Investigating hole making performance of Al 2024-T3/Ti-6Al-4V alloy stacks: A comparative study of conventional drilling, peck drilling and helical milling

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Received: 1 December 2021 / Accepted: 14 March 2022 / Published online: 24 March 2022 © The Author(s) 2022

Abstract
This work reports a comparative study on different hole making methods, namely conventional drilling, peck drilling and helical milling, for Al 2024-T3/Ti-6Al-4V stacks in aircraft applications. The impacts of different hole making methods with constant or varied machining parameters across the stacked structures have been investigated. The resulting exit burr, hole surface roughness/microstructural change and fatigue behaviour of the machined stacks have been characterized in detail. Results show that the exit burr formation is most severe for conventional drilling and least burr is produced in helical milling coupons. Deploying varying parameters (i.e. optimal parameters for each individual metal layer) across the stacks can effectively reduce the burr formation in conventional drilling and peck drilling. 3D surface morphology shows that Al 2024-T3 hole surface contains multiple scratches and trenches, while Ti-6Al-4V hole surface features regular feed marks. Helical milling leads to the highest Al 2024-T3 hole surface roughness, which can be attributed to the abrasion caused by the evacuated Ti-6Al-4V chips. Sub-surface microstructural analysis shows that the Ti-6Al-4V layer is more prone to machining-induced microstructural change (i.e. white layer formation and/or grain plastic deformation along machining direction). The relatively low fatigue performance of stacks produced by conventional drilling and peck drilling with constant parameters can be related to the presence of the brittle Ti-6Al-4V white layer in these coupons. Deploying varied parameters across stacks in conventional drilling and peck drilling can effectively eliminate Ti-6Al-4V white layer formation and improve the stacks fatigue life by 72% and 38%, respectively. Helical milling leads to the longest stack fatigue life (~100% and 40% greater than conventional drilling and peck drilling, respectively).

Keywords Al 2024-T3/Ti-6Al-4V stack · Drilling · Helical milling · Fatigue

1 Introduction
Aluminium alloy/titanium alloy stacks are typical stacked structures deployed in aerospace applications, particularly in manufacturing of aircraft wings and frames [1]. Such stacked materials are designed to provide enhanced mechanical properties such as high stiffness-to-weight ratio [2]. To date, mechanical fastening is still considered the most pivotal process for joining stacked materials in aircraft assembly [3] and millions of fastener holes are produced each year. Fastener holes are known to be the common sites for fatigue crack initiation and propagation, which accounts for 55% of in-service failure of aircraft structural components [4]. Therefore, effective hole making process which produces qualified holes is highly desirable for enhancing productivity and ensuring the reliability of the aircraft.

One-shot conventional drilling would be a preferred process for hole making of stacked materials due to its better positional accuracy and productivity. However, the conventional drilling for Al and Ti alloys has shown several limitations, such as high thrust force, poor heat dissipation and severe drill exit burr [2]. In addition, the drill bit is prone to severe damage including flank wear, edge chipping and adhesion [5], especially in drilling of difficult-to-machine
Ti alloys. The hole making performance of conventional drilling can be crucially affected by the drilling parameters (mainly feed rate and cutting speed) and tool geometry. Previous studies show that in drilling of Ti-6Al-4V [6] and Al 2024 [7] alloys, thrust force increases with feed rate as a result of increased chip thickness and material removal rate. Aamir et al. [8] carried out analysis of variance (ANOVA) for drilling of AA2024-T3. Results showed that percentage contribution of feed rate, drill size and spindle speed was 67.33%, 29.53% and 0.81%, respectively. Cantero et al. [9] carried out dry drilling of Ti-6Al-4V and significant microstructural change (white layer) was observed on the machined surface and the thickness of white layer increased with tool wear. Zhu et al. [10] compared different drill bits in hole making of Al 2024-T351/Ti-6Al-4V stacks. Results show that double cone drill produces lower thrust force as compared to step drill and multipoint drill. Adhered Ti-6Al-4V chips were found on all drill bits’ cutting edges. Giasin et al. [7] conducted full factorial experiment on drilling of Al-2024-T3, and the thrust force and the resulting burr height both increase with feed rate and decrease with spindle speed. Zhu et al. [11] investigated the hole making performance of TiAlN-coated and uncoated drill bits in drilling Al 2024-T3/Ti-6Al-4V stacked material. They reported that the thrust force of uncoated tool was ~10 N higher than that of coated tool. Additionally, cutting speed played a more influential role in determining hole diameter, roundness and cylindricity for both types of cutting tools. Bonnet et al. [12] established a multi-scale model based on material local deformation. The model is proven effective in simulating heat generation and transfer during drilling of Ti-6Al-4V. Tian et al. [13] developed a regression model to predict the tool wear in longitudinal-torsional composite ultrasonic vibration-assisted drilling of Ti-6Al-4V. Results showed that the model can accurately predict the tool flank wear with an average error of 6.05%.

