Lubricant Coatings for Mobile Dry Drilling of Stacked Aluminium Alloys

Siti Rozakiyah Assurin Hassan (sr.assurin@gmail.com)
Seberang Perai Polytechnic https://orcid.org/0000-0002-3679-5277
Paul T Mativenga
University of Manchester
Kevin Cooke
Berry-Hill-Industrial-Estate
Hailin Sun
Berry-Hill-Industrial-Estate
Susan Field
Berry-Hill-Industrial-Estate
Mark Walker
Broughton, Airbus UK
Jason Chodynicki
UK-taffordshire WS13 8LH, United Kingdom
Colin Sharples
UK-taffordshire WS13 8LH, United Kingdom
Boris Jensen
DK-7451 Sunds, Denmark
Morten F. Mortensgaard
DK-7451 Sunds, Denmark

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Abstract

Aluminium alloy stack materials offer good strength-to-weight ratio and are used for high strength airframe structures. For the panels to be joined, numerous holes have to be drilled and due to structure size mobile drilling heads are used. The drilling process releases lubricant oil which becomes airborne or collects on the shop-floor and presents a health and safety hazard. Avoiding this oil release is therefore a major driver for developing dry drilling processes. However, drilling aluminium alloys in the absence of cutting fluids is a challenging task due to its tendency to adhere to the cutting tool, and the high thermal conductivity of the workpiece. Owing to their low coefficient of friction, carbon-based coatings are an option to improve the machinability of aluminium alloys. This paper presents an industrial collaboration study on the performance of carbon-based coatings in dry drilling aluminium alloy 2024 and 7150 stacks. CVD Diamond, a hard DLC, Doped MoS_2 and doped amorphous carbon (Doped a-C) were evaluated in comparison with an uncoated WC drills. Coating performance was assessed in terms of tool wear, hole diameter, and surface roughness. The results revealed that CVD diamond coated drills outperformed other coatings in terms of tool wear and hole quality. The coating enabled lower aluminium pick-up on the drills as well as minimised variations in diameter deviation and hole surface roughness. The work shows the capability for dry drilling of stacked aluminium alloys and hence eliminating the health and safety risk associated with use of oil in mobile drilling heads.

1. Introduction

Stacked aluminium alloys are commonly used in the aircraft industry as main components in aircraft structure due to their mechanical properties such as high strength-to-weight ratio. During the drilling process, mobile drilling heads are moved along large airframe structures and cutting fluid is sprayed on the workshop as the drill breaks through. This poses issues in terms of workplace health and safety as workers breathe in the fumes or step on floors made slippery by the residue. The development of cutting fluid-free drilling processes would enable the aerospace industry to address health and safety concerns. This would also create substantial cost reduction [1] and reduce the environmental burden associated with cutting fluid production, delivery and disposal.

Cutting fluids are used in drilling to help reduce friction and heat as well as to flush out chips from the cutting zone. The hypothesis for this research was that careful selection of cutting conditions, tooling and solid lubricant coatings assisted with compressed air systems could enable dry drilling of aluminium alloys.

In previous work, Hanyu et al. [2] concluded that due to excellent anti-sticking properties, smoother surface diamond coating led to longer coating durability compared to conventional rougher surface diamond coating in dry cutting conditions. Coldwell et al. 2004 [3] investigated the cutting performance of Graphit-IC™, Dymond-IC, and MoST coatings during the drilling of BS L168 aluminium alloy. The researchers found that less aluminium build-up occurred with Graphit-iC™ coated drills. For Al-Si alloys, it was reported that when TiB_2, Graphit-iC™, Dymon-iC™ and MoST™ coated drills failed adherent workpiece material was blocking the flutes [4]. The Graphit-iC™ coated drills performed better and prolonged drilling time with minimum amount of adherent material.

Dasch et al. [5] tested hydrogenated diamond like coating (H-DLC), non-hydrogenated diamond like coating (NH-DLC), blend coated (NH/H-DLC) and diamond (t-C) during the dry drilling of 319 Al alloy. Based on power consumption, they concluded that the combination of graphitic and H-DLC-coated drill was superior. However, the NH-DLC coating performed worse than the uncoated drills, a result attributed to high aluminium adhesion and flute clogging. Bhowmick and Alpas [6] in dry drilling of 319 aluminium reported that H-DLC-coated drill produced consistently lower average torque and thrust force compared to NH-DLC drills. These studies are supported by Zolgharni et al. [7] who reported that DLC coated drills operated with significantly improved power efficiency over uncoated drills.

Although research had been conducted to evaluate the performance of different coatings, there remains no single study on drilling to a stack of aluminium materials and more critically different aluminium alloys, and no consensus on which coatings perform better during dry drilling of aluminium alloys stacks. This was the motivation for this study.

2. Experimental Details And Drilling Strategy

A stack of aluminium alloy 2024 and 7150 with thicknesses of 9.33 mm and 11.28 mm respectively was used in the drilling study. The alloys were defined by industry requirements. The drilling sequence was from aluminium alloy 2024 as the top plate into the bottom material which was aluminium alloy 7150. The material specifications are shown in Table 1.

The dry drilling experiments were conducted using Takisawa MAC V3 machining centre. ULTRACUT 370 PLUS fluid coolant was used later for the benchmarking. The tools chosen were twist drills of 6.4 mm diameter, point angle 130° and high helix 40° supplied by Kyocera Unimerco LTD. Doped MoS_2, Doped a-C and Hard DLC were specifically developed for drilling by Teer Coating LTD using Closed Field Unbalanced Magnetron Sputter Ion Plating (CFUBMSIP). The coated tools were benchmarked to uncoated and commercially available CVD Diamond coated drills. The coatings details are shown in Table 2.

The cutting parameters of 5000 rpm spindle speed and 0.25 mm/rev feed rate was selected based on pilot drilling endurance tests over a range of drilling conditions. Considering the total thickness of 20.61 mm to be drilled by a 6.4 mm drill this is not a deep hole drilling [9] application according to the CIRP keynote definition by Biermann et al [9]. However the thermal and friction challenges still needed to be addressed.

