ORIGINAL ARTICLE

Multi-spindle drilling of Al2024 alloy and the effect of TiAlN and TiSiN-coated carbide drills for productivity improvement

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Abstract

High precision drilling is required to ensure the structural integrity of the aircraft. Therefore, strict quality controls are required to ensure optimum hole quality since hundreds of thousands of holes are drilled into different aircraft structures. The large number of holes required for riveting means that their installation must be carried out in a fast and precise manner. This can be achieved using multi-head drilling tools that can drill several holes simultaneously. The current study investigated the use of a multi-spindle drill head that can produce three holes simultaneously. Uncoated carbide and TiAlN-coated and TiSiN-coated carbide drills were used to assess cutting forces, hole surface roughness, burr formations and tool condition when machining Al2024 aerospace alloy under dry machining conditions. Analysis of variance was employed for estimating the relationships between the input parameters (spindle speed, feed and tool coating) and the studied hole quality metrics. Furthermore, a regression model was developed with a regression coefficient (R^2) of more than 90% for the prediction of measured responses. Interestingly, better results in lower thrust force and surface roughness were obtained using the uncoated carbide drills compared with TiAlN and TiSiN, while the performance of TiAlN was found to be better than those obtained from TiSiN.

Keywords Multi-spindle drilling · TiAlN · TiSiN · Thrust force · Surface roughness · Hole quality

1 Introduction

Riveting, which is achieved by hole drilling, is the most common method used for the assembly of aircraft structures. The number of holes in an aircraft structure can vary from several thousand to multi-million [1]. Boeing 747, introduced in 1969, contained six million parts, of which half are fasteners [2]. The quality of holes is essential to ensure assembled structures in the aircraft to maintain high structural integrity during the life service of the aircraft. Hole quality metrics such as the surface roughness, burr formations and geometrical tolerances such as hole size and circularity are of great importance. For example, the inside of the hole must be free of defects such as burrs that could promote structural weaknesses under the stress of flight. Moreover, hole size, which is out of the recommended tolerance range, can increase the vibrations in the aircraft structure and promote increased levels of high cycle fatigue and crack propagation [3]. Moreover, the contact between the cutting tool and the chip during the drilling process can promote thermal and mechanical stresses, which can increase the surface roughness in the hole. This, in return, would create undesirable regions of stress concentration from which cracks can initiate [4]. The fuselage skins of modern aircraft are usually made of aluminium and titanium alloys [5]. Machining holes in those alloys are generally carried out without coolants, which increases heat and oxidation on the tool and workpiece. Moreover, it can promote faster tool wear and lower the overall hole quality. Therefore, cutting tools are coated with thin films of chemical compounds that can substantially enhance the properties and performance of a cutting tool.

The advancement in cutting tools is one of the most important aspects of any cutting operation due to high economic demands in the manufacturing industry. A cutting tool must

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be stronger and efficient to machine materials at the highest possible productivity [6]. High productivity is achieved at a high cutting speed that associates a large amount of heat which might increase the power consumption, and subsequently, the cutting force increases [7]. In this regard, coatings on the tools have been introduced to increase the life of the tool, thus reducing the manufacturing cost due to less frequent tool changes [8].

Chemical vapour deposition (CVD) and physical vapour deposition (PVD) hard coatings are two techniques employed for cutting tools for improving tool life and machining performance. In the CVD technique, thin films are deposited on the cutting tools through various chemical reactions, whereas the PVD technique includes the deposition of the thin film on the tools through a physical technique such as sputtering and evaporation [7]. Coatings are deposited on the substrate either as a single layer or as a multi-layer depending on the requirement of applications [9].

In the manufacturing industry, drilling is the most commonly used material removal process, in which the goal is to improve the surface finish and dimensional accuracy to increase productivity [10]. However, it is difficult to achieve all these parameters when it comes to machining aluminium alloys. Therefore, there is a high possibility of tool wear in the machining of aluminium, especially in a dry cutting environment [11]. Hence, the selection of an appropriate cutting tool is required, which is crucial for the improvement of productivity in any manufacturing industry [7].