Peck drilling is another common hole making method where the drill bit is fed into predetermined depth of the workpiece in each step and then retracted to the initial position above the workpiece surface before the next cutting step. Peck drilling is known to prolong the drill bit tool life [14] in Ti alloy hole making and is effective in improving chip removal and heat dissipation, especially for deep holes [15]. However, there is a lack of literature on peck drilling of Al/Ti stacks, where the complex interaction of the chips with the two metal layers, as well as the resulting hole quality is yet to be understood.

In recent years, helical milling process has emerged as an alternative hole making method for aerospace stacked materials. This technique has several advantages over conventional drilling, including reduced cutting force, better heat dissipation and improved chip evacuation condition [16]. Qin et al. [17] conducted a comparative study on helical milling and conventional drilling of Ti-6Al-4V. Results showed helical milling generated lower cutting force, less tool wear and higher machining accuracy compared to conventional drilling. Sun et al. [2] compared conventional drilling and helical milling in terms of the machined hole microstructure and post-machining fatigue behaviour of Ti-6Al-4V and Al 2014-T3. Experimental results showed that helical milling resulted in less severe plastic deformation in both Ti-6Al-4V and Al 2014-T3, leading to longer coupon fatigue life compared to that of conventional drilling. Chen et al. [18] compared the hole making performance of conventional helical milling and ultrasonic vibration helical milling (UVHM). Results suggested that UVHM produced less hole-diameter error and lower surface roughness, but larger hardness of the hole subsurface. In another comparative study, Zhao et al. [19] investigated the influence of helical milling and conventional drilling of Ti-6Al-4V alloy on the resulting tool wear and hole surface integrity. It was found that the tool life of helical milling cutter was much longer than that of the drill bit under the same cutting speed and feed rate. Furthermore, the authors confirmed that helical milling has led to a compressive residual stress within the machined hole surface, which can potentially improve the fatigue performance of the machined workpiece.

In drilling of Al 2024-T3/Ti-6Al-4V stacks, the disparate mechanical and thermal properties of Al 2024-T3 and Ti-6Al-4V layers present additional challenges. For example, high feed rate and cutting speed are favourable for hole making of Al 2024-T3 alloys to mitigate the built-up edge effect [20, 21], whereas low cutting speed is usually required for hole making of Ti-6Al-4V alloys to reduce the cutting temperature [22]. As such, adaptive hole making process that utilizes different parameters optimized for each individual layer at different stages of machining has been proposed [23, 24].

To date, there is a lack of comparative study on different hole making techniques under the context of Al 2024-T3/Ti-6Al-4V stacks. The research concerning the hole surface/subsurface damage produced under constant/varying hole making parameters across the stack, as well as the fatigue performance of the stacked coupon with open holes, is yet to be investigated. In this study, different hole making methods, namely conventional drilling, peck drilling and helical milling, have been investigated for hole making of Al 2024-T3/Ti-6Al-4V stacks. In particular, the effect of constant and varied machining parameters across the stack has been investigated, and the resulting drill exit burr formation, hole wall morphology/microstructure change and the machined workpiece fatigue life have been compared.
2 Experiment

2.1 Materials

Al 2024-T3 alloy sheet manufactured in accordance with British standards BS EN 2090:2005 was provided by Smiths Advanced Metals, UK. Grade 5 Ti-6Al-4V titanium alloy manufactured in accordance with AMS 4911 standard was supplied by NeoNickel, UK. The nominal chemical compositions and mechanical properties of the Al 2024-T3 and Ti-6Al-4V alloys are summarized in Tables 1, 2, 3 and 4.