Table 1
Workpiece material composition and properties [8]

	2024 aluminium alloy	7150 aluminium alloy
Material Composition	Al (90.7–94.7%), Cr ≤ 0.10%, Cu (3.8–4.9%), Fe ≤ 0.50%, Mg (1.2–1.8%), Mn (0.30–0.90%), Si ≤ 0.50%,Ti ≤ 0.15%, Zn ≤ 0.25%	Al (87.1–90.1%), Cr ≤ (0.04%), Cu (1.9–2.5%), Fe ≤ 0.15%, Mg (2.0-2.7%), Mn ≤ (0.10%), Si ≤ 0.12%, Ti ≤ 0.06%, Zn (5.9–6.9%), Zr (0.08–0.15%)
Young Modulus (GPa)	73.1	71.7
Elongation (%)	> = 15	12
Yield strength (MPa)	290	565
Vickers Hardness	139	174

Table 2
Details for coatings

	Coating Thickness (μm)	Hardness (Hv)	Coefficient of friction	Pin on disk test wear rate (m^3/Nm)
Doped MoS_2	1.1	919	0.03	8.6×10^{-17}@ 40N
Doped a-C	2.2	1704	0.1	5.8×10^{-17}@20N
CVD diamond	8.0	10 000	0.6	-
Hard DLC	3.2	2288	0.09	2.1×10^{-16}@40N
Uncoated	-	1479	-	-
- Property not evaluated in coating facility.				

A thermal simulation model was developed to estimate the temperature field. A model was developed for the axisymmetric finite element model of the rectangular workpiece, created with ABAQUS CAE 6.13 finite element software. The thickness and dimension of actual workpiece stack were identical to the experimental condition. The elements were type C3D8T which were eight-node temperature and trilinear displacement.

From pilot drilling and force measurement a heat flux was determined and then initially 100% of heat flux was loaded on the stack through the hole as thermal load. To represent the heat that flow into the workpiece during the drilling process, heat flux was applied to the elements located directly on the hole surface area. This value was then reduced until the measured and modelled temperatures were matched at multiple points. The measured temperature was based on the figures recorded during the hole drilling test. By simulated single hole drilling the diameter of heated zone was established found as 56 mm. The premise was to minimise the thermal coupling when drilling consecutive holes.

The thermal load simulation was conducted under two different strategies: sequential drilling and Z-strategy. Figure 1 shows the effect of hole position on plate surface at the feed rate of 0.25 mm/rev and spindle speed of 5000 rpm. In the sequential method, each hole was drilled in a straight line pattern while, in the Z-drilling strategy, the sequence of hole drilling followed a 'Z' pattern. The Z-drilling strategy eliminated thermal coupling between consecutively drilled holes and this was validated by substantial improvement of tool life from circa 30 holes to over 1700 holes. The Z-drilling strategy was therefore used for the subsequent study on different coatings.

The initial idea was to continue drilling until drill breakage or failure occurred. However, due to the cost and limited number of workpieces components, machining was discontinued after the completion of 1728 holes for each coating. Four types of coating were tested, with uncoated tool as a benchmark.

Hole diameters were inspected using a Bowers XT Range gauge with maximum resolution up to 0.001 mm. Each hole was measured a total of four times to get the average reading. The measured responses were cross-sectional diameters at successive depths of 4.85 mm from the top plate upper surface and 6.35 mm at the bottom of the exit plate, adherence of materials on drill tips and surface roughness of the drilled holes which was measured using Taylor Hobson Surtronic 25 at a sampling length of 0.8 mm and evaluation length 2.5 mm.

3. Results And Discussions

3.1. Assessment hole diameter

In industry, deviation of diameter is an important factor frequently used to evaluate hole quality. Figures 2 and 3 show the effect of coatings on hole size. In general variation in diameter deviation was more pronounced in aluminium alloy 2024 due to higher ductility and the lower thermal conductivity properties of the alloy. Higher thermal conductivity and hardness aluminium alloy 7150 led to more consistent diameter deviations.

Taking into account that the actual hole diameter variations also depended on tool substrate diameter and coating thickness, the standard deviation of drilled hole diameter was used as a more comparable measure to evaluate coating effectiveness and results are shown in Fig. 4. Smaller values are desirable.

The standard deviation of hole diameter indicates the diameter variation being more pronounced in the more ductile aluminium alloy 2024 compared to aluminium alloy 7150. CVD Diamond, Hard DLC and doped MoS_2 coated tools produced less variations compared to doped a-C and uncoated tools in both workpiece materials.

3.2. Evaluation of Surface roughness (Ra)

Figure 6. Surface roughness (Ra) in aluminium alloy 7150 drilled holes

The majority of coated tools showed similar surface roughness until the sudden rise of roughness appeared. Consistent with the result in aluminium alloy 2024, it could be seen that modified Graphit-IC coated drills produced the lowest surface roughness value compared to other coatings in the experiment. Fluctuations in surface roughness occurred the least with CVD diamond-coated drills.

3.3. Drill condition

Images of flank faces are shown in Fig. 7. None of the tools reached end of life criterion as defined by 0.3 mm flank wear by ISO 8688. Micrographs from SEM revealed that uncoated drill experienced severe adhesion, built-up edge and abrasive wear on its main cutting edge compared to coated drills. The main cutting edge was covered by built-up edge from aluminium alloys. Although adhesion of workpiece was also evident with other drills, the amount was significantly less than that found on uncoated types. Despite presenting significant abrasive marks near the primary cutting edge, Doped MoS_2 coated drills were able to keep coating integrity even after extensive use. Low coefficient of friction of Doped MoS_2 facilitated the smooth removal of chip during drilling. For CVD Diamond coated drill, delamination occurred. In addition to the relatively higher coefficient of friction, it seems likely that the coating failed as a result of poor adhesion between coating and substrate.

The wear rate quantification from pin-on-disk test showed that coatings with high wear rate also had significant wear effects (see Table 2). Doped a-C tested at 20N ball load provided the evidence for the hypothesis. The fact that it was tested at 20N indicates this coating to be less tough than DLC and Doped MoS_2 and might not withstand the 40N test. The hard DLC, comparable to Doped MoS_2, demonstrated a much higher wear rate compared to Doped MoS_2 coating. In combination with small coefficient of friction, these could be the main factors why doped MoS_2 was able to maintain its coating until test completion. From the chipping and wear morphology, it is possible to rank the coatings in the following best-to-worse order: CVD diamond > Doped MoS_2 > Hard DLC > Doped a-C.

