83.89	91.14	94.70	97.45	99.06	100.00
Check on significant interaction	BXC two-way table								
Optimum combination of significant factor level	A0B1C1								

Fig. 4 Pareto AVONA for circularity

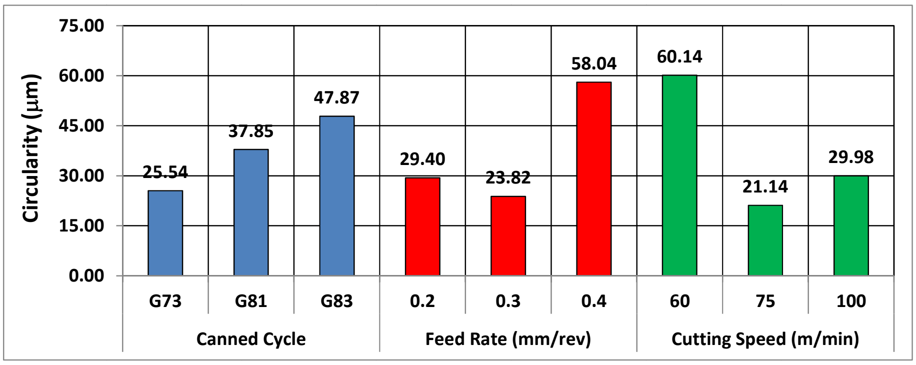


Fig. 5 Average variation of circularity under three input parameters

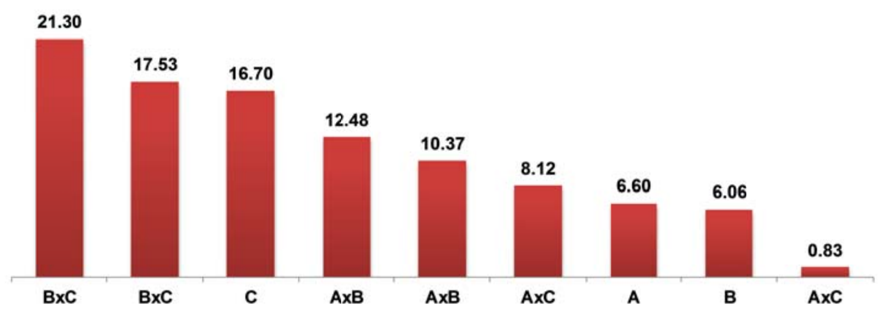
Due to the significant interaction between feed rate and cutting speed (B×C), a two-way table was developed for the selection the optimum combination of parameters B and C. The two-way table showed that B1C2 yields the lowest surface roughness. The optimum level of the remaining parameter canned cycle (A) was chosen as A2 from the Pareto ANOVA (Fig. 6). Overall, the best combination for achieving the lowest surface roughness was A2B1C2, i.e., a high level of canned cycle (G83), a medium feed rate (0.3 mm/rev), and a high cutting speed (100 m/min).

The variation in average surface roughness under three input parameters is shown in Fig. 7. As illustrated in Fig. 7, the influence of three input parameters on surface roughness is small, indicating considerable interaction effects between input parameters. G83 produced the best surface roughness, followed by G73 and G81. Fig. 7 also shows that with the increase of the feed rate, the surface roughness value increases, whereas for cutting speed, the surface roughness values decreases with the increase in cutting speed. This is in line with the conventional machining wisdom.

VI. Discussion

The findings indicate that the canned cycle has a significant effect on diameter error (contribution ratio 43.58%), and relatively small effects on circularity (contribution ratio 7.25%) and surface roughness (contribution ratio 6.60%). Significant interactions between feed rate and cutting speed (B×C) were present for circularity (total contribution ratio 40.19%) and surface roughness (total contribution ratio 38.83%).