Haja Syeddu Masooth and Jayakumar [12] worked on dry machining of AA5052 to assess the surface roughness and cylindricity of the holes. The drill bits used were uncoated HSS (high-speed steel) and TiN, AlCrN, TiAlN HSS-coated drills. It was found in their study that the TiAlN performed better by giving lower values of surface roughness, less cylindricity error and less tool wear. Kuram [13] evaluated the surface roughness, top burr width and tool wear using monolayer and two-layer coated inserts in milling of Al2124 aluminium alloy. It was concluded that coated inserts with two layers (TiCN + TiN and AlTiN + TiN) and monolayer TiCN-coated inserts gave better machining performance with respect to AlTiN and TiAlN-coated inserts. In another study by Wang et al. [14], the life of TiSiN tools was found longer than TiAlN when high-speed machining experiments were performed to analyse the wear and breakage of the tools. Dumkum et al. [15] reported that the TiAlN gave the lowest surface roughness and smallest tool wear while TiN-coated drills resulted in the lowest thrust force and torque. Kurt et al. [16] recommended using HSS-Co 5%, during dry drilling of Al2024 for minimal hole diameter deviations compared with an uncoated, TiN and TiAlN-coated drills.

The above studies indicate that most previous studies with different tool materials and coatings are based on the one-shot drilling process or other machining processes. Furthermore, the

use of the coatings on wear mechanism needs further understanding where the relationship between coating's characterization and machining performance needs further assessment. Also, the coatings on the tools used in the machining of aluminium are still contradictory and need further research. Therefore, this study investigates the effect of cutting tool coatings (TiAlN and TiSiN) on the machinability of Al2024 using the multi-hole simultaneous drilling approach, which has received less attention from researchers. Multi-spindle drilling is useful for manufacturing industries where machining time and high productivity are essential for the machining process [17–20]. The coatings were selected based on their excellent hardness and high thermal and oxidation resistance [21]. Therefore, the selection of suitable tool material together with the use of multi-hole drilling would further enhance productivity in any manufacturing industry.

2 Materials and methods

In this study, drilling experiments were conducted using a vertical turret manual milling machine in a dry environment using an adjustable SUNHER type MH30/13 multi-spindle drill head. The spindle speeds selected were 1007, 2015 and 3025 rpm, while the feed rates were 0.04, 0.08 and 0.14 mm/rev, similar to the previous studies [6]. Furthermore, aggressive drilling results in high vibration and cutting temperature that could affect the hole quality [22]. A set of three drill bits each for uncoated carbide, TiAlN and TiSiN were tested using the multi-spindle simultaneous drilling process. First, drilling was carried out using uncoated carbide drills, and then the same procedure was carried out for TiAlN and TiSiN. The workpiece material was Al2024 aluminium alloy which is used in the fuselage skins of aircraft [23]. The cutting tools were 6 mm uncoated, TiAlN-coated and TiSiN-coated carbide twist drills. Some of the properties of cutting tools used in this study are given in Table 1. The point angle and helix angle of the drill bits were 140° and 30°, respectively. The thickness of the workpiece was 10 mm.

A KISTLER 9257A dynamometer was used to measure the thrust force (F_z) [26]. The average surface roughness (R_a) was measured using the surface roughness tester, and the burrs were observed using the digital microscope, similar to a previous study [27]. The tool conditions were examined with the use of an optical microscope. Analysis of variance (ANOVA) and regression analysis were also performed to find the

Table 1 Properties of cutting tools [21, 24, 25]

Coatings	Oxidation temp (°C)	Hardness (GPa)	Friction coefficient
TiAlN	700-800	32	0.5-0.7
TiSiN	1000	35	0.6
Uncoated	500	26	0.4-0.6

percentage contribution of the input parameters and develop a model for predicting the output parameters. The details of the machines/equipment used in the study are given in Fig. 1.

3 Results and discussion

3.1 Analysis of thrust force

Figure 2 shows that the feed had a high influence on average thrust force (F_z) compared to the spindle speed. As the feed