2.2 Cutting tools

Eight-millimetre carbide jobber drill bits (GUHR No.5517, K10-K20 grade) and 6-mm carbide end mill cutters (GUHR No.6716) were purchased from MSC industrial supply, UK. The carbide twist drill bits have a point angle of 118 degree, a flute length of 75 mm and an overall length of 117 mm. The 4 flute end mill cutters have 30-degree right hand spiral flutes, with a cutting edge length of 13 mm and an overall length of 63 mm. The end mill cutters were coated with TiAlN SuperA coating to enhance their abrasion resistance.

2.3 Test coupons

The metal sheets were cut into 100 mm×20 mm×4 mm coupons using a waterjet cutter following ASTM E466-15. The aluminium and titanium pieces were then bonded together using Araldite 2-part epoxy to form coupon stacks.

2.4 Hole making

Three hole making methods, namely conventional drilling (CD), peck drilling (PD) and helical milling (HM), were investigated. All the hole making methods were conducted in dry condition using a Bridgeport VMC1000/20 CNC machine. Figure 1 depicts the three different hole making methods deployed. A centre hole was produced in each Al 2024-T3/Ti-6Al-4V coupon stack. The machining sequence was set to be from Al 2024-T3 to Ti-6Al-4V in line with previous study [10]. This is because the greater stiffness of Ti-6Al-4V can effectively support the upper Al 2024-T3 layer during the hole making process. Five identical coupons were produced for each set of machining parameter, and the cutting tool was replaced after producing every five coupons to eliminate the effect of tool wear. For the three hole making methods, coupon stacks produced with constant cutting parameters were named as CD-C, PD-C and HM-C; for holes made with varied parameters (i.e. deploying optimal parameters for each individual metal layer) across the stack, the resulting coupons were named as CD-V, PD-V and HM-V, respectively. The different hole making methods and their respective machining parameters are listed in Table 5. The tangential feed of HM-C and HM-V was set to be 0.04 mm/rev based on previous study [2]. Considering the conical point of the drill bit, for CD-V and PD-V, the machining parameters were changed when the conical point touched the top surface of the bottom Ti-6Al-4V layer, as the titanium layer is more prone to damage formation. The parameters were selected according to published literature [5, 21] and per tool supplier’s recommendation.

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**Table 1** Chemical composition of Al 2024-T3 (weight%) [25]

| Element | Al | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Other |
|---------|----|----|----|----|----|----|----|----|----|-------|
| Min     | REM | -  | -  | 3.8 | 0.3 | 1.2 | -  | -  | -  | 0.05 Each (Max) |
| Max     | REM | 0.5| 0.5| 4.9 | 0.9 | 1.8 | 0.1| 0.25| 0.15| 0.15 Total |

**Table 2** Mechanical properties of Al 2024-T3 [25]

| Material thickness (mm) | UTS (MPa) | 0.2% proof stress (MPa) | Elongation on 50 mm (%) |
|-------------------------|------------|-------------------------|-------------------------|
| 4                       | 427.48     | 275.79                  | 15                      |

**Table 3** Chemical composition of Ti-6Al-4V (weight%) [26]

| Element | Ti | Fe | C   | N   | O   | H   | Y   | Al | V | Impurity elements |
|---------|----|----|-----|-----|-----|-----|-----|----|---|-------------------|
| Min     | REM | -  | -   | -   | -   | -   | -   | 5.5| 3.5| <0.4 Total       |
| Max     | 0.3 | 0.08| 0.05| 0.2 | 0.015| 0.005| 6.75| 4.5|   |                   |

**Table 4** Mechanical properties of Ti-6Al-4V [26]

| Material thickness (mm) | UTS (MPa) | 0.2% proof stress (MPa) | Elongation on 50 mm (%) |
|-------------------------|------------|-------------------------|-------------------------|
| 4.06                    | 920        | 866                     | 10                      |
2.5 Microstructural analysis

The hole-entry and hole-exit morphology along with the chips produced during hole making was analysed using Nikon SMZ745 Stereoscopic Microscope. The machined coupons were sectioned through the hole centre using an electrical discharge machining (EDM) wire cutter. Alicona InfiniteFocus G5 microscope was used for hole wall 3D morphology scan, burr height analysis and surface roughness (Rz) measurements. A filter waviness of 2500 μm was selected based on ISO 4288, and 5 measurements were taken in each analysis for repeatability.