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	36.97	33.61	32.30	30.73	42.93	35.52	40.56	34.07	30.28
1	38.93	33.60	33.05	36.06	32.32	34.52	34.61	30.42	43.67
2	31.40	40.09	41.95	40.50	32.05	37.26	32.13	42.80	33.35
Sum of squares of difference (S)	91.42	83.98	172.88	143.58	231.23	11.54	112.50	242.80	295.01
Contribution ratio (%)	6.60	6.06	12.48	10.37	16.70	0.83	8.12	17.53	21.30



Cumulative contribution	21.30	38.83	55.53	68.01	78.38	86.50	93.10	99.17	100.00
Check on significant interaction		BXC two-way table							
Optimum combination of significant factor level		A2B1C2							

Fig. 6 Pareto AVONA for surface finish

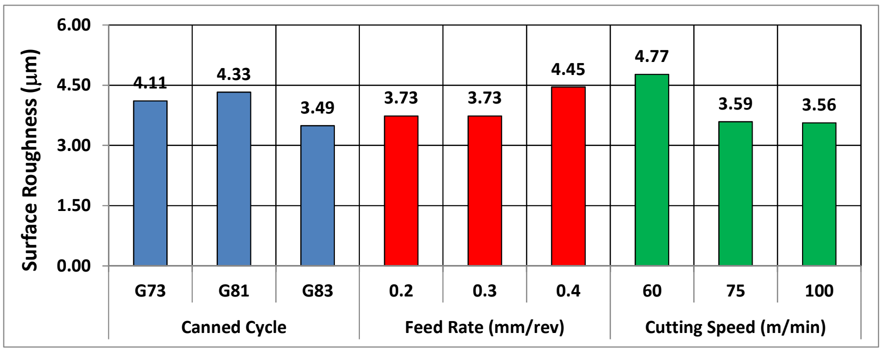


Fig. 7 Average variation of surface roughness under three input

Further analysis of hole size variation for the three canned cycle is presented in Table III. It shows that in all three cases, the holes were oversized, which is common in drilling operations. Galloway [23] concluded that it is caused by the variation in relative lip heights of the drill. Drill hole oversize also depends on the work material [24]. Other possible reasons include a runout of the drill when attached to the machine, thermal distortion, a nonsymmetric point angle, and a runout of the chisel edge [25]. For an 11.7 mm diameter hole produced by drilling, the anticipated oversizing is 80 microns [26]. All three canned cycles produced holes within the expected range; however, compared to G81 and G83, G73 produced (diameter) errors that were two times larger.

TABLE III
COMPARISON OF SIZE VARIATION

Size Characteristics	Unit	G73	G81	G83
Nominal diameter	mm	11.700	11.700	11.700
Measured mean diameter	mm	11.754	11.728	11.725
Diameter error	µm	54.3	28.1	24.6
6 × standard deviation	µm	158.5	104.1	80.9
Process capability tolerance	IT	11.931	11.018	10.470

The precision of a manufacturing process is often expressed by the international tolerance (IT) grade [27]. The smaller the grade of IT number, the higher the precision of the process. The IT grades of traditional machining processes used for making holes varies between IT05 (for fine cylindrical grinding) and IT13 (for drilling) [28]. The following formula [28], [29], based on the tolerance standards for cylindrical fits, was used for calculating the IT grade in which process capability tolerance was replaced by six times the standard deviation of measured hole size variation data.

$$PC = \left(0.45\sqrt[3]{X} + 0.001X\right) 10^{\frac{IT-16}{5}} \quad (1)$$

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

The expected IT grade for a drilling operation is between IT10 and IT13 [28]. All three canned cycles produced diameter errors within the expected range. G83 produced the best results in terms of both diameter error and process capability tolerance, followed by G81 and G73.

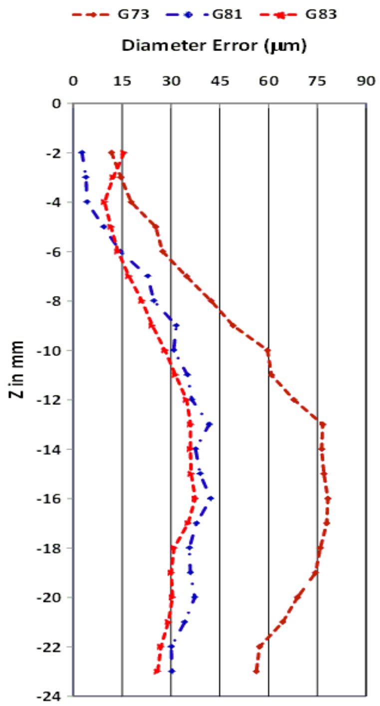


Fig. 8 Change of diameter error along hole axis

Changes in average diameter error and circularity along the axis for different canned cycles are illustrated in Figs. 8 and 9, respectively. Fig. 8 shows that G83 produced the least shape variation flowed by G81 and G73. Examination of Fig. 8 also reveals that the hole dimeter gradually increased to a peak value and then decreased after passing half of the drilling depth producing a barrel shape. This type of shape variation is typical in most drilling operations, as reported in the literature [5], [30], [31]. This is probably caused by the thermal expansion of the drill bit during penetration and subsequent cooling when it reaches the opposite end. It is worth noting that there is no noticeable change in the shape of the holes due to different canned cycles, suggesting that the oversizing and the shape variation occur during drill penetration and not during drill withdrawal.

