Dry Drilling: Feasibility of Aluminium Alloy Stack Material in Aerospace Structures

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Abstract
The aerospace industry drills millions of holes annually on stacked airframe structures. Unfortunately, as the drill breaks through cutting fluid is sprayed on the machining environment and workshop. The scientific challenge is to develop a viable and cost effective drilling process that can operate without cutting fluids. Development of dry drilling processes will enable the aerospace industry to substantial improve the machining environment and addressing the health and safety issues for their workers. The main purposes of this study is to determine the effectiveness of coating capability, effect of machining parameters and influence of swapping the position of stacked materials on the cutting performance and quality of holes drilled. Successful baseline experiments employing various cutting parameters and tool coating were conducted and showed promising results. Trials indicated CVD diamond-coated drills produce remarkable higher thrust compared to other coatings. However, regardless of coating used, most severe deviations of diameters were captured at lower feed and speed. In term of surface roughness, results have pointed out that Standard MoST seem to be the promising coatings in reducing the hole surface roughness.

Keywords: stack workpieces, aerospace structures, coatings

1.0 Introduction

The aerospace industry has developed hybrid stack material for the purpose of enhancing and improving the characteristic of airframe structures. Bi-material which is comprised of two different materials offers significant benefits from their combined materials properties (Cassada, Liu, and Staley, 2002). Owing to excellent resistance to fatigue crack growth, high ductility, and toughness, aluminium 2024 alloy has been one of the most widely used alloys in aircraft fuselage construction (Dursun and Soutis, 2014). However, the alloy has a relatively low yield strength. The needs of higher compressive strength in aircraft structure led to a combination with aluminium 7150 alloys. In response to the increasing concern of safety and health combined with the high costs of maintaining and eventual disposing of cutting fluids, there is paradigm shift from wet to dry machining. Although aluminium is a relatively soft material that can be easily machined (Dasch et al., 2006), drilling these aerospace aluminium alloys is challenging due to these materials tend to adhere to the cutting tool. Moreover, due to absence of cutting fluid, there is an excessive temperature at the tool-workpiece contact area leads to premature tool wear.

Recent advancement in the varieties of tool coatings has been the key driving force in improving the feasibility of dry machining of airframe structures. Important properties of a coating for drill, besides good adhesion to the substrate are; a combination of high wear resistance and abrasion, crater and built-up edge, low friction coefficient hence the reduction in cutting temperature. The application of hard coating benefited in preventing chip-workpiece adhesion, however they are not facilitates in chip removing process. The need for low friction coating has promoted research in to use of soft coating (Coldwell et al., 2004).

A number of studies have exploited the feasibility of dry drilling of aluminium alloys as an aircraft material. Aluminium alloys are among the challenging materials with regard to dry machining. Due to a high level of thermal conductivity, the alloys absorb substantial heat from the machining process. Moreover, the high degrees of thermal expansion cause deformations (Bono and Ni, 2001). Problems associated with chip formation also arise with regard to the low melting and softening point. Many aluminium alloys are susceptible to adhesion with the tool thus led to a remarkable build-up in the flute area. This possibility heightens the potential of chips clogging, excessive and rapid tool wear and also affecting the quality of holes produced. The issues have received considerable critical attention not only to the manufacturing personnel's as the main player but also to the academic researchers to address it. The application of different coatings, developing the ideal tool geometries, accessing various cutting tool and optimizing machining parameters are among the most prevalent options (Nouari et al., 2003; Kalidas, DeVor and Kapoor, 2001; Reddy, Kumar and Thirupathaiah, 2013). This paper will present the results of an investigation to determine the effectiveness of coating capability and effect of machining parameters on the cutting performance and quality of holes drilled of aluminium alloys stack materials used in the aircraft components.

2.0 Experimental detail

The materials used as the stacked workpieces for the experiments are Aluminium alloy 2024 and 7150 supplied by Kyocera with thicknesses of 9.33 and 12.6 mm respectively. Both types of alloy have widespread usage in aircraft structures especially wing and fuselage structures due to interesting mechanical and thermal properties, such as high strength, fatigue resistance and superior strength-to-weight ratio. The specifications of the workpiece materials are listed in Table 1. The coatings tested in the experiments are CVD diamond, Standard MoST, Modified MoST, Standard Graphit-IC, Modified Graphit-IC, Standard TiB_2, Modified TiB_2 and multilayer TiB_2+MoST.

Table 1: Material composition and mechanical properties of workpieces (Aluminum Standards and Data, 2001)

	Aluminium alloy 2024	Aluminium alloy 7150
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

All drilling tests were conducted using a CNC vertical machining HAAS Automation's VF-2SS with a maximum 12,000 rpm inline direct-drive spindle. Prior to the actual trials, a series of pilot studies were conducted by means of DOE approach. Three different cutting parameters were selected: (i) 3000 rpm, 0.15 mm/rev, (ii) 5000, 0.25 mm/rev and (iii) 8000 rpm, 0.4 mm/rev. This selection was made based on open literature in aluminium alloy dry drilling. Holes were drilled in rows, with a centre spacing of 10 mm between consecutive holes. The holes were drilled to a depth of 24 mm.

