Feasibility of tool configuration and the effect of tool material, and tool geometry in multi-hole simultaneous drilling of Al2024

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Abstract

The use of the multi-spindle head in drilling technology can reduce the drilling cycle time by simultaneously producing multiple holes in one go. However, selecting the appropriate drill material and geometry is critical to overcoming the challenges of multi-hole drilling to ensure high-quality holes. This study investigates the use of the multi-spindle head with different tool configuration, tool materials and tool geometry during multi-hole simultaneous drilling of Al2024. A comparison is made among the high-speed steel drills (diameter: 6 mm, point angle: 118°) and two different carbide drills (diameter: 6 mm and 10 mm, point angle: 140°) as well as the maximum and minimum possible center to center tool distances of the multi-spindle head. The experiments are based on measuring the thrust force, evaluating the hole quality in terms of surface roughness and burrs, the formation of chips and post drilling tool conditions. The results showed that carbide drills with high point angle and smaller diameter generated less thrust force, produced higher quality holes, and formed less built-up edge due to short chips. Besides, tools of the multi-spindle head can be adjusted in any position without affecting the hole quality which is useful for increasing productivity at a higher rate in manufacturing industries.

Keywords: Multi-spindle head; Tool configuration; Tool material; Tool geometry; Hole quality

Nomenclature

B	:	Burrs
BUE	:	Built-up edge
CTCD	:	Center to center tool distance
D (mm)	:	Diameter
F (N)	:	Cutting force
f (mm/rev)	:	Feed
HSS	:	High-speed steel
n (rpm)	:	Spindle speed
R_a (μm)	:	Surface roughness
V_c (m/min)	:	Cutting speed
V_f (mm/min)	:	Feed speed
Y	:	Circularity error
Z (mm)	:	Hole size
θ (°)	:	Point angle
Ψ (°)	:	Clearance angle

1. Introduction

Drilling is the most important machining operation for producing holes in the production of a part [1]. The drilling process is used in many applications such as the aerospace, aircraft, and automotive industries

[2]. In automotive industries, 40% of the total material removal process is carried out using the drilling process [3]. Furthermore, it is estimated that in a medium-sized plane, 85,000 rivets are required for joining various parts of the aircraft to shape its final structure [4]. In addition, around 2000 holes are needed in the flap skins of the aircraft to attach them to the frame [3]. The problem in the drilling process arises due to high cutting forces, high surface roughness (R_a), the formation of burrs, generation of long and thick chips, as well as deviation from hole size and circularity error [3]. In addition, the built-up edge (BUE) and the tool wear are other issues in most of the drilling processes where the selection of appropriate tools are required that add additional cost to the manufacturing industries [5]. Therefore, to obtain high dimensional accuracy and long tool life, drilling performance depends on many factors such as the drill and work-piece materials, the drill geometry, the cutting speed (V_c) and the feed rate (f), presence or absence of coolants, and the type of drilling machine [6, 7].

Various drills are available in the industry depending on the application where the most common is the high-speed steel (HSS) and carbide tools [8]. Regarding the drill types, the twist drill remains the most economical choice for hole making where the point angle, helix angle and drill size are important [9]. In this regard, many researchers have studied the influence of drill type, drill geometry and drill materials under a variety of drilling parameters and conditions, some details of past studies are summarized in Table 1.

Table 1 Studies on tool material and tool geometry using one-shot drilling process

Material	Drilling parameters/Tools	Objective	Reference
Al2024	HSS (coated and uncoated) $V_c = 30, 45$ and 60 $f = 0.15, 0.20$ and 0.25 $\theta = 118^\circ$, and 130° $D = 10$	R_a, Z, Y	[10]
Al7075	HSS drills $V_c = 4, 12$, and 20 $f = 0.1, 0.2$, and 0.3 $\theta = 90^\circ, 118^\circ$, and 135° $D = 5$	B, R_a	[11]
Al2024, Al7075, Al7050	HSS $V_c = 20, 30$ and 40 $f = 0.05, 0.1$, and 0.15 $D = 8, 10$, and 12	B, R_a	[12]
Al-6061, Al-6351, Al-7075	HSS $n = 90, 200, 250$, and 400 $f = 0.15, 0.2, 0.3$, and 0.36 $D = 10$ $\theta = 90^\circ, 118^\circ$	F, Z	[13]
Al6061	HSS $n = 600, 800$, and 1000 $V_f = 0.3, 0.5$, and 0.6 $D = 8, 10$, and 12 $\theta = 100^\circ, 110^\circ$, and 118° $\Psi = 4^\circ, 6^\circ$, and 8°	F	[14]
Al7075	Tungsten carbide $V_c = 40, 80$ and 120	R_a	[15]

	$f = 0.05, 0.1, \text{ and } 0.15$		
	$\theta = 120^\circ, 130^\circ, \text{ and } 140^\circ$		
	$D = 5$		
Al7075	Tungsten carbide	F	[16]
	$V_c = 40, 80 \text{ and } 120$		
	$f = 0.05, 0.1, \text{ and } 0.15$		
	$\theta = 120^\circ, 130^\circ, \text{ and } 140^\circ$		
	$D = 5$		
Al6061	$n = 2500, 3750, \text{ and } 5000$	R_a	[17]
	$f = 0.08, 0.1, \text{ and } 0.12$		
	$D = 8, 10, \text{ and } 12$		