To evaluate material transfer, five separate samples were taken cross-sections of the flute near the cutting corner and rake face of drills after 1728 holes. The EDX results indicated that the aluminium element could be found in the scan area for all drills as summarized in Fig. 8.

Doped a-C (c) Doped MoS_2 (d) CVD Diamond (e) Hard DLC

It could be deduced from the chart that CVD diamond-coated drills enabled the lowest aluminium pick-up with approximately 72% reduction in aluminium pick compared to an uncoated tool. For the hard DLC, the aluminium pick up was significantly reduced by 35%. The best performance coatings had higher hardness of 10000 HV and 2288 HV as previously reported. From this, it could be concluded that low coefficient of friction has to be combined with high coating hardness to enhance coating effectiveness.

3.4. Benchmarking to drilling with cutting fluid

To compare the performance of CVD Diamond in dry drilling to flood condition, a separate test was done with similar cutting parameters as in dry drilling. Variations in average hole diameter and surface roughness were compared with previous findings. Figures 9 and 10 show the hole diameter in each work material. In terms of trend, no significant change was demonstrated between flood and dry conditions although dry drilling produced holes that were somewhat larger. Machining with coolant improved deviation of hole due to functionality of cutting fluid in reducing workpiece thermal deformation.

This is indicative of the ability of CVD Diamond coated drills to maintain its effectiveness in machining even without coolants or cutting fluids. Figures 11 and 12 shows the variations in hole surface roughness of stack materials for cutting in flood and dry condition.

Regardless of workpiece material, the Ra was consistently higher when cutting was performed without any cutting fluid. The variation in surface roughness was not critical for the application.

Conclusion

In a typical aircraft, aluminium alloy 2024/7150 panels are used as airframe structures. The drilling process releases lubricant oil which becomes airborne or collects on the floor. Avoiding this oil release is therefore a major driver for developing dry drilling processes. The results outlined in this study suggests that a drilling strategy that reduces thermal coupling between subsequently drilled holes and choice of lubricant coatings contribute dry drilling capability of aluminium alloy stack materials. CVD diamond coated drills enabled least aluminium material adherence to the tool, surface roughness consistency across the number of holes drilled and minimised hole diameter variation in both workpiece materials. The outstanding cutting performance of CVD diamond-coated drill could be attributed to its high hardness, good wear resistance and high adhesive property of the coating to the carbide tool substrate. The high number of dry drilled holes (> 1728) and the comparison to drilling with cutting fluids proved that dry drilling with Doped MoS_2, Doped a-C and CVD diamond is effective and able to perform in a competitive. Further work on this project demonstrated the advantage of coated tools in reducing burr width, the substantial results could not be contained within this manuscript. Additionally the vibration assistance tool known as MITIS was used for further process improvement and validation in industry to process capability index Cp and Cpk.

Declarations

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Declarations

As the corresponding author of this manuscript, I make the following declarations on behalf of myself and all other co-authors.

a. Funding

Not Applicable

b. Conflicts of interest/Competing interests

We wish to confirm that there are no known conflicts of interest associated with this publication

c. Availability of data and material (data transparency)

We wish to confirm that the data that support the findings of this study are available on request from the corresponding

author. The data are not publicly available due to their confidentiality.

d. Code availability (software application or custom code)

Not Applicable

e. Ethics approval

Not Applicable

f. Consent to participate

Not Applicable

g. Consent for publication

We give our consent for all the photograph and other images to be published in The International Journal of Advanced Manufacturing Technology. We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere. The text of the article may be edited for style, grammar, consistency, and length in the course of the review process.

h. Authors' contributions

The authors confirm contribution to the paper as follows:

Siti Rozakiyah Assurin Hassan designed and performed the experiments and analysed the data, Paul T Mativenga supervised the findings of this work, Kevin Cooke, Hailin Sun and Susan Field prepare the coated tools, Mark Walker contributed to sample workpiece preparation. Jason Chodynicki and Colin

Sharples aided in interpreting the results. Boris Jensen and Morten F. Mortensgaard contributed to the design and implementation of the research, to the analysis of the results.

All authors listed on the title page have contributed significantly to the work and agreed on submission to this journal.

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Figures

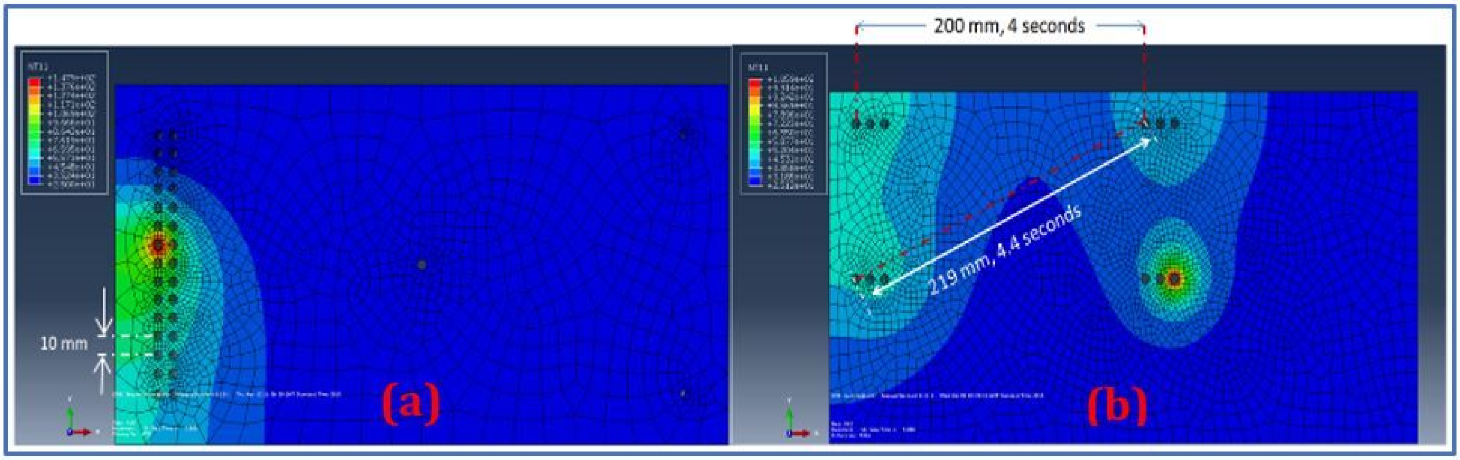

Figure 1

Simulation in Abaqus 6.13 of thermal load in (a) sequential drilling, and (b) Z-sequence drilling.