In order to reveal the sub-surface microstructures of the machined hole entry/exit as well as that of the bonded interface, sectioned samples were mounted in clear Claro-fast resin, ground and polished using a Buehler Ecomet 30 machine following ASTM E3-11. The polished Al 2024-T3 surface was etched with Keller’s reagent (3 ml hydrochloric acid, 2 ml nitric acid, 2 ml water). The polished surface was observed using a Nikon SMZ745 Stereoscopic Microscope. The microstructural features such as grain size, grain boundary, and inclusion were examined. The images were captured using a digital camera and analysed using ImageJ software. The average grain size was calculated using the linear intercept method.

Table 5 Different hole making methods and their specific machining parameters

| Methods                        | Acronym | Tool diameter (mm) | Cutting speed (m/min) | Spindle speed (rpm) | Axial feed rate (mm/rev) |
|--------------------------------|---------|--------------------|-----------------------|---------------------|-------------------------|
| Conventional drilling          | CD-C    | 8                  | 50                    | 1989                | 0.1                     |
| (constant parameters)          |         |                    |                       |                     |                         |
| Conventional drilling          | CD-V    | 8                  | Al layer: 100 Ti layer: 15 | Al layer: 3979 Ti layer: 600 | Al layer: 0.2 Ti layer: 0.063 |
| (varied parameters)            |         |                    |                       |                     |                         |
| Peck drilling                   | PD–C    | 8                  | 50                    | 1989                | 0.1                     |
| (constant parameters)          |         |                    |                       |                     |                         |
| Peck drilling                   | PD-V    | 8                  | Al layer: 100 Ti layer: 15 | Al layer: 3979 Ti layer: 600 | Al layer: 0.2 Ti layer: 0.063 |
| (varied parameters)            |         |                    |                       |                     |                         |
| Helical milling                 | HM-C    | 6                  | 50                    | 2652                | 0.1                     |
| (constant parameters)          |         |                    |                       |                     |                         |
| Helical milling                 | HM-V    | 6                  | Al layer: 100 Ti layer: 15 | Al layer: 5305 Ti layer: 796 | Al layer: 0.2 Ti layer: 0.063 |
| (varied parameters)            |         |                    |                       |                     |                         |
acid, 5 ml nitric acid, 2 ml hydrofluoric acid, 190 ml distilled water) for 20 s and Ti-6Al-4V surface was etched by Kroll’s reagent (2 ml hydrofluoric acid, 10 ml nitric acid, 88 ml distilled water) for 30 s [2]. Optical microscopy was carried out using a Nikon Epiphot optical microscope, and more in-depth microstructural analysis was carried out using a scanning electron microscope (SEM) FlexSEM 1000 (Hitachi Ltd., Japan) with an acceleration voltage of 10 kV.

2.6 Fatigue testing

Fatigue tests on stacks with open holes were performed on a Walter and Bai Series LFV Fatigue Machine, in accordance with ASTM E466 and ASTM E606. Low cycle fatigue testing (LCFT) was conducted with a maximum stress of 252.35 MPa (60% of the ultimate tensile strength (UTS) of Al 2024-T3) at a frequency of 5 Hz. The stress ratio R was set to be 0.1, and therefore, the minimum stress value was 25.235 MPa. The parameters were chosen based on UTS of Al 2014-T3, as 60% UTS of Ti-6Al-4V is greater than that of Al 2024-T3, which will cause premature failure of the Al 2024-T3 layer. The fatigue testing parameters are summarized in Table 6. For each group, four coupons were tested for repeatability and the mean value were taken.

| $R$ | Frequency (Hz) | Area ($m^2$) | $\sigma_{\text{min}}$ (MPa) | $\sigma_{\text{max}}$ (MPa) | % of UTS | $F_{\text{min}}$ (KN) | $F_{\text{max}}$ (KN) | Amplitude (KN) |
|-----|----------------|--------------|-----------------------------|-----------------------------|---------|----------------------|----------------------|----------------|
| 0.1 | 5              | $9.672 \times 10^{-5}$ | 25.235                      | 252.35                      | 60      | 2.44                 | 24.41                | 21.97          |