The drills used for the cutting tests were cemented tungsten carbide tools twist drills, designation NL55 TL 94, manufactured by Kyocera. These drills have a point angle 130° and 40° high helix geometry. All drills measured 6.40 mm in diameter. For each cutting parameter, five holes were drilled so as to get consistent values for thrust and torque measurement. Stacked workpieces of dimension 10 cm by 22.5 cm were clamped centrally on the dynamometer. The thrust and torque measurement data were collected using Kistler Dynamometer 9257A data acquisition system equipped with 3-Channel Amplifier type 5070 and Dynoware software.

The surface roughness of drilled holes was measured using the Taylor Hobson surface roughness instruments Surtronic 25 fitted with an EPT-01049 diamond stylus probe. The diamond stylus tip radius is 5μm with 0.01μm resolution and the system was set at a sampling length of 0.25 mm and drive speed of 1mm/sec. Hole cylindricity was inspected using a coordinate measuring machine (CMM) Nikon LK G-90C equipped with Camio Software for data acquisition. To obtain the average diameter of holes, ten-touches points were coordinated on the circumference of cross-sectional diameters at successive depths of 1mm starting at the top, 4.7/6 mm at the middle and 8/11 mm at the bottom for each alloys component.

3.0 Results and discussion

3.1 Measurement of cutting force/torque

Thrust force is generated by the chisel edge of the drilling tool as it cuts the workpiece. Figure 1 shows an average thrust force in all experimental conditions. Results point out that for the top skin material, average thrust forces were smaller with Graphit-IC coated drill regardless of standard or modified types in all experiments. This might be due to the characteristic of Graphit-IC coating, which has the ability to minimize the adhesion of material to the drill. The coating most likely improved the lubricity at tool-workpiece contact, thus reducing the machining forces.

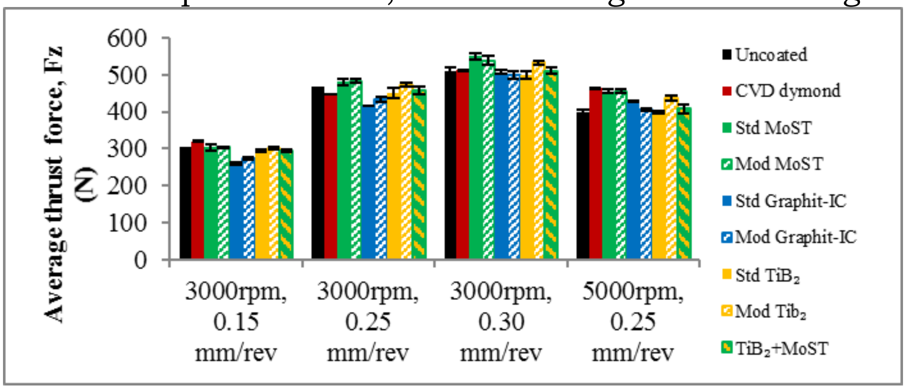

Figure 1: Average thrust forces in Al 2024

However, different outcomes were observed in bottom skin material (see Figure 2). MoST seem to be the promising coatings in reducing the average thrust force in harder material. The results also indicated that CVD diamond-coated drills produce remarkably higher thrust force in the entire test window for Al 7150.

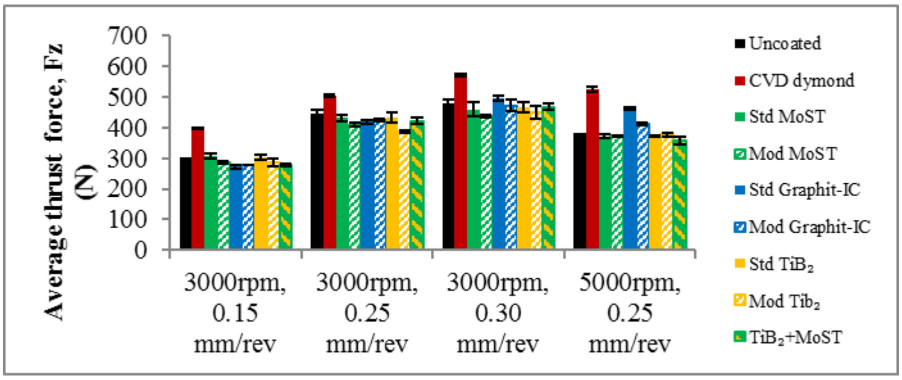

Figure 2: Average thrust forces in Al 7150

The recorded torque values varied considerably throughout the test. According to the graph in Figure 3, even the value of torque does not have much difference between each coating; both modified Graphit-IC and standard TiB_2 coated drills exhibit much lower torques in Al 2024 components. This finding suggested that chip evacuation while drilling with these three coated drills in softer material was more efficient than other coatings tested.