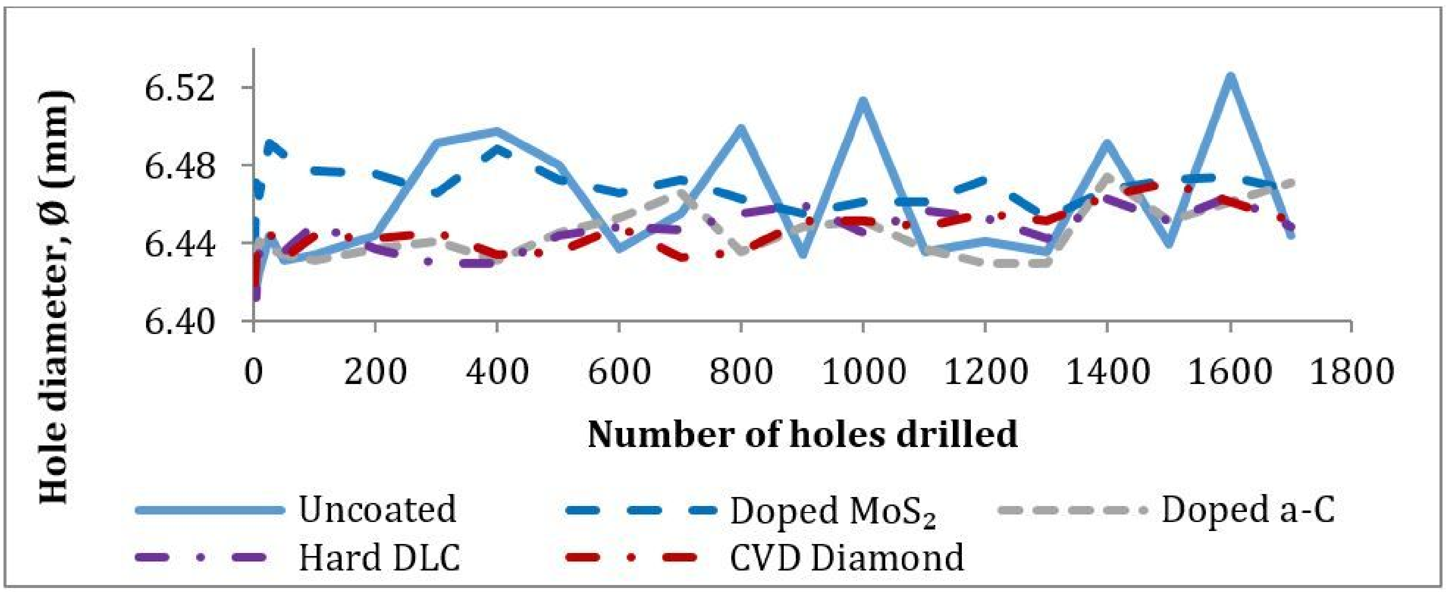

Figure 2

Hole diameter in aluminium alloy 2024

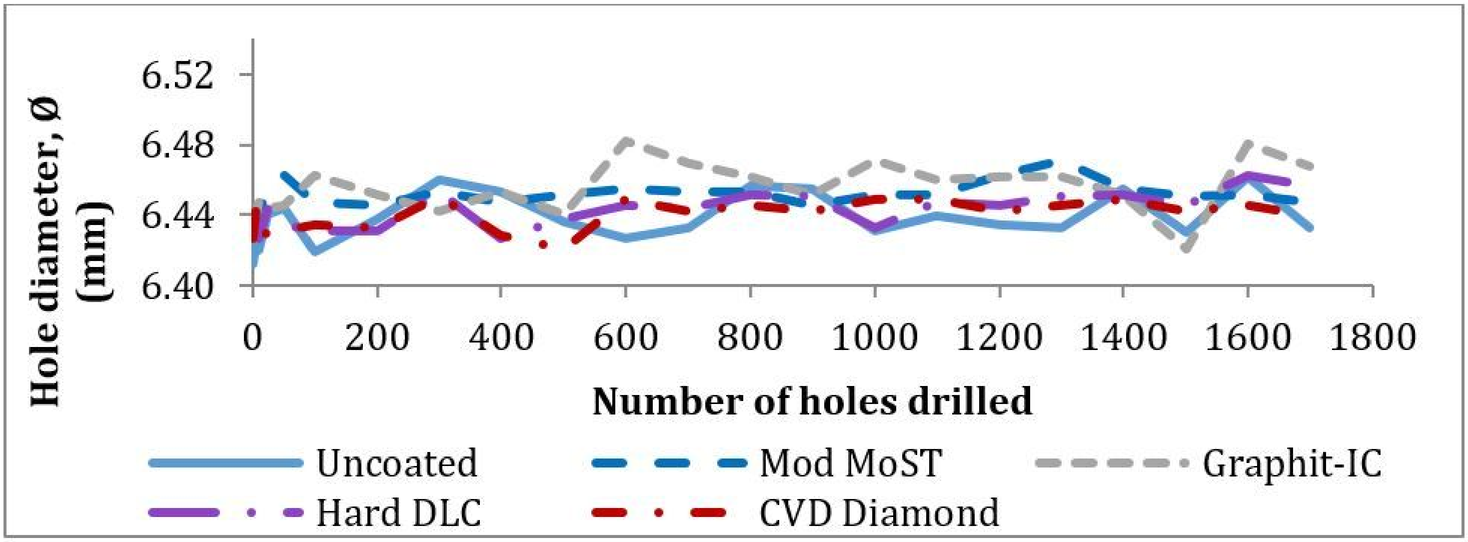

Figure 3

Hole diameter in aluminium alloy 7150

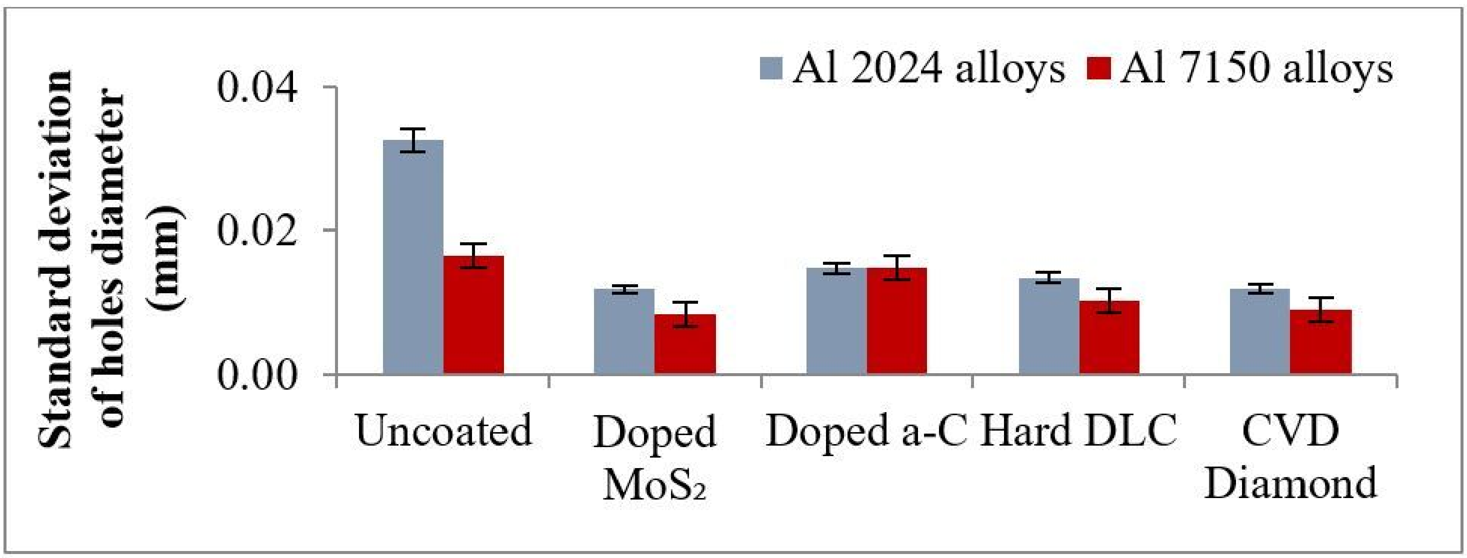

Figure 4