Cutting forces: F (N), Cutting speed: V_c (m/min), Feed rate: f (mm/rev), Feed speed: V_f (mm/min)
Diameter: D (mm), Surface roughness: R_a (μm), Circularity error: Y , Hole size: Z (mm), Burrs: B , Spindle speed: n (rpm), Point angle: θ ($^\circ$), Clearance angle: Ψ ($^\circ$),

For instance, Kurt et al. [10] concluded that higher V_c and f led to higher values of R_a and roundness due to an increase in drilling temperatures, vibrations and chatter. Apart from hole size, the effect of the drill point angle was found insignificant on R_a or hole roundness. Kilickap [11] has concluded that low burr height and low R_a were obtained at low V_c and f , and a high point angle. The burr height was more affected by the point angle followed by the f , and V_c whereas the R_a was more influenced by the V_c followed by the point angle and less affected by the f . Köklü [12] has concluded that a combination of low V_c , f and small drill diameter minimized the burr height and lowered the R_a . In case of the burr height, the f was a significant factor to its increase while the V_c had a major contribution in increasing the R_a . It was also investigated that the drill diameter showed a lower impact on hole quality; however, the best results were examined at the lowest drill diameter. In another study by Reddy et al. [13], it was concluded that low spindle speed, low f and a low point angle contributed to a less diametral error and lower values of R_a . The thrust force was more affected by the spindle speed while the impact of point angle on thrust force and hole quality was found insignificant. However, the authors did not give any reason on the significance of either the drilling parameters or tool geometry on the thrust force and hole quality. Furthermore, in a study by Sreenivasulu and Rao [14], different drilling parameters and tool geometry were considered to perform one-shot drilling experiments on Al6061. The authors reported that the thrust force was more affected by the V_c . Other significant factors include the point angle, followed by the f and drill diameter. Besides, the clearance angle was found insignificant on the thrust force. Furthermore, the torque was affected in a sequence of point angle, V_c , clearance angle, drill diameter and f . However, the authors did not discuss their results to show the significant impact of process parameters on thrust force and torque. Yaşar et al. [15] found that the R_a was more affected by the V_c followed by f while the point angle showed less impact on the R_a . It was also discussed that high V_c and f were responsible for higher R_a . However, the best values of lower R_a were obtained at a point angle of 130° . Gunay et al. [16] used the same drilling parameters in one-shot drilling of Al7075; however, their investigation was on the thrust force. It was reported that the highest contribution to thrust force was due to the f with minimal impact of point angle and V_c . Son and Nguyen [17] concluded that during one-shot drilling process of Al6061, the R_a was more affected by the spindle speed followed by the drill diameter while the f was found less

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4 influential on the R_a . However, the study did not show any reason for how the different drilling parameters
5 affected the R_a of holes drilled in Al6061.
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7 The above studies indicated that drilling parameters, tool materials and tool geometry have a direct
8 impact on the cutting forces and hole quality metrics such as R_a , burr formation, circularity and hole size.
9 Therefore, to obtain good quality holes, a suitable combination of drilling parameters along with
10 appropriate drill material and drill geometry is required. Previous studies also showed that most of the
11 work was based on one-shot drilling process, while none of the studies focused on multi-hole drilling
12 which is one of the needs for manufacturing industries for increasing productivity without a compromise
13 on hole quality.
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16 A multi-spindle head or poly-drill head carry multiple tools and can perform simultaneous machining
17 operations such as drilling, countersinking, reaming, or tapping two or more holes in one operation [18-
18 20]. In our previous study [21], multi-spindle drilling process was compared with one-shot single drilling.
19 The drill selected was HSS with a point angle of 118° and a diameter of 6 mm. The testing material was
20 Al5083. It was concluded that lower values of R_a , and small burrs were obtained in multi-spindle drilling.
21 In addition, low BUE on tools was observed due to the formation of short and well-broken chips. Most
22 importantly, the cycle time was reduced in multi-spindle drilling which has a direct impact on higher
23 productivity. In another study [22], the Taguchi method and fuzzy logic approach were used for the
24 optimization and prediction of drilling parameters in multi-hole drilling process. It was also found that the
25 low V_c and f should be used as optimized drilling parameters for better hole quality. However, more
26 research is needed to find appropriate drill material, drill type and geometry to further improve the drilling
27 process in multi-spindle simultaneous drilling process.
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30 Therefore, in this study, a comparison between the two drill materials, which include HSS and carbide,
31 were made in terms of a point angle, drill size and tool configuration. The tool type selected was a twist
32 drill with different drill geometry. The point angle and drill size of the HSS drills were 118° and 6 mm,
33 while that of carbide drills were, 6 and 10 mm size with a point angle of 140° . The HSS and carbide drills
34 of diameter 6 mm were compared with different point angles of 118° and 140° . The carbide drills with a
35 point angle of 140° were compared with a diameter of 6 mm and 10 mm. In addition, the performance of
36 the multi-spindle drilling was checked by the adjustment of different tool arrangements based on
37 maximum and minimum possible center to center distances using carbide drills of diameter 6 mm and a
38 point angle of 140° . The study aims to perform multi-hole drilling tests, a drilling technology which is rarely
39 discussed in previous literature. To fill this gap in the literature, the performance of multi-hole drilling
40 process was assessed with different tool materials, tool geometry and tool configuration. The study would
41 be useful for manufacturers who are interested in increasing their productivity. Finally, Analysis of
42 variance (ANOVA) was used to evaluate the percentage contribution of drilling input parameters on the
43 output parameters.
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2. Materials and methods

2.1. Workpiece material

The workpiece material used in this work was aluminium Al2024 with a thickness of 10 mm and a size of 150 x 200 mm². Al2024 is mainly used in the fuselage and wings of the aircraft due to its excellent fatigue and high tensile strength [23]. Furthermore, in one of our studies [24], Al2024 was suggested for better hole quality, the formation of short chips, and less built-up edges due to its good machinability in multi-hole simultaneous drilling process. Some of the details of Al2024 are given in Table 2 [25].