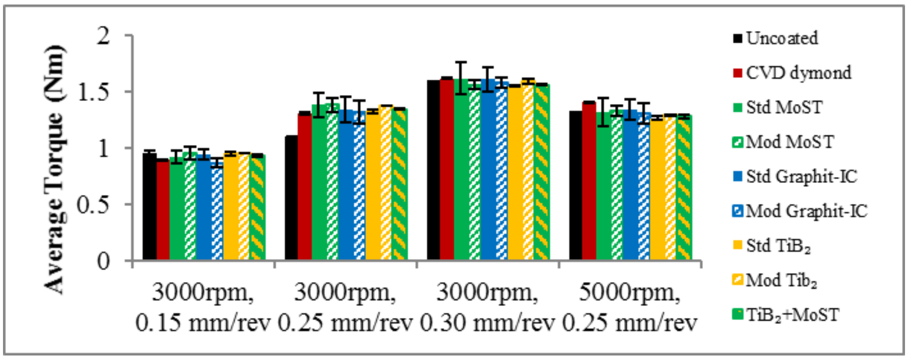

Figure 3: Average torque in Al 2024

For bottom skin material (see Figure 4), it seems that standard and modified Graphit-IC yields not much difference compared to CVD diamond, which remarked as the highest torque emitted than other coatings.

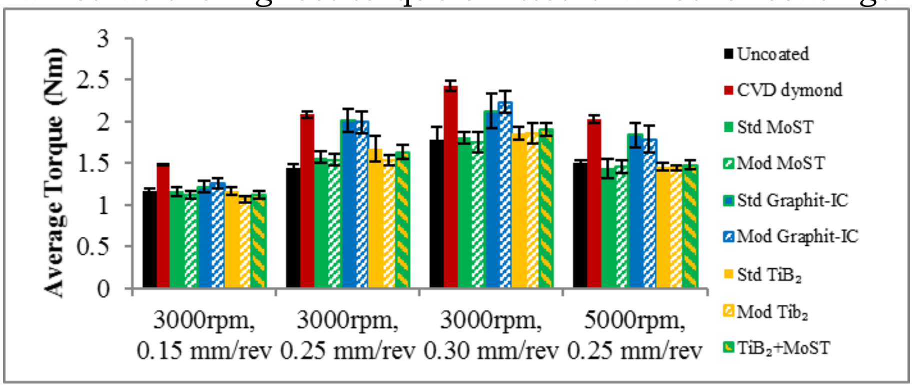

Figure 4: Average torque in Al 7150

In all test conditions, all coatings show increased torque in bottom skin material compared to the first material. Practically, as tool drilling through the components, due to increase of contact area between tool and hole surfaces, the torque possibly will increase as a result of difficulties in removing chips from the deep hole. In this experiment, significant increase of torque when the tool was drilling the second material was observed with CVD diamond and modified Graphit-IC coated drill than other coatings, as shown in Figure 5. The charts indicated high amount of torque variation obtained in CVD diamond and Modified Graphit-IC associated to occurrences of chip clogging in the bottom material.

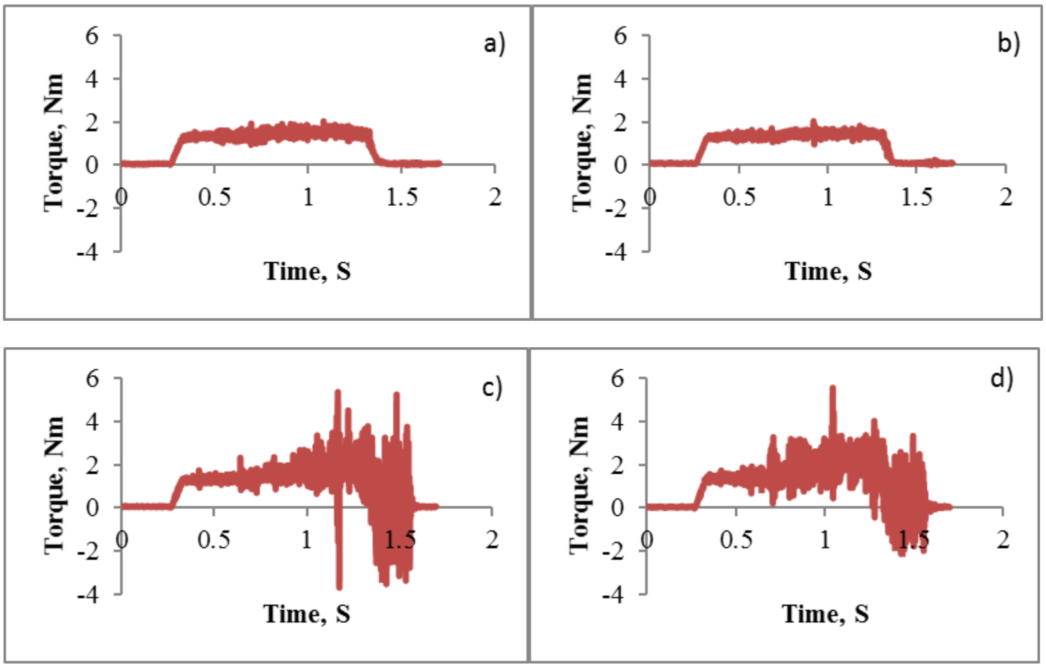

Figure 5: Torque profiles at 5000 rpm, 0.25 mm/rev for a) Uncoated b) Mod MoST c) Modified Graphit-IC d) CVD Diamond

In relation to cutting parameters, this experiment has found that the minimum values for torque and force shown at lowest speed and feed rate (3000 rpm and 0.15 mm/rev). Overall figures have suggested that the increase of force and torque was consistent with the increase of feed rate. There were small differences observed of torque and forces measurements when data was compared at different feed rate but with the same speed; however, the discrepancies were not significant.