Standard deviation of hole diameters in aluminium 2024 and aluminium 7150 alloys

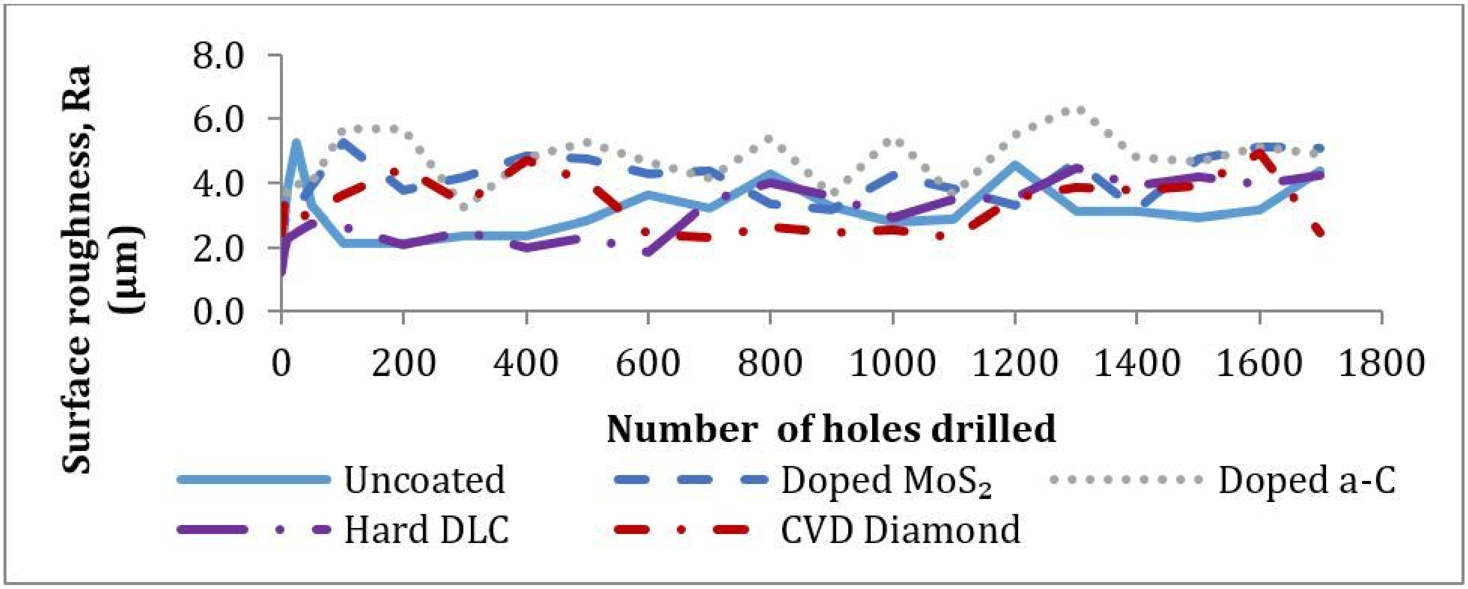

Figure 5

Surface roughness (Ra) in aluminium alloy 2024 drilled holes

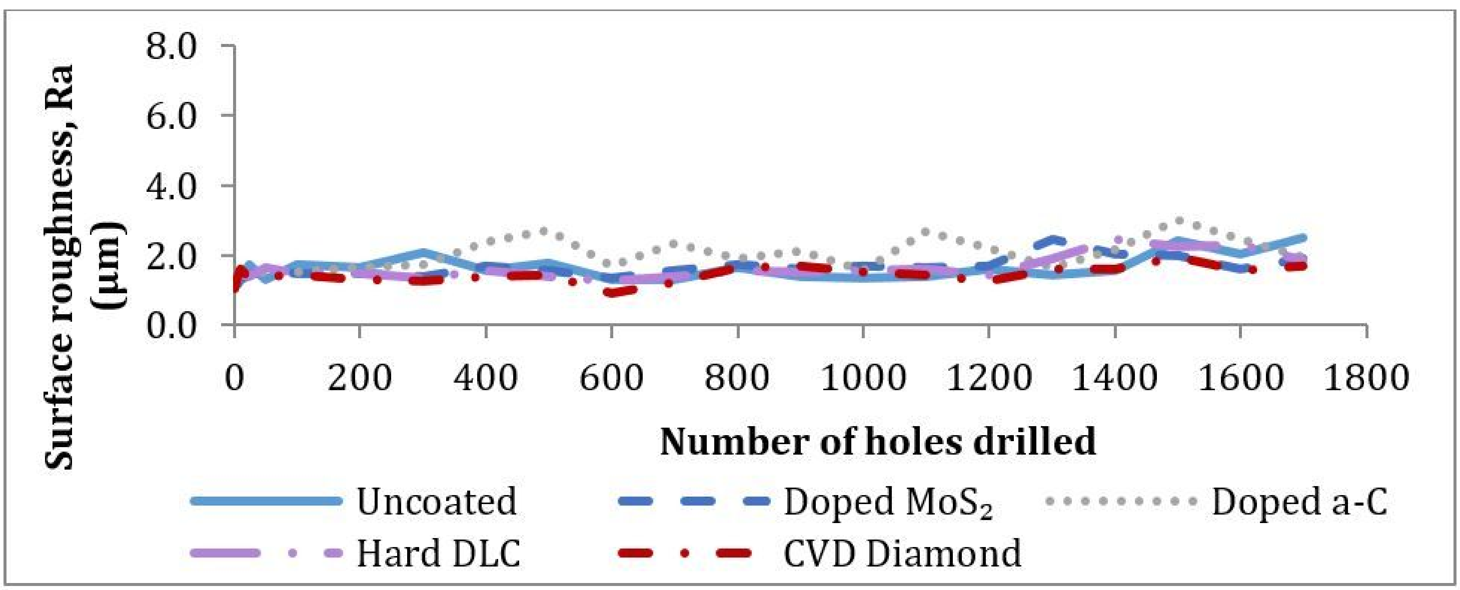

Figure 6