Table 2 Composition and properties of Al2024 [25]

Composition in wt% Al2024									
Element	Cu	Mg	Si	Fe	Mn	Z	Ti	Cr	Al
wt%	3.8-4.9	1.2-1.8	0.5	0.5	0.3-0.9	0.25	0.15	0.1	Balance
Properties of Al2024									
Ultimate tensile strength (MPa)			483		Machinability			70%	
Modulus of elasticity (GPa)			73.1		Thermal conductivity (W/m-K)			121	
Hardness, Brinell			120		Hardness, Vickers			137	

2.2. Cutting tools

The tools used in this study were HSS and carbide twist drills. The description of cutting tools is given in Table 3. The twist drill was selected because it represents an industrial standard [26]. The diameters of 6 mm and 10 mm were selected based on previous studies and come in the common range of tool size used in aerospace alloys [3]. HSS drill with a point angle of 118° was selected as they are the most commonly used [10] where the reason for the use of carbide tool is the combination of its high hardness and toughness [27]. Besides, a carbide drill with a high point angle and high helix angle is recommended dry drilling of Al2024 for better hole quality [28, 29].

Table 3 Cutting tools

Description of the drill bits			
Type	Twist drill	Twist drill	Twist drill
Material	HSS	Carbide	Carbide
Point angle	118°	140°	140°
Drill diameter (mm)	6	6	10
Helix angle	30°	30°	30°
Number of flutes	2	2	2

2.3. Machine setup and cutting parameters

The drilling experiments were performed on vertical milling machining using a multi-spindle head. The details of the manual milling machine are given in Table 4. The manual milling machine has a maximum spindle speed of the 3450 rpm and three constant feeds. Therefore, the spindle speeds selected in this

study were 1007, 2015, and 3025 rpm. The spindle speed on the manual milling machine was measured using a tachometer while the feed was adjusted each time from low, medium and high corresponds to 0.04, 0.08, and 0.14 mm/rev, respectively. The combination of these drilling parameters was considered based on the available spindle speed and feed of the vertical milling machine. Also, according to machinery's handbook [30], for twist drill with a diameter in the range of (3.175 – 6.35 mm), the recommended feed rate should be (0.05–0.15 mm/rev), where the higher values in the feed ranges should be used for soft materials like aluminium and brass.

Table 4 Specifications of manual milling machine

Manual milling machine			
Model			5KS, 5KV
Worktable	Table size		1270 x 254
	Travel (X, Y, Z)		780, 410, 490;450 (auto)
Spindle	Span of spindle to worktable		85–575
	Span of spindle: Centerline to column		50–640
	Spindle head swivel		45°
	Quill travel (mm/rev)		127
	Feed speed (mm/rev)		0.04/0.08/0.14
	Spindle speed (rpm)		65–3450
Spindle motor			3HP
Length x Width x Height			1740x1740x2370
Area			1520x2310x2370
Net Weight (Kgs)			1600
Maximum load of worktable (Kgs)			300
Maximum cutting capacity	Diameter of face mill		101.6
	Diameter of drill		19

2.4. Multi-spindle drill head and tool configuration

The multi-spindle drill head used in this study was an adjustable **SUNHER type MH 30/13** which has three flexible spindles that can give three holes at the same cutting conditions when a single hole is produced during one-shot drilling process. Therefore, a multi-spindle drill head can be used for the condition of higher productivity at a high rate [31]. The tools in the multi-spindle head can be adjusted in any position in a range of 39 -141 mm [32]; however, the maximum and minimum possible distances selected in this study were based on the area of the dynamometer. Therefore, the selected minimum and maximum center to center tool distances (CTCD) were 39 mm and 75 mm, respectively given in Figure 1. To complete our experiments using all drill types and configuration of tool arrangement, a total of 108 holes were drilled using a multi-spindle head without the use of coolant.

Figure 1 Tool arrangements in multi-spindle head

2.5. Measurement of thrust force

In this work, a 3-component piezoelectric Kistler type 9257BA force dynamometer was used for the measurement of thrust force. Although, there are other methods available in the literature for the measurement of cutting forces [33]; however, KISTLER dynamometer is widely used in industries due to its compact design, simple operation and robustness. The dynamometer is rustproof and safe against the cooling agent or splash water. In addition, the top plate of the dynamometer is integrated with thermal isolation; therefore, it is highly insensitive to temperature effects. The dynamometer has four 3-component sensors, each with three pairs of quartz plates that convert the forces into electric charges [34]. The charge amplifier then transforms the electric charges into the voltage signals through a high insulated cable. Finally, Kistler's DynoWare software is used for data processing [35]. In this study, type 5233A1 control unit and 5697A2 Kistler data acquisition system were used.