3.2 Measurement of surface roughness and diameter deviation

Aiming at establishing the effect of coating from quality of holes perspectives, two responses were evaluated, which are surface roughness and diameter deviation of the workpiece. Figure 6 and 7 give information about Ra measured after completed the experiments. With regards to surface roughness in Al 2024, it was clearly shown that by average Standard MoST coated drill produced the lowest surface roughness in all tests. Meanwhile, CVD diamond, standard Graphit-IC and modified Graphit-IC were three coatings which show significantly rougher surface finish in the entire test window. A major factor that effect surface roughness is cutting edge radius. The thickness of CVD diamond coated drill is relatively bigger than other coatings, subsequently give much bigger cutting edge radius. As the radius of the cutting edge increases, plowing effect become more predominant, resulting in much deteriorated surface finish.

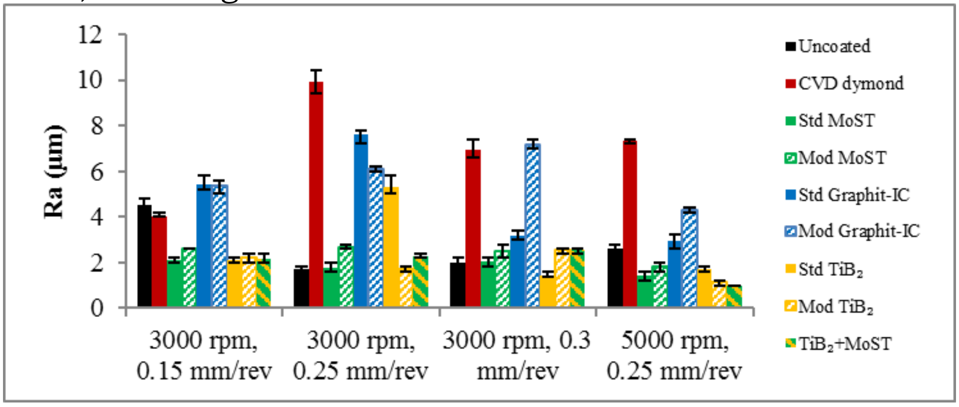

Figure 6: Ra in Al 2024

The surface roughness measurements in the second material are substantially smaller than the first material. Uncoated drill gave the maximum roughness value at higher cutting speed. Throughout the entire cutting conditions, modified MoST coated drill outperformed other drills in keeping the lowest surface finish. Minimum Ra value was found a machining parameter of 3000 rpm and 0.3 mm/rev. If the consideration were made based on Ra value, thus these results have pointed out that Modified MoST is the best coating for dry drilling of aluminium alloy.

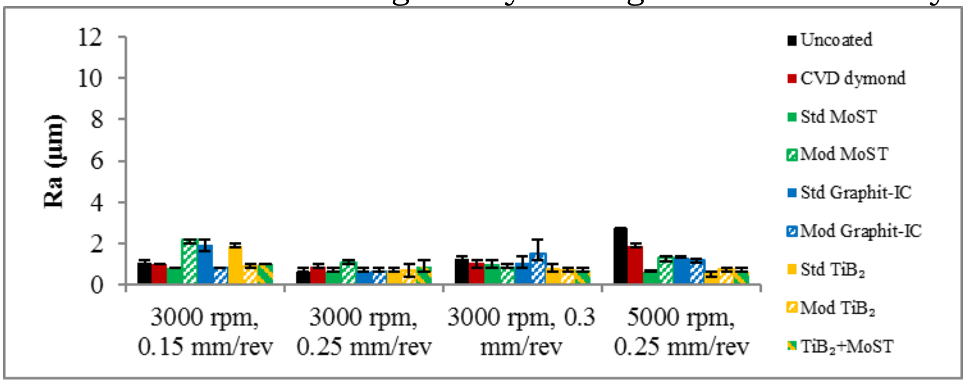

Figure 7: Ra in Al 7150

For Al 2024, as cutting speed increase, all coatings show an improvement in surface finish. Standard Graphit-IC and standard TiB_2 coated drill shows considerable decrease of Ra for more than 60%. However, the trends for second materials contradict the earlier findings. Only standard TiB_2 and a multilayer of TiB_2+MoST coated drill demonstrates a decrease in Ra whereas the other coatings indicated the opposite trend. The largest difference was shown by uncoated drill when it rose to 2.728 µm, about four times folded compared to reading at 3000 rpm spindle speed.

The next parameter evaluated was the diameter deviation. Figure 8 illustrates hole diameter deviations at all condition tested. Consistent with the surface roughness, in general, the deviation is most likely to happen more on the top region, which is Al 2024. It was clear that there was a significant interaction between those two responses. CVD diamond coated drill produced maximum diameter deviation at both 0.25 mm/rev and 0.3 mm/rev feed rate with cutting speed of 3000 rpm. However, at highest speed test in the experiment, uncoated drill exhibited the most serious deviation compared to other coatings. All throughout, not only producing deviation within allowable tolerances, both standard and modified MoST MoST also gave the lowest diameter deviation, which revealed to be the best coatings among the other coatings tested in the experiments.