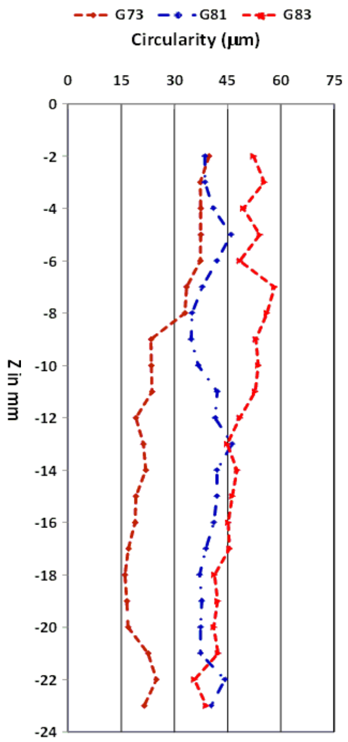
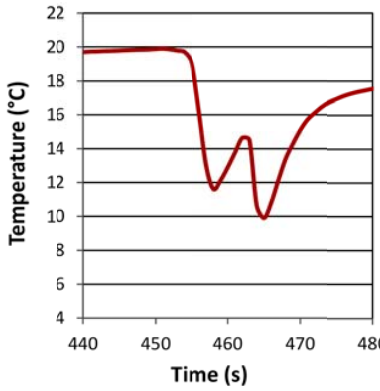


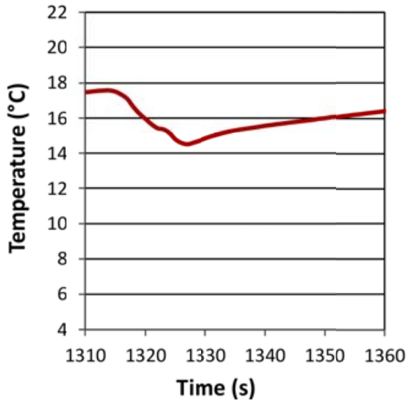
Fig. 9 Change of circularity along hole axis

In cryogenic drilling, where cryogenic liquid is externally applied on the workpiece, the hole size enlargement caused by the drill bit during drilling operation is further increased when the workpiece goes back to ambient temperature from a very low temperature during drilling. Therefore, a drop in workpiece temperate during drilling is an important factor influencing the size variation in externally applied cryogenic drilling. Typical workpiece temperature profiles for the three canned cycles used are illustrated in Fig. 10. The thermocouple was place at one corner of the workpiece; hence, the distances from the machined hole were different. Therefore, for this analysis, the temperature drop is considered rather than the actual measured temperature. To supplement this analysis, the change of the drilling thrust force for the canned cycles used for the same cutting conditions (feed rate = 0.2 mm/rev and cutting speed 60 m/min) is included (see Fig. 11).

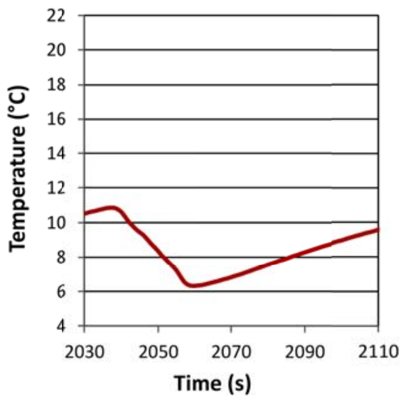
Fig. 10 shows that the temperature drop in G73 is about three times higher than in G81. This is due to the fact that in G73, the machining time is higher than in G81 (see Fig. 11 (a)), which allows the application of more coolant on the same hole. The cooling action in G73 is further increased as the coolant is trapped in the hole during pecking because the drill is not completely withdrawn from the hole. In case of G83, the machining time is higher (see Fig. 11 (c)); however, the temperature drop is slightly more than in G81 because in this case, the drill bit is completely withdrawn from the hole; as a result, coolant is not directed at the hole during this period.