was increased, the F_z increased, while increasing the spindle speed showed less variation in F_z. The high generation of F_z due to the high feed meant that the tool penetrated faster; therefore, at high feed, the tool has to cut maximum material from the workpiece, which increased the F_z due to an increase in uncut chip thickness [28, 29]. Also, at high feed, the load on the tool increased, which increased the F_z [30]. It is also shown in Fig. 2 that the lowest F_z was obtained using the uncoated drills in multi-spindle drilling as compared to the TiAlN-coated and TiSiN-coated drills. Besides, the value of F_z from TiAlN was lower than that obtained from TiSiN-
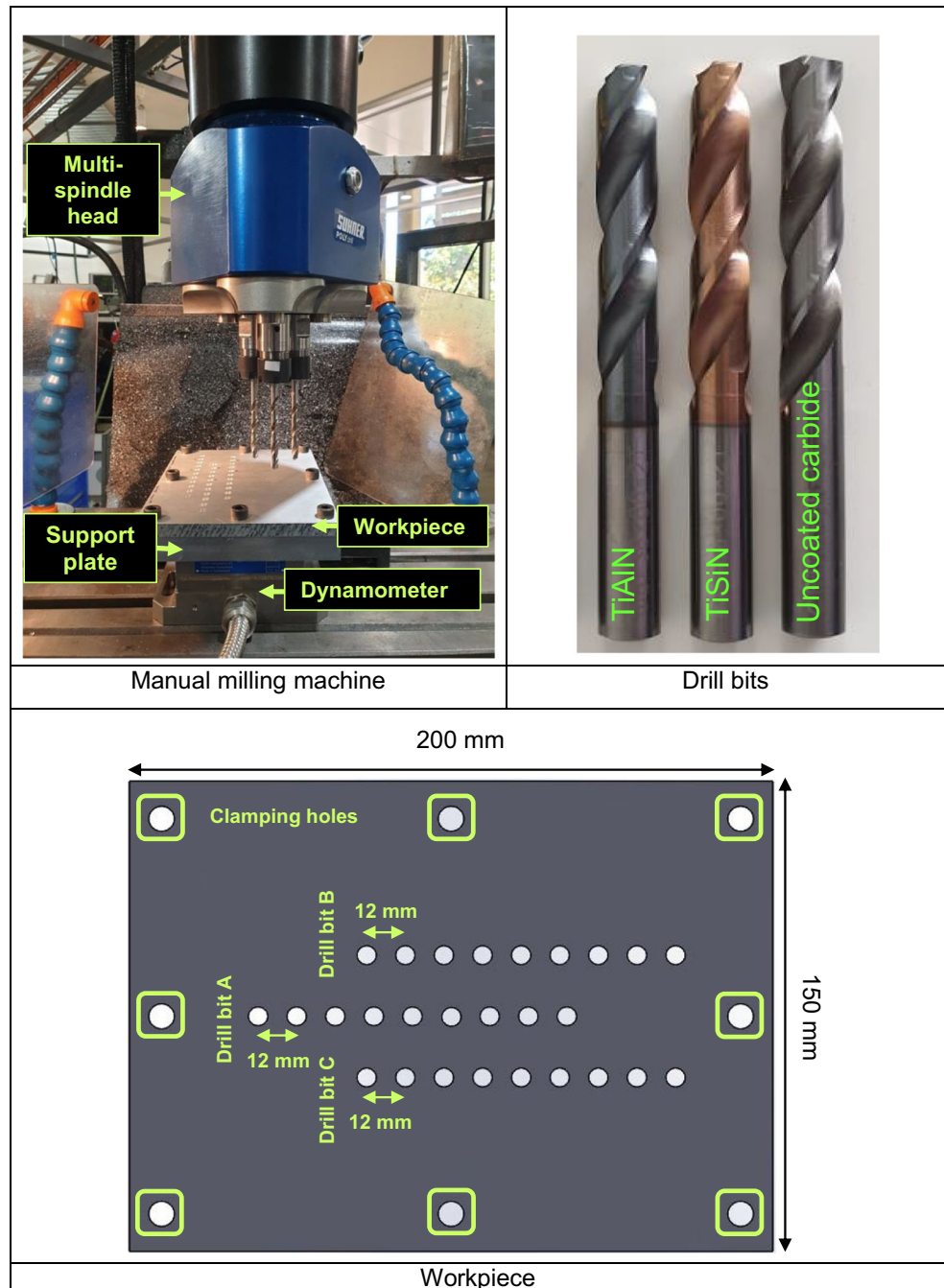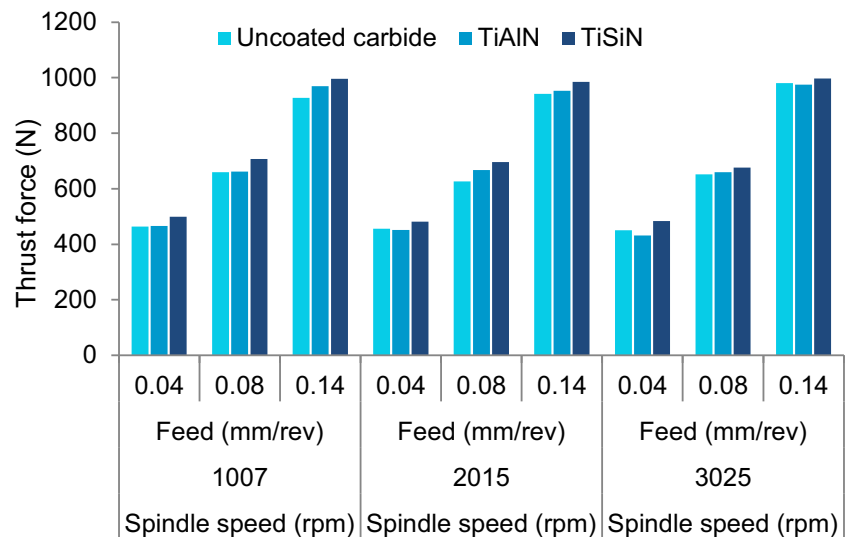
Fig. 1 Details of experiments

