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ORIGINAL ARTICLE

Experimental study of inverted drilling Al-7075 alloy

Jin-Yih Kao[1] · Chun-Yao Hsu[1] · Chung-Chen Tsao[1]

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Abstract
Al-7075 alloys are drilled using an inverted drilling method to investigate the effect of hole performances (enlargement, roundness, and surface roughness). Additionally, this study uses a gray-Taguchi methodology to optimize the multiple performance characteristics for the machining parameters in the dry drilling of Al-7075 alloy. The experimental results indicated that holes are enlarged using TiAlN- and TiN-coated drills by only 68.9% and 75.0% more than if an uncoated drill is used. The analysis of variance (ANOVA) results for the multiple performance characteristics in dry drilling Al-7075 alloys show that the spindle speed has a significant effect among all drilling parameters. Uncoated drill experiences the maximum wear, followed by the TiN-coated drill and then the TiAlN-coated drill. In an inverted drilling machine arrangement, chips fall out of the workpiece that is being drilled to prevent chips clogging and tool wear caused by secondary cutting. The values for the enlargement, roundness, and surface roughness for the inverted drilling are 95.5%, 88.8%, and 83.0% that for standard drilling, respectively. Using inverted drilling creates better hole quality and less tool wear than standard drilling.

Keywords Al-7075 alloy · Inverted drilling · Gray-Taguchi methodology · Dry drilling · Coated drill

1 Introduction

Drilling with twist drills, which can be applied to various materials to generate a through hole, is one of the commonly used machining processes in many industrial components [1]. It is, however, a fact that chips to fall from the drill can produce clogging during drilling a blind hole. So, an inverted drilling is a well choice to prevent the chips clogging and tool damage in drilling a blind hole in aerospace, mold (or die) automotive, and other industries. However, the application of the inverted drilling has some limitations because of the clamped difficulty of workpiece, especially for large-scale parts. Drilling involves two types of processes: chip formation, including extrusion operations that are caused by a wedge point drill, and a shearing process that is caused by the cutting edge of the drill [2]. Belluco et al. [3] reported that the best performance for drilling austenitic stainless steel with HSS-Co tools was obtained using cutting oil, yielding a 177% increase in tool life and 7% decrease in thrust force, respectively. Dolinsek [4] studied the chip transformation process on the cutting edges using a quick-stop device for the drilling processes to establish a cutting model for the drilling austenitic stainless steels.

Traditional experimental tests require a large number of experiments and data to determine which parameter (or process) significantly affects the performance characteristics. The Taguchi method is a powerful optimization tool that increases experimental efficiency and extensively used to design and improve product (or process) quality in various industries [5]. Kurt et al. [6] utilized the Taguchi experimental design and an analysis of variance (ANOVA) to measure the effect, the contribution, the significance, and the optimal dry drilling parameter settings. The characteristics of the drilling processes were estimated, included the surface finish and hole diameter accuracy. Shivapragash et al. [7] focused on the material removal rate and surface roughness for the dry drilling of Al-$TiBr_2$. On the other hand, the gray relational analysis (GRA) based on gray theory can solve the complicated interrelationships between various response factors under poor, incomplete, and uncertain information [8–10]. Tarng et al. [9]

✉ Jin-Yih Kao
jykao@mail.lhu.edu.tw

✉ Chung-Chen Tsao
aetcc@mail.lhu.edu.tw

[1] Department of Mechanical Engineering, Lunghwa University of Science and Technology, Taoyuan 33306, Taiwan

Table 1 Drilling parameters and their levels

Type of operation		Blind hole		
Machine		Automatic drilling machine (KSA-16 B)		
Workpiece material		Al-7075		
Workpiece dimension		300 mm × 200 mm × 50 mm		
Twist drill diameter		5 mm (HSS)		
Cooling and lubrication		Dry		
Symbol	Level	1	2	3
A	spindle speed (rpm)	910	1420	2000
B	feed rate (mm/rev)	0.06	0.08	0.10
C	depth of pecking (mm)	4	5	6

investigated submerged arc welding process parameters in hardfacing by gray-Taguchi methodology. Prasanna et al. [10] utilized Taguchi and gray relational analysis to optimize the process parameters of small hole in dry drilling Ti-6Al-4V alloy.

Al-Zn-Mg-Cu (7xxx series) alloys, which have the highest strength of all aluminum alloys, are used in aerospace because of their outstanding mechanical properties and relatively good resistance to corrosion and fatigue [11]. Cakıroglu et al. [12] studied the drilling parameters (cutting speed, feed rate, and cutting tool) for cutting Al-7075 alloy, using the Taguchi method with an L_{18} orthogonal array. They proved that the empirical equations are a good agreement with experimental results using optimized drilling parameters. Chen et al. [13] showed that the Taguchi method gives enhanced machining efficiency on surface roughness for an end-milled Al 7075-T6 alloy. Braic et al. [14] reported that using various coated tools (TiN, TiAlN, and TiAlZrN) on dry drilling can improve machining performance (tool life and flank wear) over that for uncoated drills.