3 Results and discussion

3.1 Exit burr

Hole making of Al 2024-T3 and Ti-6Al-4V can easily induce burr formation at the hole entry and exit. Burr formation can deteriorate the precision and reliability of structural assembly, and expensive deburring process is usually required to meet the assembly specification. Figure 2 shows the typical optical images of hole entry (Al 2024-T3 side) and exit (Ti-6Al-4V side). The hole exit burr was much more severe than that on the hole entry side. This is consistent with previous report by Zhu et al. [10], and the larger at hole-exit can be attributed to the lack of support underneath. Figure 3 reveals the 3D profile of the exit burr produced from different hole making methods. Figure 4 depicts the average burr height at hole exit produced by different hole making methods. The results suggest for both constant or varied hole making parameters, CD always produced the largest exit burr. For both CD-V and PD-V, adopting varied hole making parameter across the stacks can significantly reduce the hole exit burr as compared to CD-C and PD-C (58.9% reduction for CD and 85.8% reduction for PD). The exit burr height is less sensitive to hole making parameters for HM. The effective reduction of burr height by utilizing varied parameters across layers can be attributed to the fact that lower drilling feed rate can generate reduced thrust force [27], which can potentially lower the machining temperature [28] and suppress the material flow, and hence reducing the burr formation at hole exit. According to previous study by Rana et al. [29], burrs form during the metal hole making as a result of cutting force, temperature and material deformation. The fact that HM produced the least hole exit burr in all cases can be attributed to the distinct advantages of HM method: 1) significantly reduced thrust force: the material removal is by cutting rather than extrusion (as with CD and PD) [30]; 2) better heat dissipation compared to CD [2] due to the larger clearance between the milling cutter and hole wall.

Fig. 2 Hole entry and exit morphology produced by different hole making methods
3.2 Chip morphology

The morphology of Al 2024-T3 and Ti-6Al-4V chips was inspected by means of optical microscopy and is summarized in Fig. 5. Under CD-C, CD-V, PD-C and PD-V, long spiral conical chips were found for Al 2024-T3, while for Ti-6Al-4V both spiral conical- and tangled ribbon-shaped chips were produced. This is consistent with the findings from previous studies in drilling of Al 2024-T3 [31] and Ti-6Al-4V [32]. The formation of entangled ribbon Ti-6Al-4V chips can be attributed to the easily adhered chips being squeezed and compressed against the tool during their evacuation in CD and PD [33]. PD–C and PD-V can effectively reduce the chip length as compared to CD-C and CD-V, as the tool retraction movement can cause chip breakage during machining. The reduction in chips length can effectively mitigate the Ti-6Al-4V chip entanglement. For HM-C and HM-V, two different chip morphology (short ribbons and flakes) were identified. The short ribbon shaped chips were produced by peripheral cutting edge of the milling cutter, while the flaky chips were generated by the axial cutting edge [34]. The difference in the chip morphology can be attributed to the different material removal mechanisms involved. Continuous chips were produced by CD and PD, as the chip flows continuously along the drill bit flute. For HM, discontinuous chips were produced as a result of the intermittent interaction between the cutting edge and the workpiece.

3.3 Hole wall morphology

The 3D morphology of Al 2024-T3 and Ti-6Al-4V hole wall was analysed. As can be seen from Figs. 6 and 7, irregular scratches and trenches are evident on the Al 2024-T3 hole surface, while Ti-6Al-4V hole surface features regular feed marks. The scratches and trenches on Al 2024-T3 surface can be attributed to the low hardness (120 HV) of Al 2024-T3, which can be easily scratched by the chips produced. The hole surface roughness \( R_z \) of Al 2024-T3 and Ti-6Al-4V under different hole making conditions is shown in Fig. 8. For Al 2024-T3 layer, CD and PD coupons have similar surface roughness (~18 \( \mu m \)) regardless of the machining parameters used. HM-C and HM-V coupons have rougher surface (>25 \( \mu m \)). For Ti-6Al-4V layer, the surface finish is much smoother for all hole making methods and the \( R_z \) values are in the range of 8 ~ 10 \( \mu m \).

To assess the potential influence of Ti-6Al-4V chips on the resulting hole surface finish of the stacks, the hole surface roughness of Al 2024-T3 and Ti-6Al-4V layers within the stacks was compared with that produced by drilling/milling a single metal sheet, see Fig. 9. Figure 9a shows for Al 2024-T3, HM led to the greatest \( R_z \) for stacked coupons (~23 \( \mu m \) for HM-C and ~30 \( \mu m \) for HM-V), and lowest \( R_z \) for single Al 2024-T3 sheet (~10 \( \mu m \) for both HM-C and HM-V). In HM of stacked coupons, the intermittent cutting behaviour allows gaps between the milling cutter and the hole surface, which enables the fine Ti-6Al-4V chips to evacuate laterally and cause abrasion on the Al 2024-T3 hole surface. In contrast, the continuous conical CD/PD chips mainly move upwards along the tool bit flute, hence has less impact on the Al 2024-T3 surface finish. Figure 9b reveals no significant difference in \( R_z \) of Ti-6Al-4V in stacks and in single sheet. This is because Ti-6Al-4V is much harder and is placed at the bottom of the stack and hence less affected by the Al 2024-T3 chips.