Fig. 2 Average thrust force

coated drills. This is because of the limited adhesion of the TiSiN coating, despite its increased strength and fatigue properties [31]. However, the difference in F_z was insignificant. The rise in F_z was less than 7% for TiAlN, while that of TiSiN was less than 11% with respect to the F_z generated from uncoated carbide drills under the selected drilling parameters.

TiAlN coating contains aluminium which means that it is chemically reactive to aluminium and could easily bond with a cutting surface of the same material, i.e. Al2024. This is mainly due to the metallic crystal and ionic crystal features of TiAlN coating. The chemical reactivity causes the cutting tool and workpiece to adhere together, and some of the cut chip would permanently stick on the cutting tools and cause a built-up edge (BUE). The BUE might be responsible for the slight increase in F_z with the increase of spindle speed. However, as shown in Fig. 2, the increase in F_z is minor, which could be attributed to the low cutting parameters used in the current study. Uncoated carbide drills appear to perform better relative to the coated cutting tools; this could be due to the lower friction of coefficient relative to the other tool coatings. However, this claim is only an assumption since the actual friction coefficient was not measured in the current study and is only based on the data provided by the tool supplier and open literature. Indeed, it can be seen that the performance of uncoated carbide drills becomes similar to TiAlN and TiSiN when drilling at higher spindle speeds. Similarly, it is speculated that drilling at higher spindle speeds beyond 3000 rpm would further increase the F_z when drilling using uncoated carbide drills due to the low oxidation temperature of the carbide material (~500 °C). It is also expected that the performance of TiSiN and TiAlN coating in terms of F_z would remain similar at higher cutting parameters due to their higher oxidation temperature,

which is almost as twice as that for uncoated carbide tools. A firm conclusion can be made—in terms of generated thrust forces—that drilling Al2024 does not require the use of coated tools when drilling at low spindle speeds and feed rates like those used in the current study. Instead, uncoated carbide drills can provide similar or better performance if used for drilling a small number of holes.

3.2 Assessment of hole quality in terms of surface roughness and burrs

Generally, in industries, surface roughness is usually measured as the average roughness (R_a: the arithmetic average of surface heights measured across a surface) [32]. A lower R_a indicates a better surface finish, which tends to increase the service life and performance of machined components [8]. Therefore, low R_a is always desirable for high-quality holes. Figure 3 shows the R_a of uncoated and TiAlN-coated and TiSiN-coated carbide drills, which shows that both the spindle speed and feed affected the R_a, irrespective of the coatings on the drill bits. The R_a increased as the spindle speed and the feed increase; however, the impact of spindle speed was more than that of the feed. The higher R_a due to high spindle speed could be due to the high temperature that affects the plastic deformation of the workpiece, which subsequently degraded the surface quality [33]. Also, the high R_a due to the high feed might be due to the increased thickness of the chips due to the high thrust force that increased the surface roughness [34].