This study combines the Taguchi method and gray theory to optimize the multiple quality performances for dry drilling of Al-7075 alloy using high-speed steel (HSS) twist drills. In order to understand the effects for the dry drilling Al-7075 alloy, three control factors (spindle speed, feed rate, and depth of pecking), each at three levels, are considered in this study. Table 1 shows the control factors and their levels for the dry drilling Al-7075 alloy. Additionally, an inverted drilling device was used to investigate the drilling behavior of the curved cutting edge of the TiN- and TiAlN-coated twist drills on the enlargement, roundness, and surface roughness during the dry drilling of Al-7075 alloy. However, there is no much literatures and information available regarding the influence of an inverted drilling method in dry drilling Al-7075 alloy owing to their tendency to machining quality when the drilling device subjected to opposite position.

2 Experimental details

Al-7075 alloy plates were used in the dry drilling experiments as the workpiece material. The mechanical and physical properties, as well as chemical composition of Al-7075 alloy, are given in Table 2 [15]. Experimental tests were conducted on a traditional automatic drilling machine (KSA-16B) using dry drilling conditions. All experiments were performed twice. Tool wear was measured using a microscope that is equipped with an X-Y table and an electronic gauge. The surface

Table 2 The mechanical and physical properties, as well as chemical composition of Al-7075 alloy

Mechanical and physical properties				
Parameter		Values		
Density (g/cm^3)		2.81		
Hardness (HB)		60.0		
Ultimate tensile strength (MPa)		228		
Tensile yield strength (MPa)		103		
Elongation at break (%)		16.0		
Chemical composition (wt.%)				
Si (0.4)	Fe (0.5)	Cu (1.2–2.0)	Mn (0.3)	Mg (2.1–2.9)
Cr (0.18–0.28)	Zn (5.1–6.1)	Ti (0.2)	Others (0.15)	Al (balance)

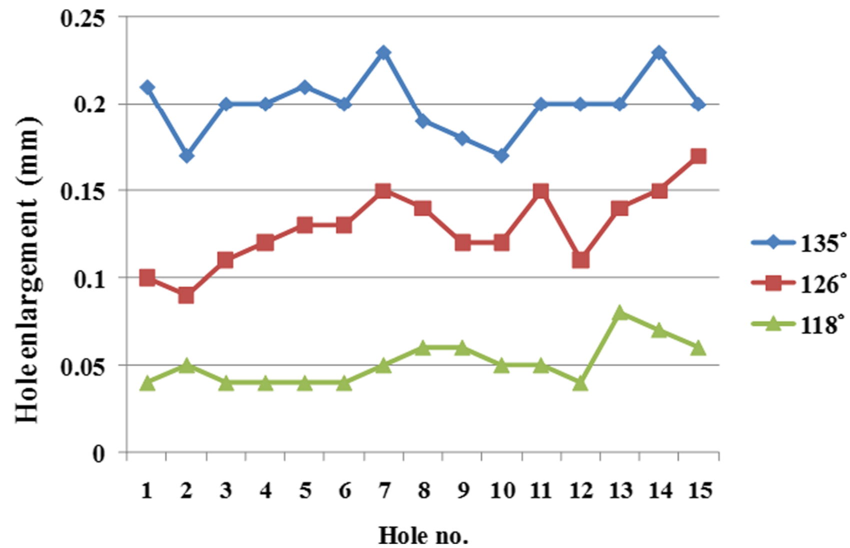

Fig. 1 The comparison of various point angles on enlargement (fixed lip clearance angle of 12°)

roughness (Ra) of Al-7075 alloy was measured by surface profilometer along the depth of the drilled hole. The sample of Al-7075 alloy was cut along the direction of hole diameter.

For comparison purposes, TiN and TiAlN films were coated onto HSS twist drills, respectively, using pulsed direct current (DC) magnetron sputtering in a mixture of Ar plasma and N_2 reactive gas, with pure Ti and Al metal targets (99.95%, diameter of 76 mm). The coating parameters were DC power (200 W), base pressure (5.0×10^{-6} Torr), sputtering pressure (2.5×10^{-2} Torr), pulse time (2 μs), and pulse frequency (25 kHz). The thickness of the TiN- and TiAlN-coated film was around 313 and 308 nm, respectively.

2.1 Analysis of the signal-to-noise ratio

The Taguchi method uses the S/N ratio to determine the performance of the process response. For experimental response variables (enlargement, roundness, and surface roughness) in this study, the S/N ratios of the lower the better (LB) are calculated using the following equations [16]:

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

where n is the number of observations and y_i represents the measured experimental value (i.e., enlargement, roundness, and surface roughness). The S/N ratio is expressed in decibels (unit: dB).