The dynamometer was firmly mounted on the machine bed and a support plate was placed on the top of the dynamometer to protect the dynamometer during the drilling process. The details of the support plate are given in Figure 2.

Figure 2 Support plate

2.6. Post machining experiments

The surface roughness of holes was measured using the surface roughness tester type TR200. The values were taken at a location of 0° , 90° , 180° , and 270° of hole edges and the average reading was considered, similar to our previous studies [21]. Besides, hole quality in terms of burrs was observed using a digital microscope. The microscope was connected to a computer via a USB. The microscope was adjusted at the top of each hole and images were captured at the entrance and the exit of the hole using Mic-Fi software. Furthermore, the post-machining tool conditions were examined using optical microscope type LEICA M80. All the details are described in Figure 3. Lastly, the size and length of the chips were visually analyzed.

Manual milling machine

Dynamometer type:
9257BA

Control unit type:
5233A1

Data acquisition type:
5697A2

Computer

Surface roughness tester

Digital microscope

Optical microscope

Figure 3 Experimental set-up

2.7. Design of experiments and Analysis of variance

The design of experiment is used to study the behaviour of two or more factors and identifies the most significant levels [36]. In this study, the number of factors includes spindle speed, feed and tool arrangement, drill diameter, or point angle for each experiment. For spindle speed and feed three numbers of levels were considered whereas two levels were used for tool arrangement, drill diameter, or point angle as per the requirement in this study. The experimental design is given in Table 5.

Table 5 Experimental design

Trial No	Spindle speed	Feed	Tool arrangement	Drill diameter	Point angle
			Carbide drill (D = 6 mm, $\theta = 140^\circ$)	Carbide drill (D = 6 mm, 10 mm) $\theta = 140^\circ$	HSS drill ($\theta = 118^\circ$) and Carbide drill ($\theta = 140^\circ$) D = 6 mm
1	1007	0.04	Max CTCT	6	118°
2	1007	0.04	Mini CTCT	10	140°
3	1007	0.08	Max CTCT	6	118°
4	1007	0.08	Mini CTCT	10	140°
5	1007	0.14	Max CTCT	6	118°
6	1007	0.14	Mini CTCT	10	140°
7	2015	0.04	Max CTCT	6	118°
8	2015	0.04	Mini CTCT	10	140°
9	2015	0.08	Max CTCT	6	118°
10	2015	0.08	Mini CTCT	10	140°
11	2015	0.14	Max CTCT	6	118°
12	2015	0.14	Mini CTCT	10	140°
13	3025	0.04	Max CTCT	6	118°
14	3025	0.04	Mini CTCT	10	140°
15	3025	0.08	Max CTCT	6	118°
16	3025	0.08	Mini CTCT	10	140°
17	3025	0.14	Max CTCT	6	118°
18	3025	0.14	Mini CTCT	10	140°

Finally, an analysis of variance (ANOVA) was used to find how much impact each input parameter has on the drilling output parameters. ANOVA is a useful statistical method for determining the impact of input parameters from experimental results in any machining process using an appropriate design of experiments [37]. ANOVA is a decision-making tool used to detect the significance of process parameters and their interaction on the response [38]. In this work, the considered process parameters were tool arrangement, drill diameter, and point angle whereas the responses were thrust force and surface roughness. ANOVA was run with a confidence interval of 95%, which is usually used by many past researchers. A confidence interval is a statistical term which is used to give a range around measurement and shows how precise or accurate the estimated statistics are measured [36]. A 95% confidence interval means that there is only a 5% chance of being the wrong estimation; therefore, the influence of each process parameter or other interactions on the responses is considered insignificant if their P-values were estimated at more than 0.05. Therefore, P-values can confirm the effect of process parameters on

responses [9]. Additionally, the percentage contribution gave the details of how much each process parameters are influential on the responses [39].

3. Results and discussion

3.1. Thrust force

The average thrust force generated during multi-spindle simultaneous drilling for the selected drills is illustrated in Figure 4. Results showed that as the feed increased the thrust force increases, irrespective of the drill types and tool arrangements. The spindle speed did not show any significant impact on the thrust force; however, as the spindle speed increased only a slight decrease or at high feeds, a slight increase was observed. The slight decrease in the thrust force due to an increase in spindle speed was due to an increase in the cutting temperature which affected the strength of the workpiece in the plastic deformation region and thus, cutting forces decreased [40]. According to Zhang et al. [41], during the drilling process, most of the heat in the plastic deformation zone and the surrounding regions at the interfaces between the tool, workpiece and chip caused the high temperature. The temperature is then partitioned between the tool and workpiece based on the thermal properties of their materials. However, the thermal conductivity of aluminium is high compared to other metals which limit the cutting temperature [42]. Therefore, the effect of the spindle speed on the thrust force was found to be insignificant. Moreover, Nouari et al. [28] observed that in terms of cutting speeds, a large increase in cutting temperature was predicted for cutting velocities superior to 170 m/min which is much higher than the cutting velocities used in the current study. Besides, the minor increase in the thrust force due to the increase in spindle speed was attributed to the increase in the number of holes which might have caused some tool wear. Thus, the tool experienced high tool-work friction which resulted in high energy consumption hence, the generation of higher thrust force [43]. Furthermore, the direct relation of the feed with thrust force was due to the increased thickness of the chips [44, 45] which not only increases the thrust force but also deteriorates the hole quality by increasing the surface roughness [46].