(a)



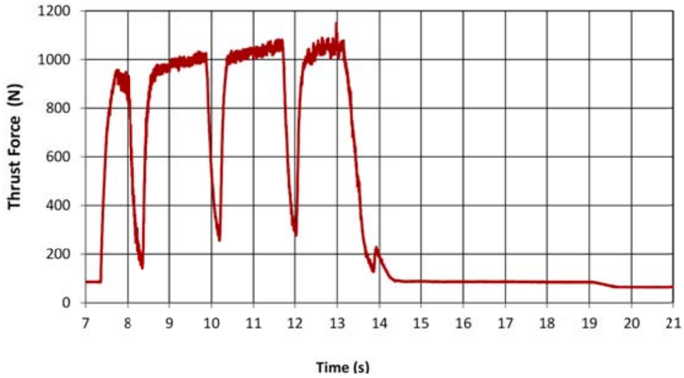
(b)



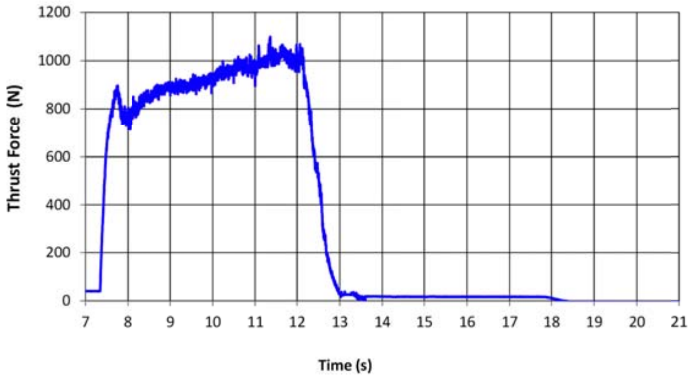
(c)

Fig. 10 Typical workpiece temperature profiles: (a) G73: 10.00 °C drop, (b) G81: 3.07 °C drop and (c) G83: 3.99 °C drop

In cryogenic drilling the cutting force components are increased with the drop of workpiece temperature, as most materials show much more resistance to deformation at a lower temperature. Fig. 11 shows that G73 produced the highest thrust force which is due to the highest workpiece temperature drop (Fig. 10). It is also worth noting that in case of G83 after each pecking step thrust force went back to its base level, whereas in case of G73 it gradually increased. The opposite nature of the diameter variations (Fig. 8) and circularity variations (Fig. 9) can be explained by the fact that with workpiece temperature drop diameter error was increased due to subsequent expansion of the workpiece, whereas circularity was reduced as more resistance to deformation at lower temperature restricts the rotational error of the dril.



(a)



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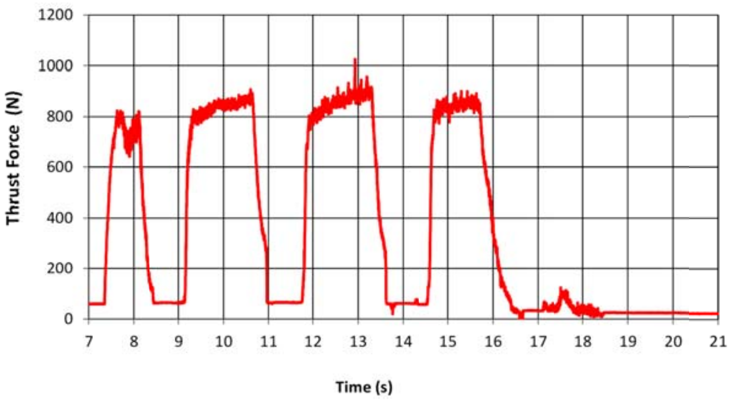

(c)

Fig. 11 Effect of canned cycle on drilling thrust: (a) G73, (b) G81 and (c) G83

VII. Concluding Remarks

The research presented in this paper demonstrates that canned cycles significantly influence diameter error. G83 produces a marginally better diameter error than G81; however, compared to G83 and G81, G73 produced two times larger diameter errors. Canned cycles have a relatively small effect on circularity. The best results for the circularity were achieved by G73. Compared to G73, G81, and G83 produced substantially worse circularity. Canned cycles have the minimum effect on surface roughness. G83 provides the best surface finish, followed by G73 and G81.

This research demonstrates that in cryogenic drilling where coolant is applied externally, achieving the required dimensional accuracy will be a major challenge due to the rapid and uncontrolled cooling of the workpiece. Future work is required for developing a predictive model needed to overcome this challenge.

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