2.2 Analysis of variance

An ANOVA and the F test are used to analyze the experimental data, in order to determine which drilling parameters significantly affect the performance characteristic [17].

$$S_m = \frac{(\sum\eta_i)^2}{9}, \quad S_t = \sum\eta_i^2 - S_m \tag{2}$$

$$S_A = \frac{\sum\eta_{Ai}{}^2}{N} - S_m, \quad S_E = S_T - \sum S_A \tag{3}$$

$$V_A = \frac{S_A}{f_A}, \quad F_{Ao} = \frac{V_A}{V_E} \tag{4}$$

where η_i is the η value for each experiment ($i = 1$–9), S_m is the sum of squares due to the means, S_T is the sum of squares due to the total variation, S_A is the sum of squares due to the parameter A (A = spindle speed, feed rate, and depth of pecking), η_{Ai} is the sum of the i^{th} level for the parameter A ($i = 1, 2, 3$), N is the repeating number of each level of parameter A, and S_E is the

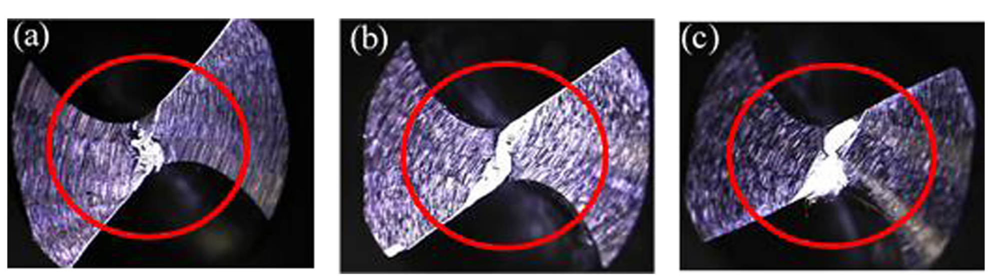

Fig. 2 Tool wear and BUE on chisel edge of twist drill at various point angles: **a** 118°, **b** 126°, and **c** 135° after drilled 15th hole

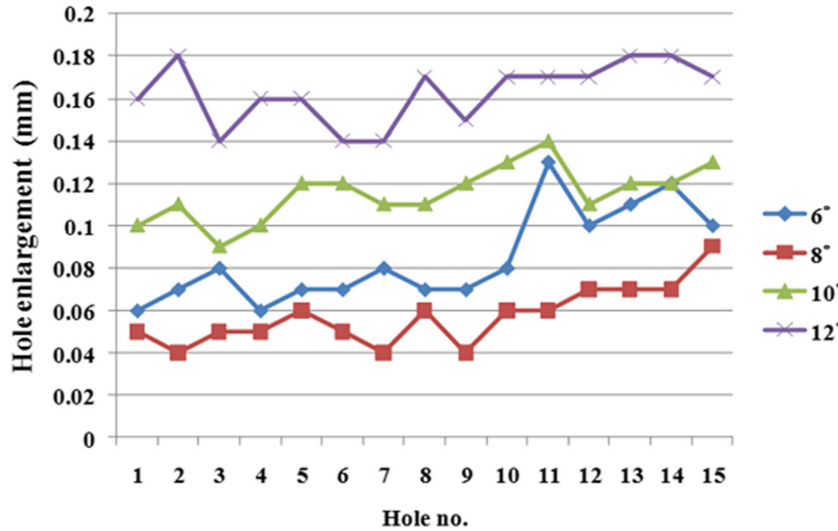

Fig. 3 The comparison of various lip clearance angles on enlargement (fixed point angle of 118°)

sum of the squares due to error. The values, f_A, V_A, V_E, and F_{Ao}, are the number of degrees of freedom, the variance, and the F test value for parameter, A, respectively.

2.3 Gray relational analysis

An orthogonal array with the gray relational analysis optimization methodology for multiple responses was used. The gray relational analysis is used to determine complicated interrelationships between multiple performance characteristics. The gray relational coefficient (GRC) is defined as [8]

$$r(x_o(k), x_i(k)) = \frac{\min_i \min_k |x_0(k)| + \zeta \max_i \max_k |x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \zeta \max_i \max_k |x_0(k) - x_i(k)|} \quad (5)$$

where $x_i(k)$ is the normalized value of the k^{th} performance in the i^{th} experiment and ζ is the distinguishing coefficient ($\zeta \in \lfloor 0, 1 \rfloor$). The value of ζ is adjusted according to the actual requirements of the system. The dry drilling parameters are equally weighted so the value of ζ is 0.5. The gray relational grade (GRG) is a weighting sum of the gray relational coefficient. It is defined as [8]

$$r(x_0, x_i) = \frac{1}{n} \sum_{k=1}^{n} r(r_0(k), x_i(k)) \quad (6)$$

where n is the number of performance characteristics. The calculated gray relational grade ranges from 0 to 1, which is called gray relational generation. Using gray relational analysis and an ANOVA, the optimal combination of dry drilling parameters can be predicted [8].

3 Results and discussion

3.1 Point angle and clearance angle

An Al-7075 alloy was drilled using a HSS twist drill of 5 mm in diameter, a spindle speed of 2000 rpm, a feed rate of 0.1 mm/rev, a depth of pecking of 5 mm, and a blind hole of 40 mm. Figure 1 shows the comparison of various point angles (118°, 126°, and 135°) on enlargement with a fixed lip clearance angle of 12°. The enlargement after drilled 15th hole is least for a point angle of 118°. Figure 2 shows the tool wear and built-up-edge (BUE) after drilled 15th hole, which often occurs at the tool tip and chip interface on chisel edge of