Figure 4 Average thrust force

Figure 4 also illustrates that the thrust force generated during the different tool arrangement of the multi-spindle head did not show any significant difference which reflects that all spindles of the multi-spindle head gave similar results at any adjusted position. Therefore, the multi-spindle head could be used for high productivity in any possible position. Moreover, the carbide drills with a size of 6 mm and a point angle of 140° showed the lowest thrust force in most of the drilling parameters as compared to the 6 mm HSS drill with a point angle of 118° . This is in accordance with Gunay et al. [16], wherein one-shot single drilling process, the smallest thrust force was obtained at the high point angle of 140° . Therefore, from experimental observations in this study along with the results from the previous study by Nouari et al. [29], the carbide drill was recommended as the best choice for dry drilling of Al2024.

Regarding the drill size, a comparison between 6 mm and 10 mm carbide drills with the same point angle of 140° have been made where the 6 mm carbide drill generated less thrust force than that measured from the 10 mm carbide drill. The generation of high thrust force of 10 mm drill was attributed to the increase in chip thickness because of covering the large cutting area. This finding is similar to the work of Köklü [12] where drills with the lowest size performed better in the drilling of aluminium alloys. Furthermore, the ANOVA result from Table 6 shows that the feed has the highest impact on thrust force as compared to the spindle speed, irrespective of the drill point angle and drill diameter. In addition, the drill diameter was found more influential on thrust force than the point angle. It should be noted that the tool arrangement did not have any effect on thrust force. The insignificant values could be found in Table 6 with p-values of more than 0.05 because the confidence interval selected in this study was 95 % [39].

Table 6 Analysis of variance for thrust force

Carbide drill (D = 6 mm, $\theta = 140^\circ$) Tool arrangement							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	13	702145	99.83%	702145	54011	177.56	0.000
Linear	5	694815	98.78%	694815	138963	456.83	0.000
n	2	304	0.04%	304	152	0.50	0.640
f	2	694508	98.74%	694508	347254	1141.57	0.000
TA	1	3	0.00%	3	3	0.01	0.926
2-Way Interactions	8	7330	1.04%	7330	916	3.01	0.151
$n \times f$	4	6119	0.87%	6119	1530	5.03	0.073
$n \times TA$	2	283	0.04%	283	141	0.46	0.659
$f \times TA$	2	929	0.13%	929	464	1.53	0.322
Error	4	1217	0.17%	1217	304	-	-
Total	17	703362	100.00%	-	-	-	-
Carbide drill (D = 6 mm and D = 10 mm, $\theta = 140^\circ$)							
Model	13	1482884	99.08%	1482884	114068	32.96	0.002
Linear	5	1434768	95.86%	1434768	286954	82.92	0.000
n	2	2018	0.13%	2018	1009	0.29	0.762
f	2	1090673	72.87%	1090673	545336	157.58	0.000
D	1	342078	22.86%	342078	342078	98.85	0.001
2-Way Interactions	8	48116	3.21%	48116	6015	1.74	0.311
$n \times f$	4	7000	0.47%	7000	1750	0.51	0.737
$n \times D$	2	6001	0.40%	6001	3000	0.87	0.487
$f \times D$	2	35115	2.35%	35115	17558	5.07	0.080
Error	4	13842	0.92%	13842	3461	-	-
Total	17	1496727	100.00%	-	-	-	-
HSS drill (D = 6 mm, $\theta = 118^\circ$) and Carbide drill (D = 6 mm, $\theta = 140^\circ$)							
Model	13	1295836	99.65%	1295836	99680	87.25	0.000
Linear	5	1241994	95.51%	1241994	248399	217.43	0.000
n	2	819	0.06%	819	409	0.36	0.719
f	2	1192201	91.68%	1192201	596100	521.77	0.000
θ	1	48975	3.77%	48975	48975	42.87	0.003
2-Way Interactions	8	53842	4.14%	53842	6730	5.89	0.052
$n \times f$	4	770	0.06%	770	193	0.17	0.944
$n \times \theta$	2	43	0.00%	43	21	0.02	0.981
$f \times \theta$	2	53029	4.08%	53029	26515	23.21	0.006
Error	4	4570	0.35%	4570	1142	-	-
Total	17	1300406	100.00%	-	-	-	-

Spindle speed: n (rpm), Feed: f (mm/rev), Diameter: D (mm), Point angle: θ ($^\circ$), Tool arrangement (TA)

3.2. Evaluation of the hole quality

3.2.1. Surface roughness

The surface roughness of holes with different tool configuration, tool materials and tool geometry is shown in Figure 5. In general, the experimental results under different drilling parameters showed that the

surface roughness of holes drilled in Al2024 increased with the increase in spindle speed and feed, regardless of the drill types and tool arrangements. The lowest surface roughness during simultaneous drilling of Al2024 was obtained at the low spindle speed and feed in all drills and tool arrangements. The reason for high surface roughness at the high spindle speed and feed was expected due to: the rise in temperature at a high spindle speed which might have increased deformation of the workpiece [3], the increase in vibration faced by the tool [10], increase in material removal rate at high feed [47] and increase in the thickness of the chips by the feed [48].