Figure 3 also shows that lower R_a values were obtained using the uncoated carbide drills following the TiAlN-coated and TiSiN-coated drills in a multi-spindle simultaneous drilling approach. This could be due to the higher

Fig. 3 Average surface roughness
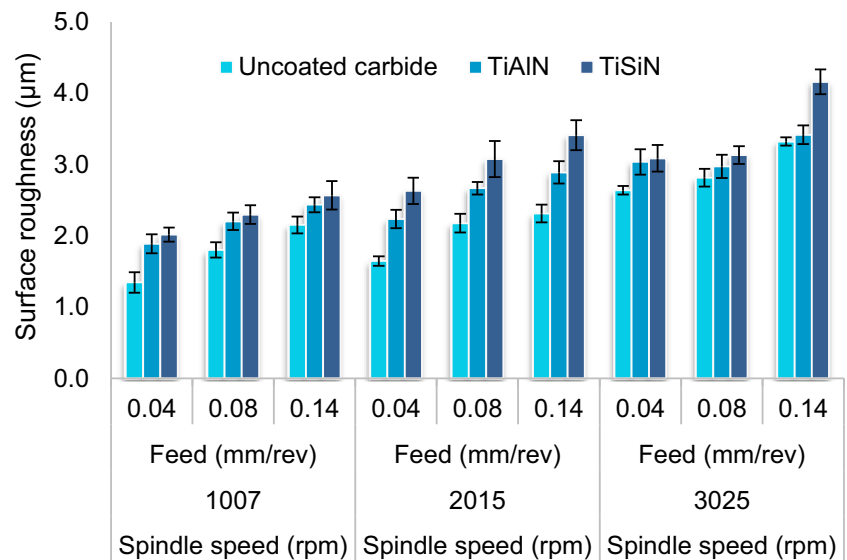
chemical affinity of aluminium for coating materials accumulated on the tools' surface due to the constant release of particles, especially silicon which caused a BUE during dry machining of aluminium. Subsequently, there was a chance of high cutting forces, hence increasing the R_a values [35]. Furthermore, it was reported that aluminium-based coatings have some drawbacks for the machining of aluminium because aluminium tends to stick to the workpiece surface. When these coatings come in contact with aluminium, they have abrasive properties that contribute to the progression of BUE [36]. However, the R_a in holes drilled using TiAlN-coated drills was lower than those drilled using TiSiN-coated drills. The reason that TiSiN has a greater R_a than TiAlN, despite its high hardness, is that TiSiN coating has restricted adhesion properties than that of TiAlN, which might have led to a reduction in tool life [31]. Besides, the coefficient of friction of TiSiN is greater than that of TiAlN-coated tools [21], and according to Prengel et al. [37], the low coefficient of friction reduces the BUE. Hence, smaller R_a values can be expected due to the lower cutting loads and less tool wear as a result of coatings' low friction coefficient [15]. Therefore, multi-spindle drilling increases productivity by drilling more than one hole and using uncoated drills would save manufacturing costs. The rise in R_a was 28.68% for TiAlN, while that of TiSiN was 33.22% with respect to the R_a obtained from uncoated carbide drills under the selected drilling parameters.

Apart from the R_a, another essential characteristic of the hole quality is burrs. According to Min et al. [38], burrs can be a source of dimensional error that interferes with the assembly parts and caused misalignments. Figure 4 shows the burrs around the holes examined from one of the drill bits of the multi-spindle head at a cutting

speed of 3025 rpm and feed of 0.14 mm/rev. Results showed that more burrs were formed at the entrance of holes than the exit side. Figure 4 also shows that neither of the coated drills performs better than the uncoated drills. An insignificant difference was found in burrs produced in multi-spindle drilling using the TiAlN-coated and TiSiN-coated drill bits.

3.3 Statistical analyses

3.3.1 Analysis of variance

Analysis of variance (ANOVA) is a statistical method used to determine the significant parameters on the response and to check how much impact input parameters in any machining process has on the output responses [6]. In this study, ANOVA was performed with a confidence interval of 95% ($\alpha = 0.05$) based on spindle speed, feed and coatings of the drills in the multi-spindle drilling approach. The selected responses were thrust force and R_a. Therefore, the P-value would consider only those values as statistically significant, which are less than 0.05. Additionally, F-values determine whether the significant effect of the parameter has on the quality characteristics. Finally, the percentage contribution describes the influence of each process parameter on the output responses [39]. Table 2 shows the ANOVA results for the thrust force and R_a.