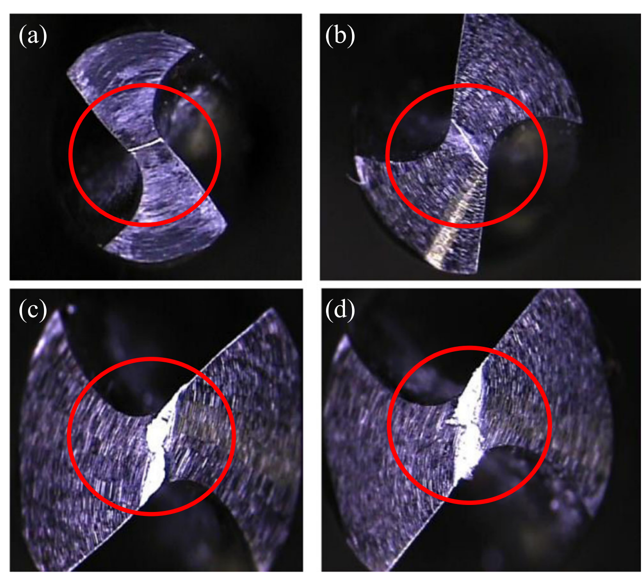

Fig. 4 Tool wear on chisel edge of twist drill at various lip clearance angles: **a** 6°, **b** 8°, **c** 10°, and **d** 12° after drilled 15th hole

Table 3 Experimental results and the S/N ratios of enlargement, roundness, and surface roughness for the dry drilling Al-7075 alloy

No.	Factors			Enlargement (μm)			S/N (dB)	Roundness (μm)			S/N (dB)	Surface roughness (Ra)			S/N (dB)
	A	B	C	104th hole	105th hole	Ave.		104th hole	105th hole	Ave.		104th hole	105th Hole	Ave.	
1	1	1	1	197	211	204	− 46.20	97	134	116	− 41.36	1.74	1.46	1.60	− 4.12
2	1	2	2	224	212	218	− 46.77	121	122	122	− 41.69	1.90	1.84	1.87	− 5.44
3	1	3	3	211	221	216	− 46.69	189	130	160	− 44.20	1.81	1.77	1.79	− 5.06
4	2	1	2	194	210	202	− 42.80	117	124	121	− 41.62	1.56	1.73	1.65	− 4.33
5	2	2	3	151	178	165	− 44.35	92	99	96	− 39.61	1.20	1.06	1.13	− 1.08
6	2	3	1	124	143	134	− 42.53	72	89	81	− 38.16	0.87	0.90	0.89	1.06
7	3	1	3	202	211	207	− 46.30	267	327	297	− 49.50	3.45	3.35	3.40	− 10.63
8	3	2	1	178	186	182	− 45.20	246	291	269	− 48.61	3.56	3.51	3.54	− 10.97
9	3	3	2	243	234	239	− 47.55	249	212	231	− 47.28	2.66	2.94	2.80	− 8.95

Note: A = spindle speed (rpm), B = feed rate (mm/rev), C = depth of pecking (mm)

twist drill for various point angles. As the point angle decreases, the enlargement (tool wear or BUE of chisel edge) decreases. It can be explained that the twist drill is characterized by a relatively high thrust force (or temperature) in drilling Al-7075 alloy due to the negative rake and null cutting speed at the chisel edge. Figure 3 shows the comparison of various lip clearance angles (6°, 8°, 10°, and 12°) on enlargement with a fixed point angle of 118°. A lip clearance angle of 8° gives the least enlargement from 0.056 mm (1st hole) to 0.095 mm (15th hole), as shown in Fig. 3. Figure 4 shows the tool wear on chisel edge of twist drill for various lip clearance angles after drilled 15th hole. As the lip clearance angle increases, the enlargement also increases. It can be explained that the strength of twist drill on the tip cannot suffer the high temperature caused by the rubbing and extreme pressure due to the increase lip clearance angle in drilling Al-7075 alloy.

Table 4 ANOVA results for the enlargement, roundness, and surface roughness

Factor	S/N ratio (dB)			Degree of freedom	Sum of square	Variance	Contribution (*P* %)
	Level 1	Level 2	Level 3				
Enlargement							
A	− 46.55	− 43.33	− 46.35	2	9.05	4.53	49.10
B	− 46.20	− 45.44	− 45.59	2	0.98	0.49	5.32
C	− 44.64	− 46.81	− 45.78	2	7.06	3.53	38.31
Error				2	1.34	0.67	7.27
Total				8	18.43		100
Roundness							
A	− 42.42	− 39.80	− 48.46	2	118.50	59.25	89.88
B	− 44.16	− 43.30	− 43.22	2	1.64	0.82	1.24
C	− 42.71	− 43.53	− 44.44	2	4.46	2.23	3.38
Error				2	7.25	3.63	5.50
Total				8	131.85		100
Surface roughness							
A	− 4.87	− 1.45	− 10.18	2	116.20	58.10	86.58
B	− 6.36	− 5.82	− 4.32	2	6.74	3.37	5.02
C	− 4.68	− 6.24	− 5.59	2	3.72	1.86	2.77
Error				2	7.55	3.78	5.63
Total				8	134.21		100

Table 5 The gray relational grade and its order in the optimization process

No.	Conditions	Gray relational grade	Order
1	$A_1B_1C_1$	0.6107	3
2	$A_1B_2C_2$	0.5607	5
3	$A_1B_3C_3$	0.5204	6
4	$A_2B_1C_2$	0.5998	4
5	$A_2B_2C_3$	0.7836	2
6	$A_2B_3C_1$	1.0000	1
7	$A_3B_1C_3$	0.3656	9
8	$A_3B_2C_1$	0.4062	7
9	$A_3B_3C_2$	0.3872	8