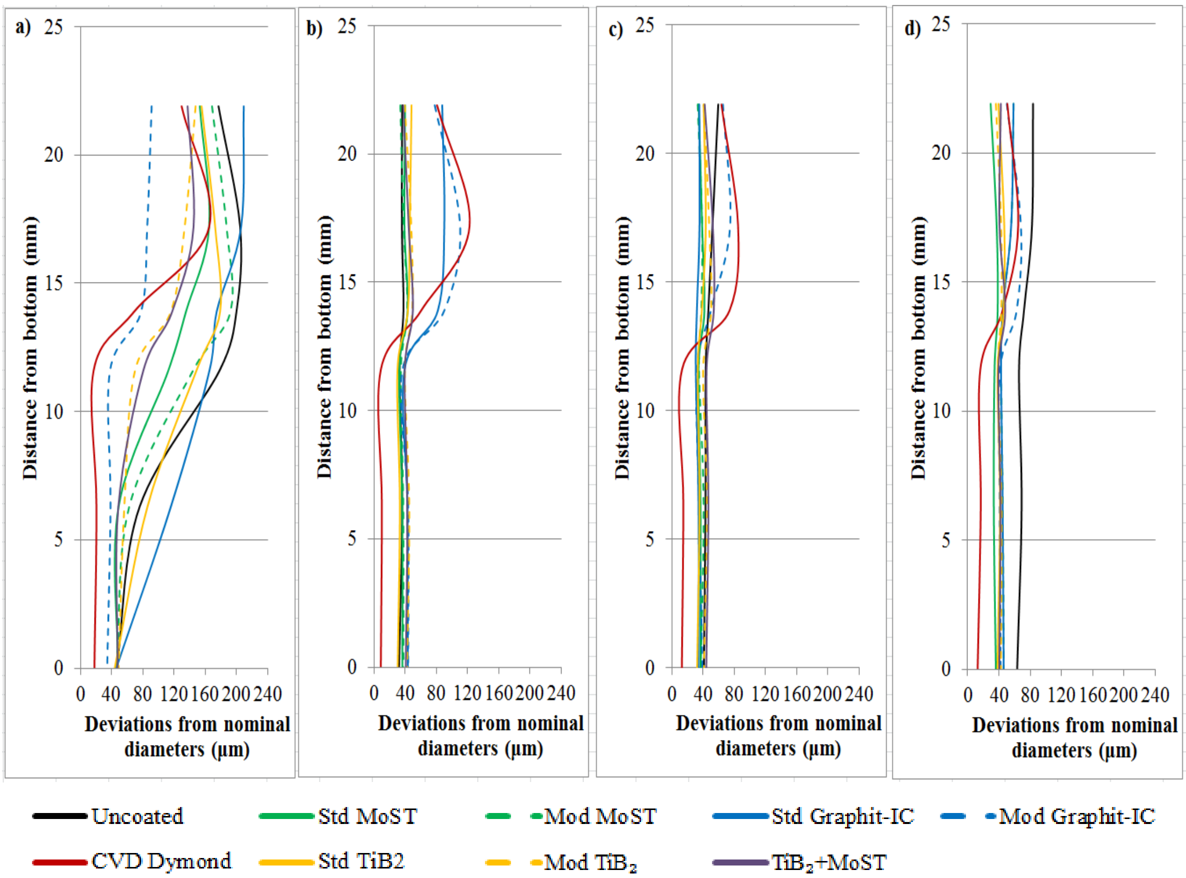

Figure 8: Holes profiles at a) 3000 RPM, 0.15 mm/rev b) 3000 RPM, 0.25 mm/rev c) 3000 RPM 0.4 mm/rev d) 5000 RPM, 0.25 mm/rev

To correlate between cutting parameters and diameter deviation, the theme identified in these responses becomes more consistent as we move from both lower feed rate to higher feed rate or lower speed to higher speed. In all trials, a majority of coated drills illustrates a similar pattern of deviations, regardless of the cutting parameters. The single most striking observation to emerge from the data comparison was the dispersion at cutting parameters of 3000 rpm and 0.15 mm/rev. All drills show the most severe deviations of diameters at lower feed and speed. Interestingly, apart from the feed, the uncoated drill was observed to be influenced from cutting speed as well. At 3000 rpm and 0.25 mm/rev, the dispersion is below 50 microns; however, the measurement goes beyond the tolerance when speed was increased to 5000 rpm. Strong evidence of ideal cutting parameters was found in the these findings that the smallest deviation happened at cutting parameters of 3000 rpm; 0.25 and 0.3 mm/rev.