Figure 5 Surface roughness

Figure 5 also illustrates that holes machined using carbide drills gave better surface roughness than holes produced using HSS drills. This result is in agreement with Nouari et al. [29] where it was concluded that during dry drilling of Al2024, the carbide drill showed lower values of surface roughness compared to HSS. It is expected that the moderate strength of the HSS drill might have made the tool unsuitable to machining [49]. Besides, the high point angle i.e. 140° of carbide drill compares to the 118° point angle of HSS might have contributed to giving low surface roughness of holes. This is because the increased point angle caused the reduction in chip sizes, especially the undeformed chip thickness which resulted in low surface roughness [50]. However, to compare both the carbide drill with the same point angle of 140° but with different drill sizes, it was examined that the carbide drill with the lower size showed the low roughness. This finding is in agreement with Köklü [12] who also recommended small diameter drills for lower surface roughness. Shetty et al. [51], also found that the increase in the contact area due to large drill size increased the cutting forces hence, the surface roughness increased. Hence, the above analysis concluded that during multi-hole simultaneous drilling of Al2024, carbide drills with a size of 6 mm and a point angle of 140° gave lower surface roughness. Therefore, the 6 mm carbide drills were also used for different tool arrangements where no significant difference in the surface roughness was found. This

should be confirmed from ANOVA in Table 7 which indicated that the percentage contribution of spindle speed on the surface roughness was the highest followed by the feed, point angle, or diameter with insignificant effect of tool arrangements.

Table 7 Analysis of variance for surface roughness

Carbide drill (D = 6 mm, $\theta = 140^\circ$) Tool arrangement							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	13	6.13156	99.88%	6.13156	0.47166	262.01	0.000
Linear	5	6.06116	98.74%	6.06116	1.21223	673.40	0.000
n	2	4.43396	72.23%	4.43396	2.21698	1231.54	0.000
f	2	1.61785	26.35%	1.61785	0.80892	449.36	0.000
TA	1	0.00936	0.15%	0.00936	0.00936	5.20	0.085
2-Way Interactions	8	0.07040	1.15%	0.07040	0.00880	4.89	0.071
$n \times f$	4	0.06651	1.08%	0.06651	0.01663	9.24	0.027
$n \times TA$	2	0.00262	0.04%	0.00262	0.00131	0.73	0.538
$f \times TA$	2	0.00127	0.02%	0.00127	0.00063	0.35	0.723
Error	4	0.00720	0.12%	0.00720	0.00180	-	-
Total	17	6.13877	100.00%	-	-	-	-
Carbide drill (D = 6 mm and D = 10 mm, $\theta = 140^\circ$)							
Model	13	8.74301	99.11%	8.74301	0.67254	34.08	0.002
Linear	5	8.35587	94.72%	8.35587	1.67117	84.67	0.000
n	2	6.67145	75.62%	6.67145	3.33572	169.01	0.000
f	2	1.29909	14.73%	1.29909	0.64955	32.91	0.003
D	1	0.38533	4.37%	0.38533	0.38533	19.52	0.012
2-Way Interactions	8	0.38714	4.39%	0.38714	0.04839	2.45	0.201
$n \times f$	4	0.13782	1.56%	0.13782	0.03445	1.75	0.301
$n \times D$	2	0.23678	2.68%	0.23678	0.11839	6.00	0.063
$f \times D$	2	0.01254	0.14%	0.01254	0.00627	0.32	0.745
Error	4	0.07895	0.89%	0.07895	0.01974	-	-
Total	17	8.82196	100.00%	-	-	-	-
HSS drill (D = 6 mm, $\theta = 118^\circ$) and Carbide drill (D = 6 mm, $\theta = 140^\circ$)							
Model	13	8.21652	99.35%	8.21652	0.63204	47.08	0.001
Linear	5	8.02852	97.08%	8.02852	1.60570	119.60	0.000
n	2	5.03060	60.83%	5.03060	2.51530	187.35	0.000
f	2	1.22370	14.80%	1.22370	0.61185	45.57	0.002
θ	1	1.77422	21.45%	1.77422	1.77422	132.15	0.000
2-Way Interactions	8	0.18800	2.27%	0.18800	0.02350	1.75	0.309
$n \times f$	4	0.06716	0.81%	0.06716	0.01679	1.25	0.417
$n \times \theta$	2	0.10121	1.22%	0.10121	0.05060	3.77	0.120
$f \times \theta$	2	0.01963	0.24%	0.01963	0.00982	0.73	0.536
Error	4	0.05370	0.65%	0.05370	0.01343	-	-
Total	17	8.27022	100.00%	-	-	-	-

Spindle speed: n (rpm), Feed: f (mm/rev), Diameter: D (mm), Point angle: θ ($^\circ$), Tool arrangement (TA)

3.2.2. Analyses of hole quality

In the drilling process, the formation of burrs depends on many factors such as the drill geometry, properties of workpiece materials, and drilling parameters [52]. Burrs can cause problems related to dimensional accuracies and require de-burring which accounts for more than 30% of the total cost of the piece produced [52]. Also, de-burring is performed manually [42] and takes 40% of the total machining time thus, affects productivity [53].

The types of burrs include uniform, transient and crown burrs as shown in Figure 6. Crown burrs are considered as the worst among all due to its irregular shape and need more attention [52, 54, 55].

Figure 6 burrs (a) uniform, (b) transient, and (c) crown [52, 54]

In the current study, small burrs were formed during the multi-spindle drilling process of Al2024; therefore, burrs at the entry and exit sides of holes were analyzed using a digital microscope given in Figures 7-10. The microscopic and visual inspection of holes for all drills and tool arrangements revealed that more burrs were observed at the exit than at the entry side of the holes. The low temperature and thrust force on the entry side of the hole can contribute to the smaller burrs [56].