3.2 Dry drilling performance evaluation

Table 3 shows the results of enlargement, roundness and surface roughness, and their corresponding S/N ratios for the dry drilling of Al-7075 alloy. The enlargement ranges from 134 to 239 μm, the value for roundness ranges from 81 to 297 μm, and the surface roughness (Ra) ranges from 0.89 to 3.54 μm. Table 4 lists the results for the ANOVA of enlargement, roundness, and surface roughness. From Table 4, the spindle speed has the greatest effect on the enlargement ($P = 49.10\%$), the roundness ($P = 89.88\%$), and the surface roughness ($P = 86.58\%$), respectively. Higher spindle speed implies higher heat generated leading to higher rise in temperature. Tool wear is directly related with the amount of heat generated during drilling. Higher tool wear is associated with less machining quality characteristics (enlargement, roundness, and surface roughness) in the drilling region.

3.3 Multiple response optimization

Using gray relational analysis and the ANOVA results, the optimal combination of drilling parameters can be predicted. Using Eqs. (5) and (6), the gray relational grade for each experiment in the L_9 orthogonal array is shown in Table 5. A higher gray relational grade shows that the corresponding S/N ratio is closer to the ideal normalized value. Experiment No. 6 ($A_2B_3C_1$) has the best multiple performance characteristics because it has the highest gray relational grade. The optimal multiple performance characteristics are converted into a single gray relational grade [9]. Table 6 lists the gray relational analysis and ANOVA results for the multiple performance characteristics. It is seen that the spindle speed has the greatest effect to the multiple performance characteristics ($P = 83.17\%$). This is in agreement with the results of Prasanna et al. [10], who found that the spindle speed significantly affects the quality of the hole. Karabulut et al. [18] reported that surface roughness values are increased when a higher spindle speed is used to machine aluminum alloy. This may be attributed to the formation of a BUE. The effect of each drilling parameter on the gray relational grade at different levels can be distinguished because the experimental design is orthogonal. The mean value of the gray relational grade for each drilling parameter level is shown as a response graph in Fig. 5. The predicted optimal drilling parameter for multiple performance characteristics is the combination $A_2B_3C_1$ (experimental No. 6, that is, 1420 rpm spindle speed, 0.10 mm/rev feed rate, and 4 mm depth of pecking). Under dry cutting conditions, the BUE chips easily form at a low spindle speed or adhere to the chips on cutter edges at a high spindle speed. For any drill rotational speed and for a fixed diameter, the hole performances during drilling decrease with increase feed rate. The increase in feed value induces greater damages on the enlargement, roundness, and roughness. It is understood that to decrease the depth of pecking, the contact length and metal being cut and cutting force are decreased too. However, the deforming and frictional forces at the cutting edge and the formation of chip thickness remain consistent at an

Table 6 Gray relational analysis and ANOVA results for the multiple performance characteristics

Factors	S/N ratio (dB)			Degree of freedom	Sum of squares	Variance	Contribution (P %)
	Level 1	Level 2	Level 3				
A	−4.994	−2.186	−8.269	2	55.61	27.81	83.17
B	−5.821	−4.990	−4.638	2	2.21	1.11	3.31
C	−4.036	−5.902	−5.510	2	5.81	2.90	8.69
Error				2	3.23	1.61	4.83
Total				8	66.86		100

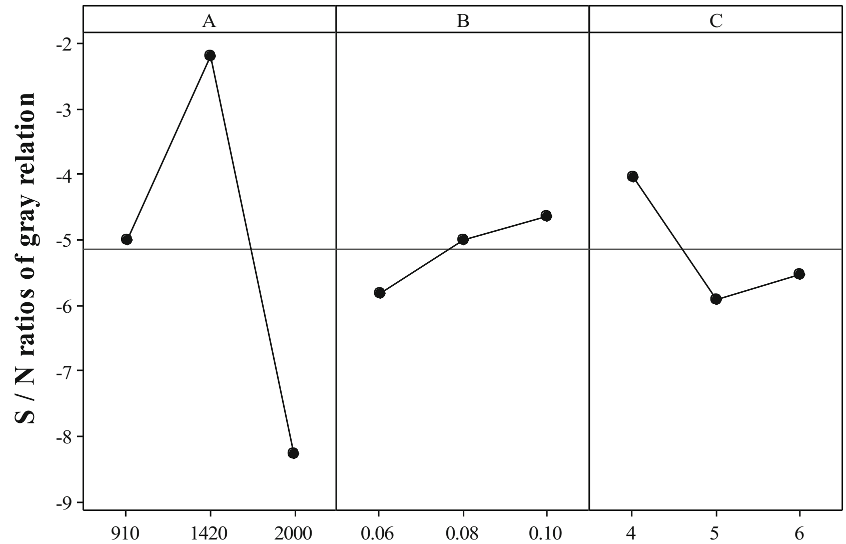

Fig. 5 The S/N graph for the gray relational grade

optimal drilling parameter. For a best multiple performance characteristics, an effective application of middle spindle speed, small feed rate, and small depth of pecking is needed in drilling Al-7075 alloy in this study. In the confirmation runs, the 105th drilled hole exhibits the least enlargement at about 134 μm, with a roundness of about 81 μm and a surface roughness (Ra) about 0.89 μm, as shown in Table 2.