Surface roughness (Ra) in aluminium alloy 7150 drilled holes

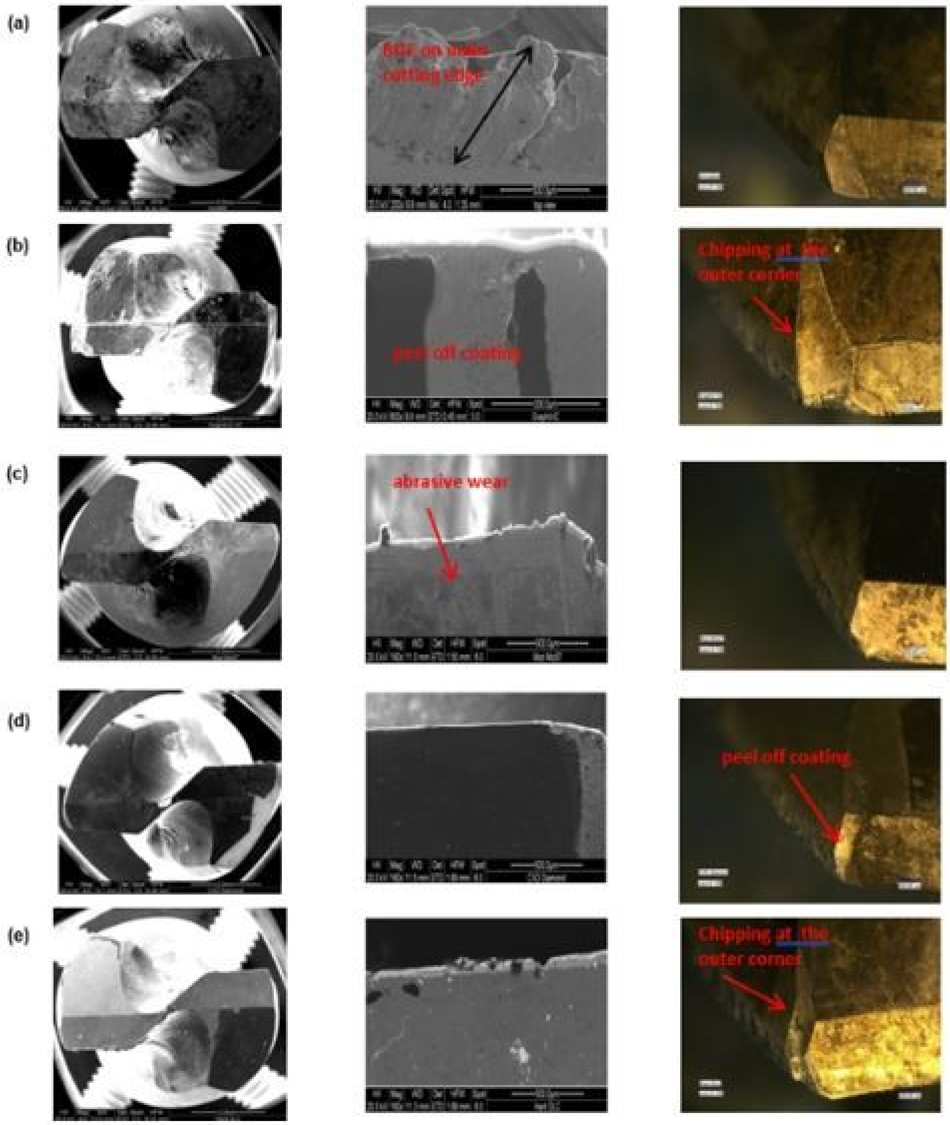

Figure 7

Micrographs of drills after drilling 1728 holes (a) Uncoated (b) Doped a-C (c) Doped MoS2 (d) CVD Diamond (e) Hard DLC