Overall, burrs increased with the increase in both the spindle speed and feed; however, the feed was found more influential than the spindle speed. According to Uddin et al. [57], low feed rate resulted in the slow insertion of drills which gave a stable and jerk-free performance where the cutting edges removed the material with small chip thickness and hole quality was less affected. Furthermore, at a high feed rate, high thrust force was generated and according to Costa et al. [52], any factor that increases the cutting force will result in higher burr size.

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4 It is also depicted from Figure 7-10 that in comparison to HSS drill, the carbide drill with a diameter of 6
5 mm and a point angle of 140° showed small burrs followed by the 10 mm carbide drill, irrespective of the
6 drilling parameters and tool arrangements. This is because the carbide drills with higher point angles of
7 140° assured the maximum lip movement in the earliest possible time to avoid work hardening, and
8 resulted in thinner burrs due to change in chip flow direction [11]. Also, the difference of drill diameter
9 was found less significant which means that drill diameter has less contribution in burrs formation. No
10 significant difference was found in the formation burrs by different tool arrangements of the multi-spindle
11 head. Therefore, the carbide drills with small size and a high point with low drilling parameters are
12 recommended to avoid the formation of more burrs. Other reasons might include chip characteristics such
13 as its length and thickness which are discussed in the following section.
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$n \downarrow f \rightarrow$		Entry holes			Exit holes		
		0.04 mm/rev	0.08 mm/rev	0.14 mm/rev	0.04 mm/rev	0.08 mm/rev	0.14 mm/rev
Drill bit A	1007 rpm
	2015 rpm
	3025 rpm
Drill bit B	1007 rpm
	2015 rpm
	3025 rpm
Drill bit C	1007 rpm
	2015 rpm
	3025 rpm

Figure 7 Hole images from carbide drill: D= 6 mm, $\theta = 140^\circ$ (maximum CTCD)

$n \downarrow f \rightarrow$		Entry holes			Exit holes		
		0.04 mm/rev	0.08 mm/rev	0.14 mm/rev	0.04 mm/rev	0.08 mm/rev	0.14 mm/rev
Drill bit A	1007 rpm
	2015 rpm
	3025 rpm
Drill bit B	1007 rpm
	2015 rpm
	3025 rpm
Drill bit C	1007 rpm
	2015 rpm
	3025 rpm

Figure 8 Hole images from carbide drill: D= 6 mm, $\theta = 140^\circ$ (minimum CTCD) [24]

$n \downarrow f \rightarrow$		Entry holes			Exit holes		
		0.04 mm/rev	0.08 mm/rev	0.14 mm/rev	0.04 mm/rev	0.08 mm/rev	0.14 mm/rev
Drill bit A	1007 rpm
	2015 rpm
	3025 rpm
Drill bit B	1007 rpm
	2015 rpm
	3025 rpm
Drill bit C	1007 rpm
	2015 rpm
	3025 rpm

Figure 9 Hole images from carbide drill: D= 10 mm, $\theta = 140^\circ$ (minimum CTCD)

$n \downarrow f \rightarrow$		Entry holes			Exit holes		
		0.04 mm/rev	0.08 mm/rev	0.14 mm/rev	0.04 mm/rev	0.08 mm/rev	0.14 mm/rev
Drill bit A	1007 rpm
	2015 rpm
	3025 rpm
Drill bit B	1007 rpm
	2015 rpm
	3025 rpm
Drill bit C	1007 rpm
	2015 rpm
	3025 rpm

Figure 10 Holes images from HSS drills D= 6 mm, $\theta = 118^\circ$ (minimum CTCD)

3.1. Analyses of chip formation

In the drilling process, as the cut chips by the cutting edge travel spiral upward in the drill flute. Therefore, its formation is governed by its complex interaction between the tool and workpiece [58]. Moreover, the chip size such as the length and thickness indicates the smoothness of the drilling process [59]. Generally, small and fragmented chips are required in the drilling process [41] because continuous chips are prone to tangle around the drills and need manual removal which interrupts the production. In addition, the formation of undesirable chips causes BUE and effects the hole quality [60].

The chips produced during multi-hole simultaneous drilling of Al2024 are given in Figure 11 which depicted that the chips were affected by both spindle speed and feed. The length of chips became shorter as the spindle speed increase and feed increase whereas, the thickness of the chip had a direct relationship with the feed and inverse relation with the spindle speed, regardless of the drill type. However, the impact of feed was found to be more influential on chips. A previous study has indicated that longer chips were formed at high cutting speed due to the increase in chip ductility at high temperatures [61]. However, in this study, the length of the chips became thin and short with the rise in spindle speed. It is expected that the drop in thrust force at high spindle speed would have possibly produced chips that are thinner and smaller in size due to a reduction in uncut chip thickness. Also, as discussed earlier, the high thermal conductivity of aluminium than other metals restricts the cutting temperature [42]; therefore, spindle speed was found to be less influential on the chips than feed. Furthermore, short and discontinuous chips were produced with high thickness as the feed increases. The high thrust force due to high feed might be the reason because high feed increased the cross-sectional area of the chips which increased the stiffness of the chips thus, made the chips easier to break [58, 62].