3.3 Cutting sequence strategy

The second part of the study was designed to determine the effect of changing the cutting sequence. Uncoated drill and three different coatings were compared in this work; standard MoST, multilayer TiB_2+MoST multilayer coatings and modified Graphit-IC. All the coatings deposited on drills by Teer Coatings Ltd. The specific chemical composition of each coating was not revealed due to confidentiality.

a. Analysis of thrust force/torque variation

The variation of thrust force and torque response obtained in two different drilling sequence is presented in Figure 9 (a) and (b). In general, thrust force signals depicted in either Al 2024 → Al 7150 or Al 7150 → Al 2024 cutting sequence demonstrates identical response and stages as mentioned earlier.

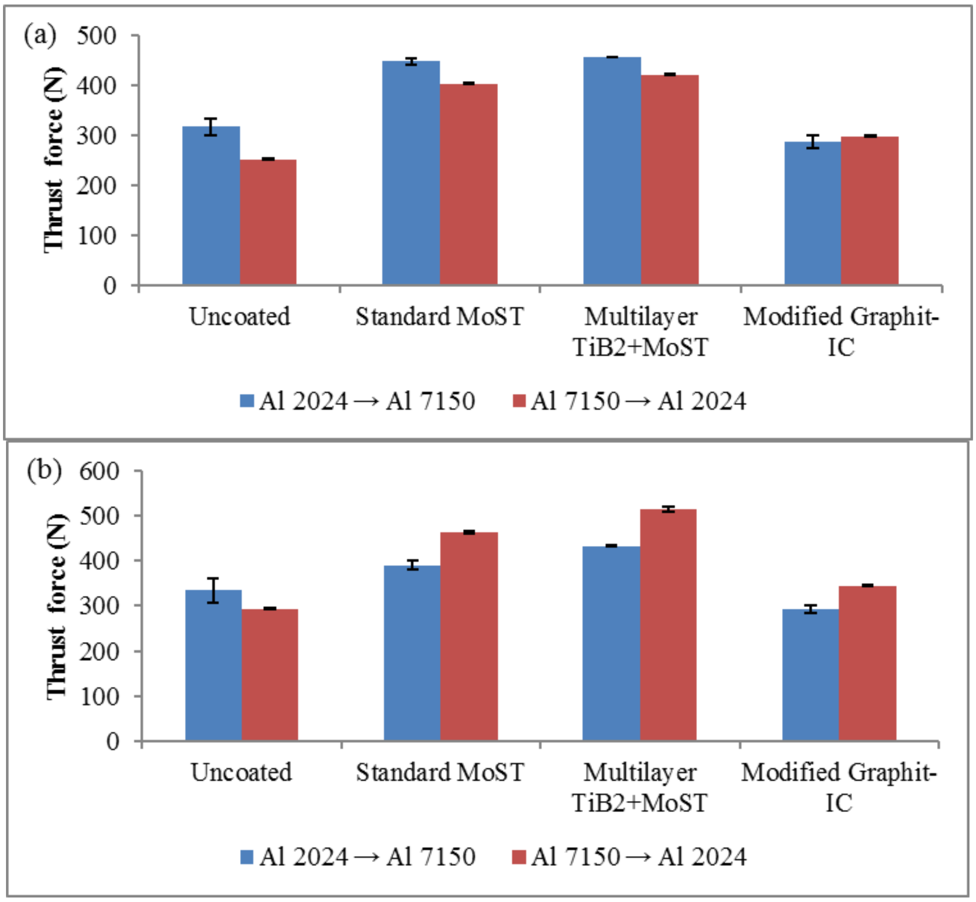

Figure 9: Comparison of thrust force magnitudes in different cutting sequences (a) Thrust force in Al 2024 (b) Thrust force in Al 7150

It can be seen from the data in Figure 9 (a) that, comparing thrust force magnitude in Al 2024, drilling from softer to harder materials (Al 2024 → Al 7150) exhibit relatively lower force magnitudes than those shown in the harder → softer (Al 7150 → Al 2024) cutting sequence for all coated drills used in the experiment. Specifically, a reduction of 4 to 45 N was seen in the new cutting sequence. Since thrust force measurement could also be related to chips evacuation, it may be the case therefore that these variations of force were due to the influence of chip transportation mechanism inside the drilled holes. When drilling from softer and stickier material, the Al 2024 chips could quickly evacuate from holes, thus produced less effect on thrust force measurement. In contrast, as the drilling sequence was changed, chips from Al 2024 at the lower stack required longer time and relatively more difficult to fully evacuated from the holes drilled. As a result, during the evacuation process, those chips produced a remarkable scratching effect to Al 7150 holes surfaces which have led to the higher amount of force produced. Further, Figures 10 depicts the comparative torque generation in each workpiece. Basically, the torque generated during drilling follow the same trend as force irrespective of cutting sequences. The torque pattern reflects the engagement of the drill to work material therefore attributed to evacuation force magnitude. Higher magnitudes of torque were recorded for all drills when drilling was operated from Al 7150 → Al 2024 suggested the possibility of chip clogging in the drill flutes.