3.4 Sub-surface microstructural analysis

Figure 10 shows that the sub-surface microstructural change of Al 2024-T3 layer at the hole entrance is negligible and does
not seem to be significantly affected by the different hole making methods. For the Ti-6Al-4V hole exit side, white layer formation is clearly visible in CD-C (~15 μm thick) and PD–C (~10 μm thick) coupons. According to Xu et al. [35], formation of such white layer is due to the synergistic effect of severe plastic deformation and phase transformation, especially under high machining temperature. White layer features fine grains and is more brittle/prone to crack initiation and propagation under loading [36]. The white layer was not evident in CD-V and PD-V (see Fig. 11b, d). This is because the lower speeds and feed rates under these conditions may lead to lower cutting temperature and reduced strain rate during the hole making process [28].
Low cutting speed eliminates phase transformation due to less heat generation during drilling Ti-6Al-4V layer. Although no white layer was found for CD-V and PD-V, severe plastic flow of the Ti-6Al-4V grains along the machining direction is clearly evident. For HM-C and HM-V (Fig. 11e, f), mild plastic flow of the grains was found, and the resulting material sub-surface microstructure is less sensitive to the spindle speed and feed rate change. This can be attributed to the intermittent HM cutting process, which is known to generate much lower cutting force and machining temperature [2].
The bonded Al 2024-T3/Ti-6Al-4V interface was inspected using an optical microscope, and the results can be found in Fig. 12. Burr formation was found in both metal layers at the bonded interface. The upward pointing Ti-6Al-4V burrs can be attributed to the peel up force experienced by the Ti-6Al-4V layer [37], and the downward pointing Al...

Fig. 10  SEM images showing sub-surface microstructure of Al 2014-T3 at the hole entrance (a) CD-C, (b) CD-V, (c) PD-C, (d) PD-V, (e) HM-C, (f) HM-V (white dashed arrows showing the machined surfaces)
2024-T3 burrs is the result of the push out force experienced by the Al 2024-T3 layer. In CD and PD coupons, the burr formation is more distinct on the Ti-6Al-4V side, where the grains were pulled up against the tool bit travelling direction (denoted by yellow arrow). Due to the greater hardness of Ti-6Al-4V (~340 HV vs. ~120 HV for Al 2024-T3), such peel-up burr can penetrate into the Al 2024-T3 layer, causing secondary damage in Al 2024-T3, see Fig. 12b inset.

**Fig. 11** SEM images showing sub-surface microstructure of Ti-6Al-4V at the hole exit (a) CD-C, (b) CD-V, (c) PD-C, (d) PD-V, (e) HM-C, (f) HM-V (white dashed arrows showing the machined surfaces)
Fig. 12  Microscopic images taken at the Al 2024-T3/Ti-6Al-4V bonded interface: (a) CD-C, (b) CD-V, (c) PD-C, (d) PD-V, (e) HM-C, (f) HM-V
3.5 Fatigue testing

Figure 13 compares the fatigue performance of coupon stacks produced by different hole making methods. For all coupons, Ti-6Al-4V layer was the first material to fail. This is because the elongation at failure for Ti-6Al-4V is 10%, whereas that of Al 2024-T3 is 15%. As a result, Ti-6Al-4V can sustain less strain during cyclic loading. As such, the quality of the Ti-6Al-4V machined surface plays a more dominant role in the fatigue performance of the stacked coupons.

As shown in Fig. 13, under constant machining parameters, the coupons machined by CD-C displayed the worst fatigue performance (~32,000 cycles to failure). PD-C led to improved fatigue life (35% increase) as compared to CD-C. This could be a result of better heat dissipation of PD-C and the thinner white layer formation in the Ti-6Al-4V layer, see Fig. 11a, c. The brittle white layer can accelerate the crack propagation and negatively impact the fatigue life of the work piece [38]. When employing varied machining parameters across the stacks, CD-V and PD-V have led to significantly prolonged coupon fatigue life — a 72% and 38% improvement compared to CD-C and PD-C. This improvement can be attributed to the lower cutting speed and feed rate deployed in CD-V and PD-V, which has effectively eliminated the white layer formation in Ti-6Al-4V, see Fig. 11b, d. No Ti-6Al-4V white layer was found for CD-V, PD-V, HM-C and HM-V coupons, and their corresponding coupon fatigue life is similar (~60,000 cycles). Although HM-C and HM-V generated much rougher surface finish in Al 2024-T3 layer, this did not seem to drastically affect the resulting fatigue life of the stacks.