The results show that for the thrust force, the most influential parameter was the feed (98.92%), followed by a minor contribution from the coating (0.7%). The impact of the spindle speed on thrust force and the linear interactions between the studied parameters were found to be insignificant as the P-value is more than

Fig. 4 Hole images at a cutting speed of 3025 rpm and feed of 0.14 mm/rev
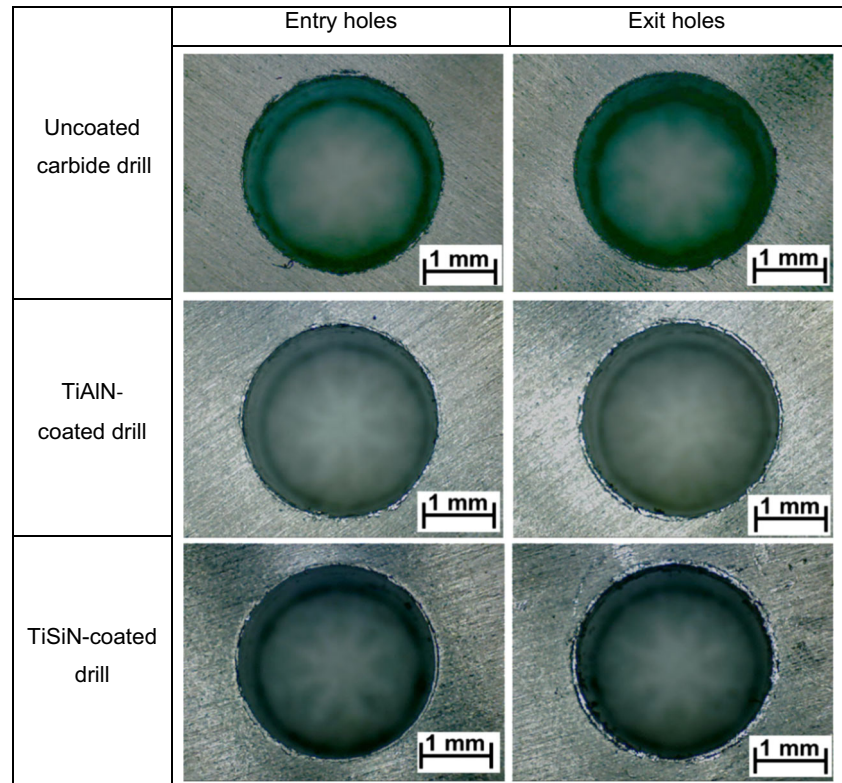
0.05. For R_a, spindle speed showed the highest percentage contribution (52.72%), followed by the coating and the feed with 20.57% and 20.43%, respectively. Linear interactions between the spindle speed and the other two parameters showed a somewhat minor contribution of less than 2.5% in increasing the R_a.

Table 2 Analysis of variance

Source	DF	Seq SS	Adj SS	Adj MS	F-value	P-value	Contribution
Thrust force							
Model	18	1,171,529	1,171,529	65,085	447.23	0	99.90%
Linear	6	1,168,684	1,168,684	194,781	1338.43	0	99.66%
n	2	467	467	234	1.61	0.259	0.04%
f	2	1,160,014	1,160,014	580,007	3985.51	0	98.92%
C	2	8203	8203	4102	28.18	0	0.70%
2-way interactions	12	2845	2845	237	1.63	0.249	0.24%
$n \times f$	4	1576	1576	394	2.71	0.108	0.13%
$n \times C$	4	718	718	180	1.23	0.369	0.06%
$f \times C$	4	551	551	138	0.95	0.485	0.05%
Error	8	1164	1164	146	-	-	0.10%
Total	26	1,172,693	-	-	-	-	100.00%
Surface roughness							
Model	18	10.2274	10.2274	0.56819	44.05	0	99.00%
Linear	6	9.6813	9.6813	1.61356	125.08	0	93.72%
n	2	5.4459	5.4459	2.72297	211.09	0	52.72%
f	2	2.1104	2.1104	1.0552	81.8	0	20.43%
C	2	2.125	2.125	1.06249	82.37	0	20.57%
2-way interactions	12	0.546	0.546	0.0455	3.53	0.041	5.29%
$n \times f$	4	0.2034	0.2034	0.05086	3.94	0.047	1.97%
$n \times C$	4	0.2531	0.2531	0.06328	4.91	0.027	2.45%
$f \times C$	4	0.0895	0.0895	0.02237	1.73	0.235	0.87%
Error	8	0.1032	0.1032	0.0129	-	-	1.00%
Total	26	10.3305	-	-	-	-	100.00%