(a)

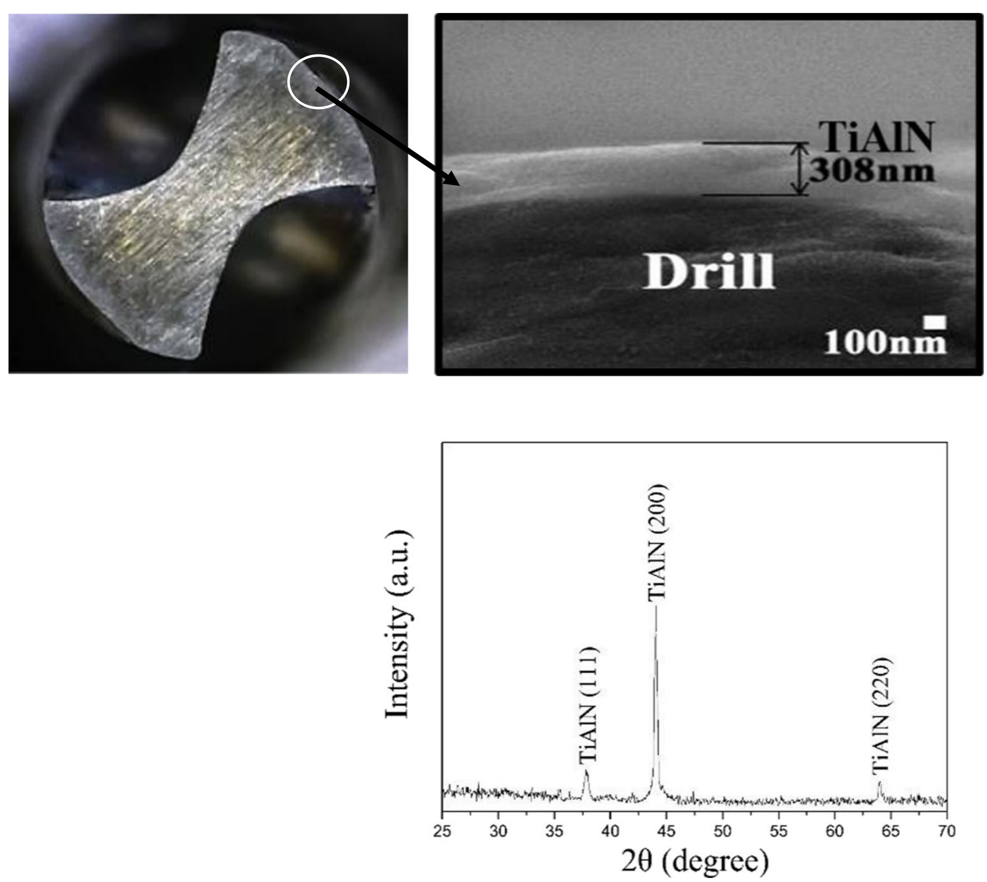

Fig. 6 SEM micrographs for the drill tool: **a** coated with a TiAlN film (308 nm) and **b** coated with a TiN film (313 nm)