4 Conclusions

In this study, conventional drilling, peck drilling and helical milling have been compared for hole making of Al 2024-T3/Ti-6Al-4V stacks. For each hole making method, effects of constant and varied machining parameters across the stack were investigated. The key findings are outlined as follows.

- HM method produces the least exit burrs among the three methods. This is due to the lower thrust force and low machining temperature generated during machining. For CD-V and PD-V, adopting varied drilling parameters across Al 2024-T3 and Ti-6Al-4V layers can significantly reduce the hole exit burr as compared to CD-C and PD-C (59% reduction for CD and 86% reduction for PD).
- The Al 2024-T3 hole surface features irregular scratches and trenches, whereas the Ti-6Al-4V hole surface shows regular feed marks. HM leads to rough hole surface finish in the Al 2024-T3 layer due to the abrasive effect of the evacuated Ti-6Al-4V chips. Ti-6Al-4V hole surface finish is not sensitive to hole making methods and hole making parameters.
- Sub-surface microstructure analysis reveals white layer formation and plastic deformation of grains are the primary damages induced in the Ti-6Al-4V hole exit. CD-C produces the most severe Ti-6Al-4V white layer formation (~15 μm). Deploying varied parameter across layers (CD-V and PD-V) can effectively eliminate the Ti-6Al-4V white layer formation. HM only leads to mild plastic flow of Ti-6Al-4V grains, due to the reduced cutting force.
- Ti-6Al-4V layer is the first material to fail during tensile fatigue testing of the stacks. CD-C and PD-C coupons with Ti-6Al-4V white layer show the worst fatigue performance. Deploying varied machining parameters (CD-V, PD-V) and HM help to prolong the coupon’s fatigue life.
- HM may be a favourable method for improved hole quality in hole making of Al 2024-T3/Ti-6Al-4V stacks, as it produces clear hole exit finish without noticeable burr formation, reduced microstructural alteration and prolonged fatigue performance. However, it is worth noting that HM is limited by its reduced productivity as compared to CD and PD. Future research on process optimization is still required to improve its machining efficiency while maintaining the hole quality.

Acknowledgements The authors would like to thank European Union’s Horizon 2020 research and innovation program (Grant No. 734272) for funding support. Mr. Jia Ge would also like to gratefully acknowledge UK Research and Innovation (UKRI) for PhD scholarship funding.
funding support from the Engineering and Physical Sciences Research Council (EPSRC) (EP/P025447/1 and EP/P026087/1) is also acknowledged. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising. Data are available upon reasonable request.

**Author contributions** Jia Ge was involved in the conceptualization, methodology, investigation, and writing—original draft. Rincy Reji contributed to the material preparation and analysis. Toby Feist was involved in the material preparation and analysis. Alexander Elmore contributed to the material preparation and analysis. John McCllelland contributed to the software and resources. Colm Higgins contributed to the software and resources. Brian McLaughlin was involved in the material preparation and analysis. Yan Jin was involved in the supervision and writing—review and editing, funding acquisition, and project administration. Dan Sun was involved in the conceptualization, methodology, investigation, writing—review and editing, funding acquisition and project administration.

**Availability of data** The data that support the findings of this study are from the corresponding author upon reasonable request.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** The authors declare that they all consent to publication.

**Conflicts of interest** The authors have no financial or proprietary interests in any material discussed in this article.