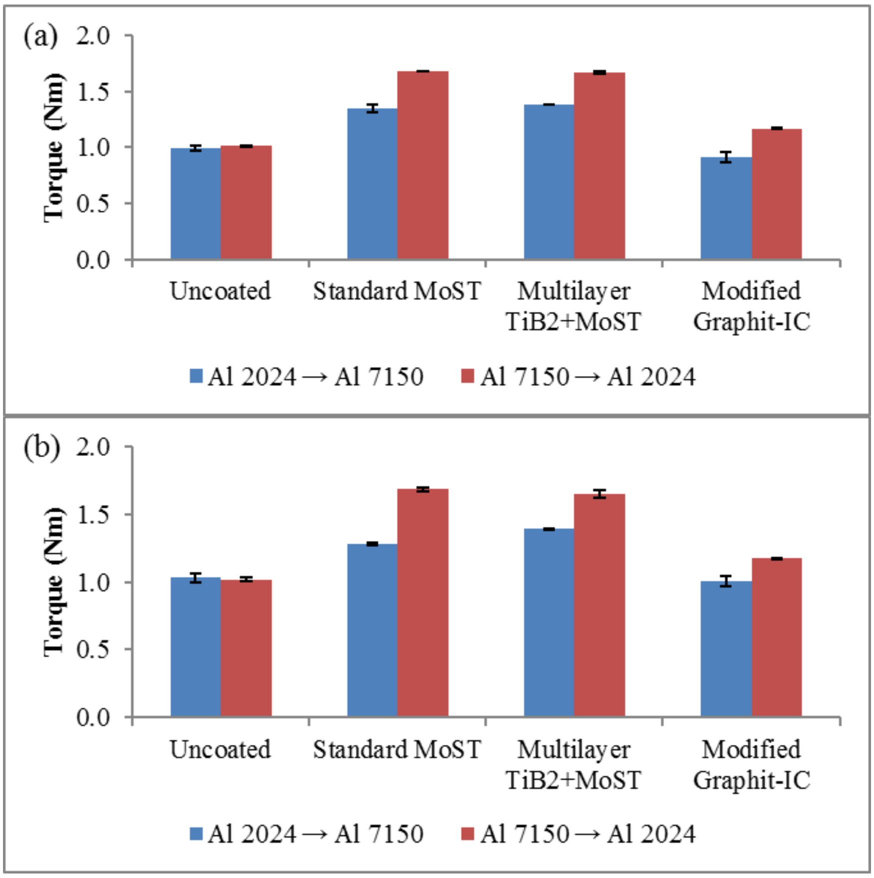

Figure 10: Variation of torque in different cutting sequences (a) torque in Al 2024 (b) torque in Al 7150

b. Analysis of surface roughness

Figures 11 illustrates the average surface roughness when drilling stack plates using different cutting sequence. As shown in these figures, the roughness values measured in the Al 2024 under Al 7150 → Al 2024 cutting sequence were significantly lower than the counterpart ones for all coated drills. Specifically, a Graphit-IC coated-drill by far illustrate the greatest benefits of the new drilling strategy. Average roughness dropped by more than half in this coating compared to initial cutting sequence. The improved surface roughness variables from new cutting sequences as shown by other coated drills, however, seems to be irrelevant for the uncoated drill. In fact, the average roughness in the workpiece drilled by the uncoated drill increased about 31% from the initial cutting sequence.

In contrast, for Al 7150, the roughness measured when drilling from harder material was much higher than those measured from softer one (Al 2024 → Al 7150). These results support the idea of previous force/torque response that Al 2024 chip evacuation affected the drilled Al 7150 hole surface.