n spindle speed, f feed, C coatings

Fig. 5 Normal probability plots for thrust force and surface roughness
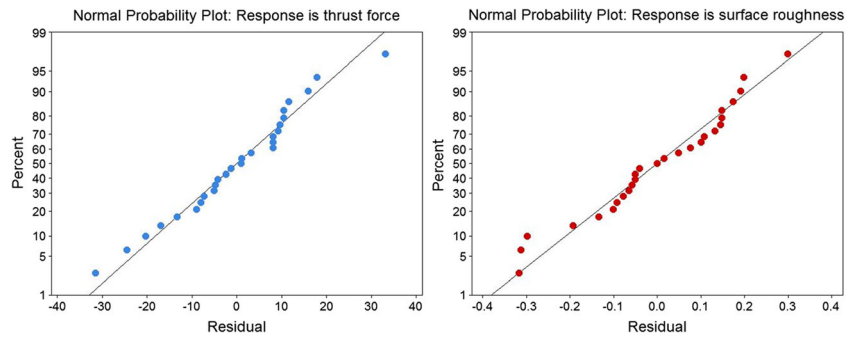
3.3.2 Regression analysis

Regression analysis is a statistical method used to develop a regression equation that analyzes the correlation between the process parameters and the responses in any machining process [40]. The coefficients in the equations estimate the relationship between each independent variable and the dependent variable. The responses are the dependent or outcome variables, and the predictors are the independent or input variables [41]. Therefore, the essential parts of a regression model include dependent variable = (constant + independent variables) + error [41].
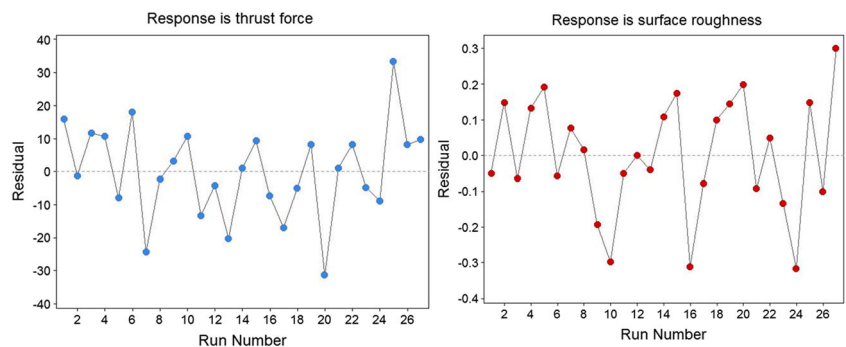
In this study, the equations obtained from the regression analysis are presented as:

$$\text{Thrust force} = 227.7 - 0.00244 \text{ Spindle Speed} \\ + 5043.7 \text{ Feed} + 20.28 \text{ Coatings} \quad (1) \\ R^2 = 99.56\%$$

$$\text{Surface roughness} = 0.237 + 0.000544 \text{ Spindle Speed} \\ + 6.800 \text{ Feed} + 0.3424 \text{ Coatings} \quad (2) \\ R^2 = 93.30\%$$

R^2 is the regression coefficient, which shows the effectiveness of the model [42]. It statistically measures how well the regression line estimates the real data points, where the values between 0.8 and 1 are highly acknowledged [43]. The R^2 values in this study are more than 90%, which indicates that the developed equations are acceptable for the prediction of thrust force and surface roughness in the selected machining variables for the multi-spindle drilling process of Al2024.

Furthermore, the adequacy of the model was investigated by analysing residuals, which are the difference between the respective observed responses and the predicted responses [44]. Figure 5 illustrates the normal probability plots for the thrust force and surface roughness which shows that all the residuals almost fall on a straight line, whereas Fig. 6 shows the statistical data about the residuals, thus confirming that the regression model matches well with the experimental data and the developed model is highly reliable.