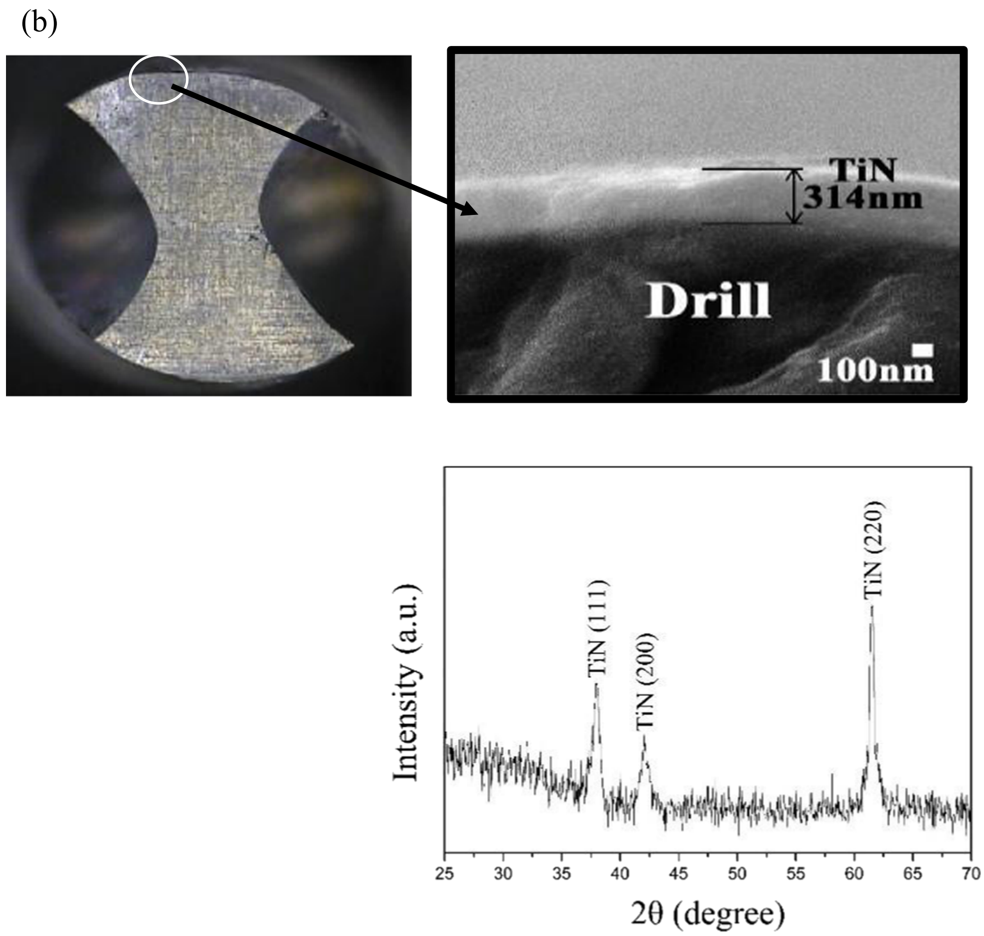

Fig. 6 (continued)

3.4 Coating TiN and TiAlN onto HSS drill

A TiN film (thickness ~313 nm, hardness ~19.8 GPa) and a TiAlN film (thickness ~308 nm, hardness ~22.3 GPa) were coated onto the drill surface using pulsed DC reactive magnetron sputtering. Figure 6 shows the SEM micrographs for the HSS twist drill and its XRD diffraction patterns. Both nitride film coatings show a cubic structure with preferred orientation (111) for TiN film and (200) for TiAlN film. This is in agreement with the results of Casas

Table 7 Hole performances of uncoated and coated cutting tools for the dry drilling of Al-7075 alloy, using the optimal drilling parameters ($A_2B_3C_1$)

Hole no.	Enlargement (μm)			Roundness (μm)			Surface roughness (Ra)		
	TiAlN	TiN	Uncoated	TiAlN	TiN	Uncoated	TiAlN	TiN	Uncoated
10th	74	75	77	41	42	45	0.22	0.26	0.40
20th	75	79	83	43	45	47	0.23	0.28	0.45
30th	76	79	87	44	47	52	0.30	0.36	0.52
40th	80	81	94	47	51	66	0.35	0.40	0.60
50th	80	82	98	50	55	62	0.39	0.45	0.65
60th	84	83	112	56	60	68	0.42	0.47	0.72
70th	85	89	121	57	61	70	0.47	0.49	0.80
80th	88	94	127	58	63	77	0.50	0.55	0.83
90th	90	97	131	60	65	79	0.54	0.62	0.86
100th	91	99	132	61	67	80	0.61	0.68	0.88
	68.9%	75.0%		76.3%	83.8%		69.3%	77.3%	

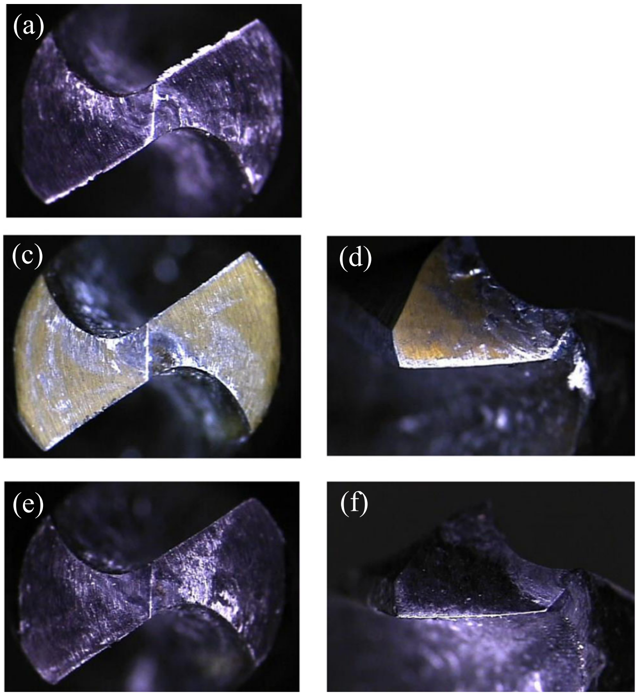

Fig. 7 Tool wear images after drilled 100th hole: **a**, **b** uncoated, **c**, **d** TiN-coated, and **e**, **f** TiAlN coated

et al. [19]. The hole performances (enlargement, roundness, and surface roughness) for uncoated and coated cutting tools were determined for the dry drilling of Al-7075 alloy, using the optimal drilling parameters ($A_2B_3C_1$) that are detailed in Table 7. Table 7 shows the relationship between hole performances for the drills and the number of holes made. The greater the number of holes that is drilled, the poorer is the hole performances for the drills. The hole performances for the three types of drills at the 100th drilled hole is compared. The amount of enlargement by TiAlN- and TiN-coated drills were only 68.9% and 75.0% of the uncoated drills, respectively. The roundness by TiAlN- and TiN-coated drills were 76.3% and 83.8% of the uncoated drills, respectively. The surface roughness by TiAlN- and TiN-coated drills were only 69.3% and 77.3% of the uncoated drills, respectively. Figure 7 shows the tool wear images after drilled 100th hole. The maximum tool wear increases with the number of holes that is drilled. The uncoated drill experiences the maximum wear, followed by the TiN-coated drill and the TiAlN-coated drill experiences the least wear. This is because the TiAlN coating film has a higher hardness than the TiN coating film.