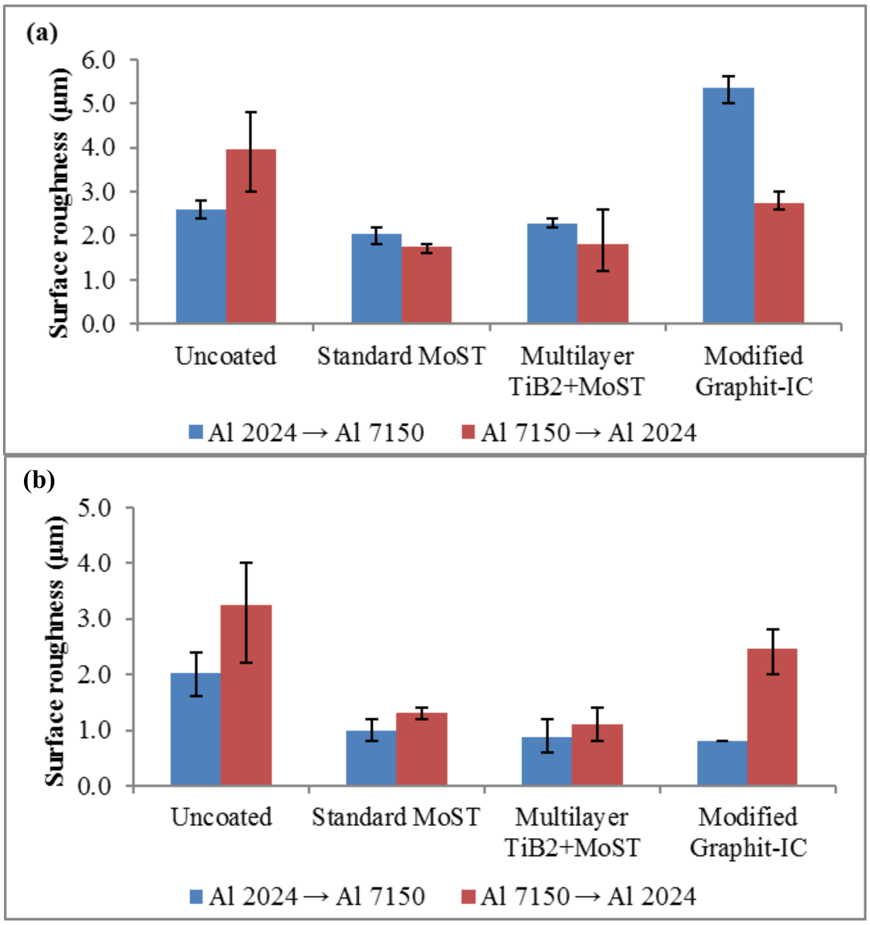

Figure 11: Variation of surface roughness in different cutting sequences (a) Ra in Al 2024 (b) Ra in Al 7150

A possible explanation for this might be that when drilling from a softer material, the sticky Al 2024 chips could quickly transport from the top part of the drilled holes thus will not produce any scratching effect on Al 7150 holes surface. On the contrary, when drilling from a harder material, during the evacuation process, a significant abrasion action exists between continues and sticky Al 2024 chips that generated at the bottom part of the stack with the upper part of drilled hole surfaces. This interaction caused severe deterioration to the hole wall. As a result, the roughness measured in Al 7150 were higher than previous cutting sequence.

4.0 Conclusion

The dry drilling performance of eight tool coatings were tested against Al 2024/7150 stack components using the performance of uncoated carbide drills as a baseline. The key observations can be summarized. With respect to the top skin material, average thrust forces were smaller with Graphit-IC coated drill regardless of standard or modified types in all experiments. Meanwhile, modified MoST and Modified TiB_2 seem to be the promising coatings in reducing the average thrust force in bottom skin material. The surface roughness measurements in the second material were substantially smaller than the first material. Standard MoST coated drill produced the lowest surface roughness in all tests. Due to bigger cutting edge radius, CVD diamond coated drills tend to produce rougher surface finish. All drills show severe deviations of diameters at lower feed and speed. Both standard and modified MoST also gave the lowest diameter deviation, which revealed to be the best coatings among the other coatings tested in the experiments. Shifting the drilling sequence from Al 2024 → Al 7150 to Al 7150 → Al 2024 seems to have a positive effect for all coated drills in term of average thrust force and surface roughness of the Al 2024 material. However, no significant improvement was found in the uncoated drill when drilling was operated from harder to the softer material or vice versa. Considering observations 1-4, this study concludes that mid-range spindle speed and feedrate is a good compromise for superior for dry drilling of aluminium alloy stack material for aerospace airframe application to reduce drill interaction time and energy input and improve the quality of holes produced.

References

2000 Aluminum Standards and Data. (2001). *Matweb-material properties.* retrievedfrom..http://www.matweb.com/search/GetReference.aspx?matid=8865

Bono, M., & Ni, J. (2001). The effects of thermal distortions on the diameter and cylindricity of dry drilled holes. *International Journal of Machine Tools and Manufacture, 41*(15), 2261–2270. https://doi.org/10.1016/S0890-6955(01)00047-5

Cassada, W., Liu, J., & Staley, J. (2002). Aluminium for aircraft.pdf. *Advanced materials and processes*, 27–29.

Coldwell, H. ., Dewes, R. ., Aspinwall, D. ., Renevier, N. ., & Teer, D. . (2004). The use of soft/lubricating coatings when dry drilling BS L168 aluminium alloy. *Surface and coatings technology*, *177–178*, 716–726. https://doi.org/10.1016/j.surfcoat.2003.08.012

Dasch, J. M., Ang, C. C., Wong, C. a., Cheng, Y. T., Weiner, A. M., Lev, L. C., & Konca, E. (2006). A comparison of five categories of carbon-based tool coatings for dry drilling of aluminum. *Surface and coatings technology, 200*(9), 2970–2977. https://doi.org/10.1016/j.surfcoat.2005.04.025

Dursun, T., & Soutis, C. (2014). Recent developments in advanced aircraft aluminium alloys. *Materials and design*, *56*, 862–871. https://doi.org/10.1016/j.matdes.2013.12.002

Kalidas, S., DeVor, R. E., & Kapoor, S. G. (2001). Experimental investigation of the effect of drill coatings on hole quality under dry and wet drilling conditions. *Surface and coatings technology*, *148*(2–3), 117–128. https://doi.org/10.1016/S0257-8972(01)01349-4

Nouari, M., List, G., Girot, F., & Coupard, D. (2003). Experimental analysis and optimisation of tool wear in dry machining of aluminium alloys. *Wear*, *255*(7–12), 1359–1368. https://doi.org/10.1016/S0043-1648(03)00105-4

Reddy, A. S., kumar, G. V., & C.Thirupathaiah. (2013). Influence of the cutting parameters on the hole diameter accuracy and the thrust force in drilling of aluminium alloys. *International Journal of Innovative Research in Science, Engineering and Technology*, *2*(22), 6442–6450.