The visual inspection showed that the chips formed by 6 mm carbide and HSS were almost similar and no significant difference was observed. However, in general, by increasing the point angle from 118°, the drill created small and fragmented chips rather than the long, stringy chips. This was because the aluminium chips formation at lower point angles produced thicker chips due to the longer cutting lips during the drilling process [63]. Furthermore, the 10 mm carbide drills showed thicken chips due to its large cross-sectional area covered by its large size [64]. Therefore, it seems that the drill size had a major contribution to the size of the chips. Figure 12 showed the tangled chips around all drills of the multi-spindle head at the spindle speed of 3025 rpm and a feed of 0.04 rev/mm, where it also gave high values of surface roughness at the same drilling parameters as indicated previously.

$n \downarrow f \rightarrow$		0.04 mm/rev	0.08 mm/rev	0.14 mm/rev		0.04 mm/rev	0.08 mm/rev	0.14 mm/rev
Carbide drill: D = 6 mm, $\theta = 140^\circ$ maximum CTCD	1007 rpm				Carbide drill: D = 6 mm, $\theta = 140^\circ$ minimum CTCD			
	2015 rpm							
	3025 rpm							
Carbide drill: D = 10 mm, $\theta = 140^\circ$ minimum CTCD	1007 rpm				HSS drill: D = 6 mm, $\theta = 118^\circ$ minimum CTCD			
	2015 rpm							
	3025 rpm							

Figure 11 Chips formation

Figure 12 Chips around 10 mm carbide drills

3.2. Post machining tool conditions

Figure 13 shows that adhesions followed by the BUE were formed on all drill types during the simultaneous drilling of Al2024. However, in comparison to the carbide drill, the HSS drills showed a high formation of BUE. According to Ratnam [65], during the machining process, there are chances of an increase in temperature at high cutting parameters caused by the increased material removal rate and friction energy. This rise in temperature softens the material where it undergoes plastic deformation; as a result, the material melts and accumulates to the tool which causes the formation of adhesion and BUE. Therefore, it is important to assess the tool wear as it affects productivity [66].

Nouari et al. [28] also observed that increase in temperature was the cause of a reduction in tool life. They reported that both cutting speed and feed rate were the functions of increasing the temperature. A high feed rate encourages the growth of contact length between the tool and chip, thus increases the interface temperature while the high cutting speed increased the plastic deformation, which then increases the temperature. As discussed earlier, the heat produced is partitioned between the tool and workpiece that depends on the thermal properties of both materials [41]. Therefore, a likely explanation for the low BUE on carbide drills might include the high thermal conductivity, low coefficient of friction, high wear resistance, and higher strength than HSS that restrict the cutting temperature and subsequent formation of BUE. Also, it is well known that tools made from carbide material can retain their stability and do not undergo any phase changes during heating and cooling [67]. Zhu and Wang [68] also recommended that drill with high hardness like carbide tools are more wear-resistant and can improve the tool life instead of HSS tools. In addition, Nouari et al. [29] also preferred the use of carbide tools on HSS for dry drilling of Al2024. Other reasons might include the lower point angle of HSS drills which had an unfavourable effect on the drill wearing because the high point angle can result in a smaller cutting edge

which caused the reduction in chip sizes and the thrust force [50]. Furthermore, the generation of high BUE using the 10 mm carbide drills was due to the formation of large chips whereas easy chip breaking and evacuation were found during a 6 mm carbide drill due to short size as aforementioned in the chips analysis. It should also be noted that no significant difference was observed in the post-machining tool conditions of either of the tool arrangements.

Figure 13 Post machining tool conditions

4. Conclusions

In this work, a multi-spindle drilling approach was used to investigate the effect of different tool materials, tool geometry, and tool configuring to increase productivity and improve the quality of holes. The conclusions drawn in this investigation include:

- The tools of the multi-spindle head can be adjusted in any arrangements as no considerable difference in all the results were found in changing the tool configurations. Therefore, multi-spindle drilling can be useful in manufacturing industries for increasing productivity at a high rate and without a compromise on the hole quality.
- During multi-hole simultaneous drilling, the carbide 10 mm drills with a point angle of 140° showed the highest thrust force which means that size of the drill can significantly increase the thrust force. However, as compared to the 6 mm HSS drills with a point angle of 118° , the carbide drills with a 6 mm diameter and point angle of 140° generated less thrust force. In addition, the highest influence on thrust force was due to an increase in feed with an insignificant impact of spindle speed.
- The surface roughness and burrs increased with the increase in spindle speed and feed, irrespective of the tool geometry, tool materials and tool arrangements; however, in the case of surface roughness spindle speed was found more influential while the edges around holes deteriorate more at a high feed. The low surface roughness was possible when carbide drills with a point angle of 140° were used. The drill diameter did not show a significant impact on either of the surface roughness and burrs. The hole quality was affected more by HSS drills with a low point angle of 118° that gave the highest surface roughness and more burrs.
- The chip size became short when drilling at high spindle speed and feed while less thickened chips were produced with low feed and high spindle speed. The point angle did not show any significant change in the shape chips; however, the drills with high diameter showed long and thicken chips due to the large cross-sectional area covered by its high size.
- The adhesion followed by the built-up edge was formed on all drill types; however, more adhesion of chips was found at HSS drills which might be due to less point angle or less strength and low wear resistance than the carbide drills. Also, the large diameter carbide drills showed a high built-up edge due to the formation of large chips whereas easy chip breaking and evacuation occurred at carbide drills of 6 mm diameter with a point angle of 140° .

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