3.5 Standard and inverted drilling using an uncoated tool

Figure 8 shows the experimental set-up for inverted drilling, using a drilling machine wherein the rotating drill spindle is

Fig. 8 Experimental set-up for inverted drilling

fed upward the workpiece to a 40 mm depth. Table 8 lists the performances for standard and inverted dry drilling of Al-7075 alloy (uncoated drill), using the optimal drilling parameters ($A_2B_3C_1$). It is seen that the greater the number of holes that is drilled, the poorer is the hole performances for the drills. The hole performances for the standard and inverted drilling at the 100th hole that is drilled show that the enlargement, roundness, and surface roughness for inverted drilling are 95.5%, 88.8%, and 83.0% of the respective values for standard drilling. Inverted drilling means that the chips fall out of the workpiece that is being drilled to prevent chips clogging and tool wear. Using inverted drilling creates less risk on tool wear

Table 8 Performance of standard and inverted dry drilling of Al-7075 alloy (uncoated drill), using the optimal drilling parameters ($A_2B_3C_1$)

Hole no.	Enlargement (μm)		Roundness (μm)		Surface roughness (Ra)	
	Standard	Inverted	Standard	Inverted	Standard	Inverted
10th	77	76	45	40	0.40	0.39
20th	83	79	47	44	0.45	0.41
30th	87	81	52	51	0.52	0.45
40th	94	82	66	53	0.60	0.49
50th	98	86	62	55	0.65	0.55
60th	112	93	68	57	0.72	0.57
70th	121	101	70	60	0.80	0.62
80th	127	113	77	65	0.83	0.68
90th	131	124	79	69	0.86	0.71
100th	132	126	80	71	0.88	0.73
		95.5%		88.8%		83.0%

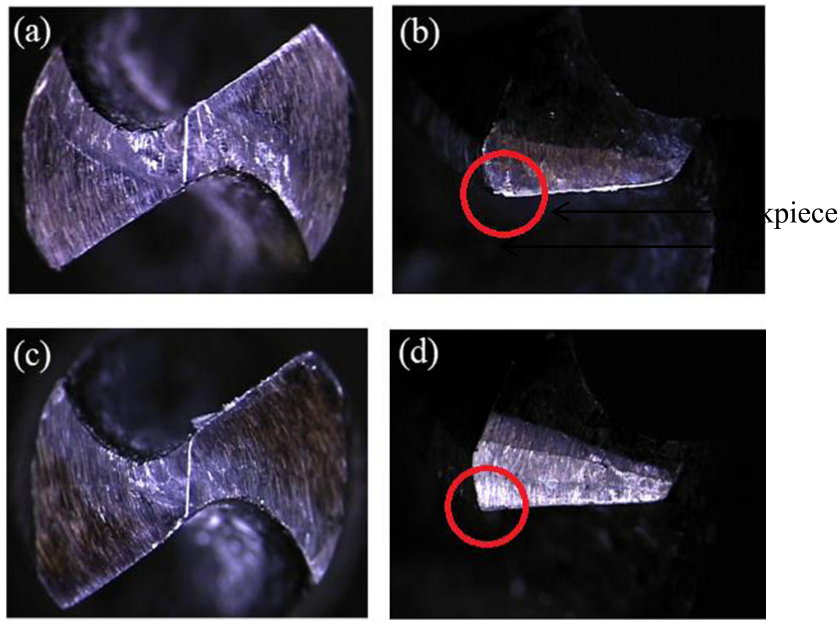

Fig. 9 Uncoated tool wear images: **a**, **b** standard drilling and **c**, **d** inverted drilling

than standard drilling, as shown in Fig. 9. The difference in tool wear is more significant as the number of holes that is drilled increases.

4 Conclusions

Gray-Taguchi optimization technique has produced a unique and powerful optimization discipline that differs from traditional practices. The two-stage effort of obtaining the multiple performance characteristics by gray-Taguchi methodology has resulted in a fairly useful method of obtaining process parameters with an inverted drilling process in order to obtain the machining quality for the dry drilling of Al-7075 alloy in this study. The ANOVA results for the multiple performance characteristics in dry drilling show that the spindle speed has a significant effect. In the confirmation runs, it is shown that multiple performance characteristics can be improved by using the gray-Taguchi methodology. The respective surface roughness for TiAlN- and TiN-coated drills is only 69.3% and 77.3% of the value for an uncoated drill. The respective enlargement, roundness, and surface roughness for inverted drilling are 95.5%, 88.8%, and 83.0% of the values for standard drilling. The experimental results using optimized drilling parameters agree well with the industrial experience due to the TiAlN and TiN films with greater hardness and better thermal properties than uncoated twist drill. The advantage of inverted drilling illustrates the chips fall out of the workpiece that is being drilled to prevent chips clogging and tool wear rather than traditional drilling. This inverted drilling process can be extended to examine the effects of other machining process.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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