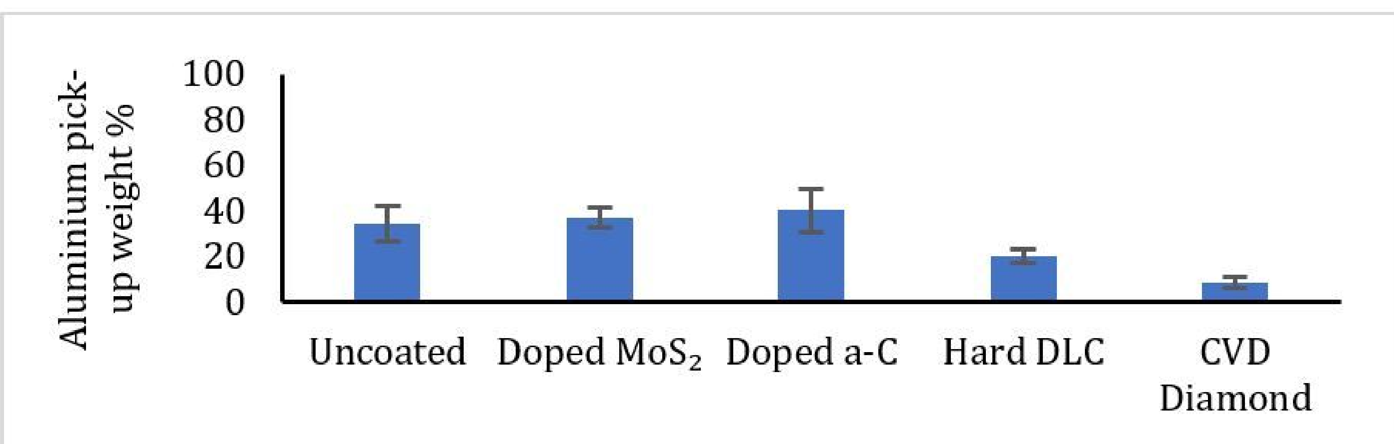

Figure 8

Percentage of aluminium pick up on drills

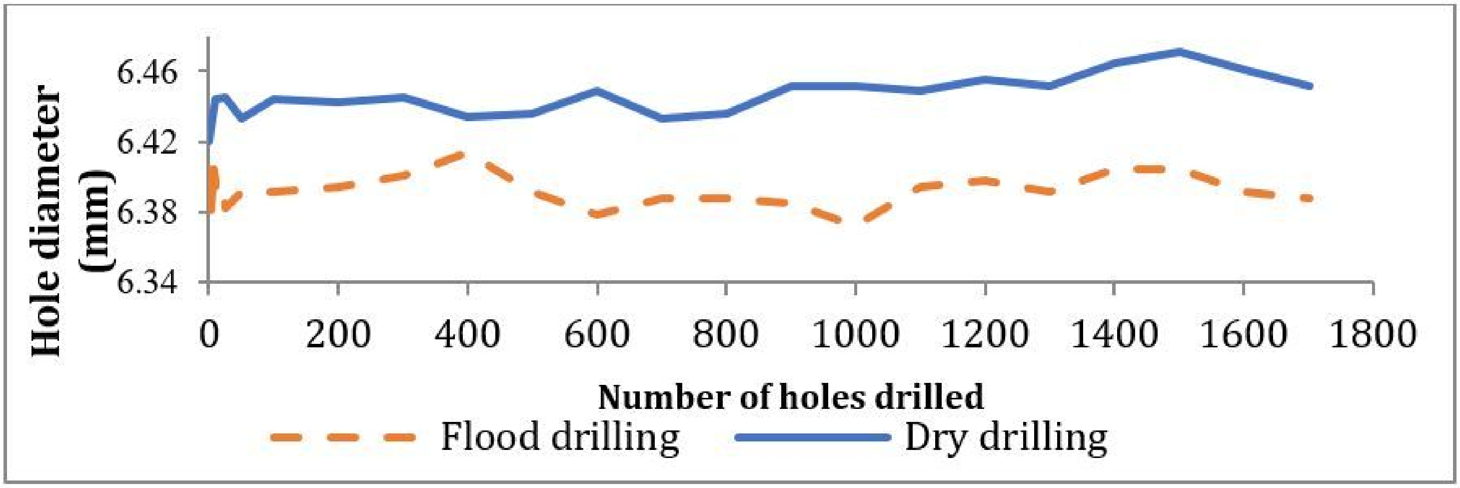

Figure 9

Average hole diameter after using CVD Diamond coated drill in aluminium alloy 2024