3.4 Post drilling tool conditions

The type of tool wear depends on the materials of the tool, the workpiece and the drilling conditions [35]. Also, as aforementioned, the usual tool wear in dry machining of aluminium is the BUE. Figure 7 shows the condition of one of the uncoated carbide and coated carbide drills used in multi-spindle drill drilling, which reveals the formation of BUE. The high BUE was found on the TiSiN following TiAlN-coated drills and the uncoated drills, which also correspond to a reason for surface roughness. According to Bouzakis et al. [31], the good performance of TiAlN than TiSiN was due to the weaker adhesion properties of TiSiN, despite the increased strength. Also, as discussed earlier, the coefficient of friction of TiSiN is more than TiAlN [21], which increased the tool wear by increasing the tendency of sticking the materials from the workpiece on the tools [15]. Besides, the reason for the high BUE of the coated drills than the uncoated drill bits might be due to the low drilling parameters selected in this study. Therefore, further investigation is required to assess the performance of

Fig. 6 Residual analysis for thrust force and surface roughness

Fig. 7 Post-machining tool condition. **a** Uncoated carbide. **b** TiAlN. **c** TiSiN
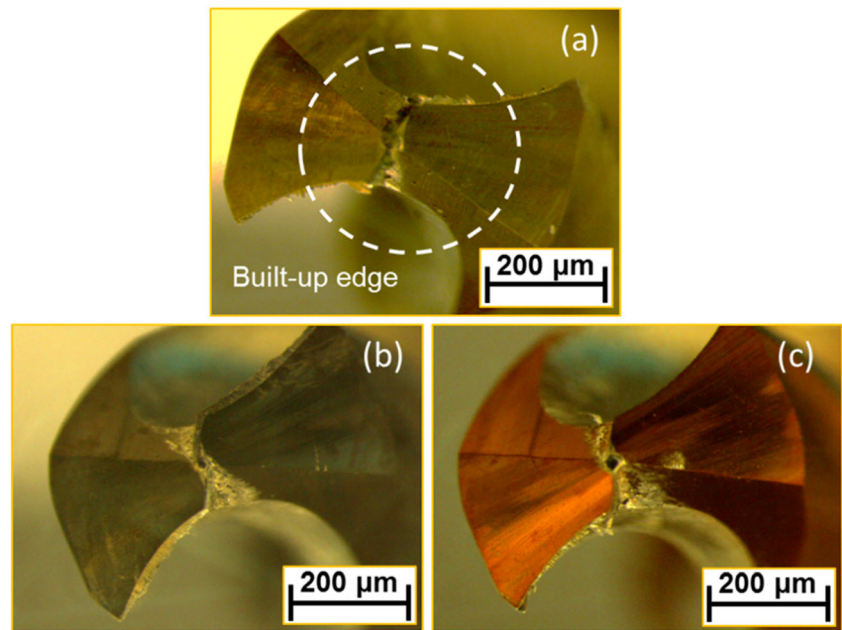
coated drills at high drilling parameters during the multi-spindle simultaneous drilling process. However, it should be noted that aggressive drilling might either increase the undesirable vibration or cutting temperature that would affect the hole quality [22].

4 Conclusions

This work investigated the use of uncoated carbide and TiAlN-coated and TiSiN-coated carbide drill bits to ensure high-quality holes in the multi-spindle drilling process for productivity improvement.

- In general, regardless of the tool coating types, the high feed increased the thrust force, while in the case of surface roughness, both the high spindle speed and feed increased the surface roughness. However, the spindle speed was found more influential than the feed. Furthermore, the burrs at the exit of the holes were more evident than those formed at the entrance of the holes. The burrs were more affected by the feed as compared to the spindle speed.
- The ANOVA results revealed that thrust force was influenced by feed followed by coatings with insignificant impact from the spindle speed. In contrast, the surface roughness was more affected by the spindle speed following the coatings and feed. Also, a regression model was developed with R^2 of more than 90%, which means that the developed equations are reliable and can be used to predict thrust force and surface roughness.

- The use of TiAlN-coated and TiSiN-coated drills compared to the uncoated drills did not significantly lower the thrust force and improve hole quality, such as lowering the surface roughness and less burr formation. The high built-up edge was found on the TiSiN following TiAlN-coated drills and the uncoated drills. Therefore, in the multi-spindle drilling approach, the uncoated carbide drill showed high performance. However, further research is required to assess coated tools at high drilling parameters in the multi-spindle drilling process.

Declarations

Ethical approval The article follows the guidelines of the Committee on Publication Ethics (COPE) and involves no studies on human or animal subjects.

Consent to participate Not applicable. The article involves no studies on humans.

Consent to publish Not applicable. The article involves no studies on humans.

Competing interests The authors declare no competing interests.

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