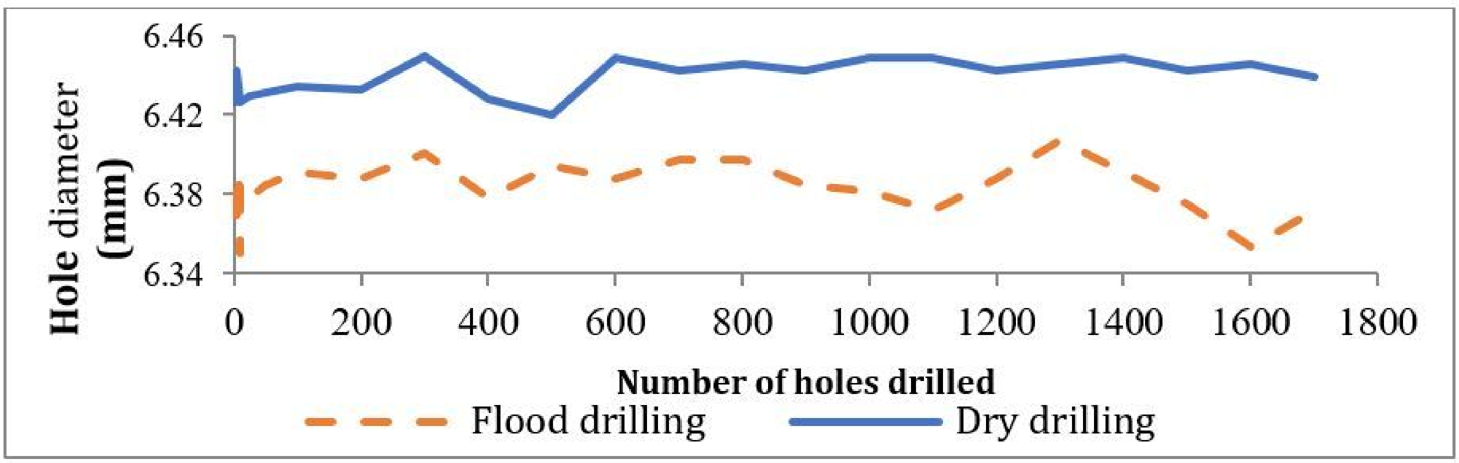

Figure 10

Average hole diameter after using CVD Diamond coated drill in aluminium alloy 7150

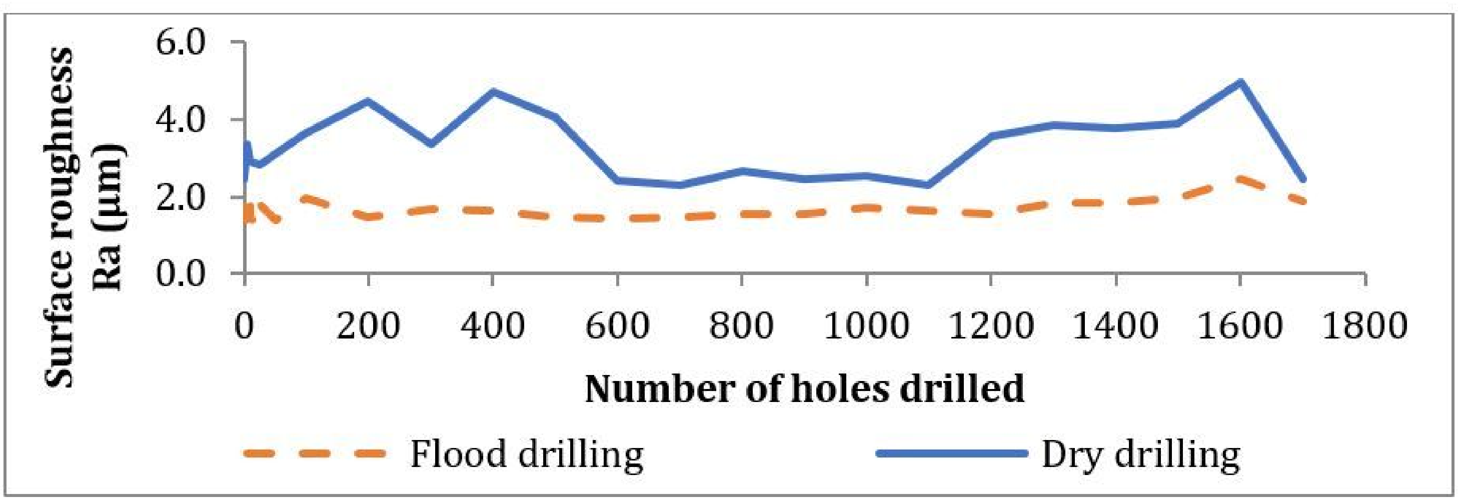

Figure 11

Surface roughness by CVD Diamond coated drill in Al 2024 alloy

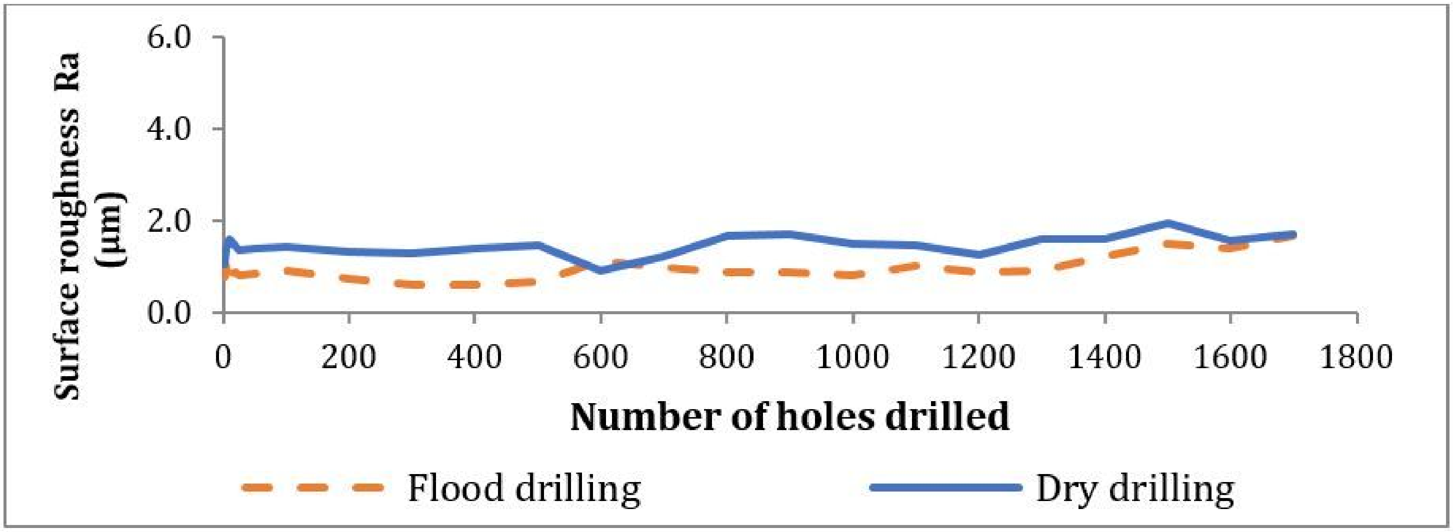

Figure 12

Average hole surface roughness by CVD Diamond coated drill in Al 7150 alloy