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**References**

1. Wei L, Wang D (2019) Comparative study on drilling effect between conventional drilling and ultrasonic-assisted drilling of Ti-6Al-4V/A12024-T351 laminated material. Int J Adv Manuf Technol 103:141–152. https://doi.org/10.1007/s00170-019-03507-6
2. Sun D, Lemoine P, Keys D, Doyle P, Malinov S, Zhao Q et al (2018) Hole-making processes and their impacts on the microstructure and fatigue response of aircraft alloys. Int J Adv Manuf Technol 94:1719–1726. https://doi.org/10.1007/s00170-016-9850-3
3. Xu J, Mkaddem A, El Mansori M (2016) Recent advances in drilling hybrid FRP/Ti composite: A state-of-the-art review. Compos Struct 135:316–338. https://doi.org/10.1016/j.comstruct.2015.09.028
4. States U, Administration FA, Service FS (2008) Aviation maintenance technician handbook: general 2008. Newcastle, Wash.: Aviation Supplies & Academics
5. Sharif S, Abd E, Sasahar H (2012) Machinability of titanium alloys in drilling. Titan Alloy - Towar Achiev Enhanc Prop Divers Appl. https://doi.org/10.5772/35948
6. Zhu Z, Sui S, Sun J, Li J, Li Y (2017) Investigation on performance characteristics in drilling of Ti6Al4V alloy. Int J Adv Manuf Technol 93:651–660. https://doi.org/10.1007/s00170-017-0508-6
7. Giasin K, Hodzic A, Phadnis V, Ayar-Soveramis S (2016) Assessment of cutting forces and hole quality in drilling Al2024 aluminium alloy: experimental and finite element study. Int J Adv Manuf Technol 87:2041–2061. https://doi.org/10.1007/s00170-016-8563-y
8. Aamir M, Giasin K, Tolouei-Rad M, Ud Din I, Hanif MF, Kuklu U et al (2021) Effect of cutting parameters and tool geometry on the performance analysis of one-shot drilling process of AA2024-T3. Metals (Basel). https://doi.org/10.3390/met11060854
9. Cantero JL, Tardío MM, Canteli JA, Marcos M, Miguélez MH (2005) Dry drilling of alloy Ti–6Al–4V. Int J Mach Tools Manuf 45:1246–1255. https://doi.org/10.1016/j.ijmachtools.2005.01.010
10. Zhu Z, Guo K, Sun J, Li J, Liu Y, Zheng Y et al (2018) Evaluation of novel tool geometries in dry drilling aluminium 2024–T351/ titanium Ti6Al4V stack. J Mater Process Technol 259:270–281. https://doi.org/10.1016/j.jmatprotec.2018.04.044
11. Zhu Z, Liu K, Sun J, Li J (2017) Investigation on performance characteristics and metallurgical transformation on drilling aluminium/titanium sandwich. J Sandw Struct Mater 21:1578–1594. https://doi.org/10.1177/10996362177242601
12. Bonnet C, Pottier T, Landon Y (2021) Development of a multiscale and coupled cutting model for the drilling of Ti-6Al-4V. CIRP J Manuf Sci Technol 35:526–540. https://doi.org/10.1016/j.cirpj.2021.08.007
13. Tian Y, Zou P, Kang D, Fan F (2021) Study on tool wear in longitudinal-torsional composite ultrasonic vibration–assisted drilling of Ti-6Al-4V alloy. Int J Adv Manuf Technol 113:1989–2002. https://doi.org/10.1007/s00170-021-06759-3
14. Kim DW, Lee YS, Park MS, Chu CN (2009) Tool life improvement by peck drilling and thrust force monitoring during deep micro-hole drilling of steel. Int J Mach Tools Manuf 49:246–255. https://doi.org/10.1016/j.ijmachtools.2008.11.005
15. Oh YT, Kwon WT, Chu CN (2004) Drilling torque control using spindle motor current and its effect on tool wear. Int J Adv Manuf Technol 24:327–334. https://doi.org/10.1007/s00170-002-1490-0
16. Pereira RBD, Brandão LC, de Paiva AP, Ferreira JR, Davim JP (2017) A review of helical milling process. Int J Mach Tools Manuf 120:27–48. https://doi.org/10.1016/j.ijmachtools.2017.05.002
17. Qin XD, Sun XT, Wang Q, Chen SM, Li H (2012) Comparative study on helical milling and drilling of Ti-6AI-4V. Key Eng Mater 499:200–204. https://doi.org/10.4028/www.scientific.net/KEM.499.200
18. Chen G, Zou Y, Qin X, Liu J, Feng Q, Ren C (2020) Geometrical texture and surface integrity in helical milling and ultrasonic vibration helical milling of Ti-6Al-4V alloy. J Mater Process Technol 278:116494. https://doi.org/10.1016/j.jmatprotec.2019.116494
19. Zhao Q, Qin X, Ji C, Li Y, Sun D, Jin Y (2015) Tool life and hole surface integrity studies for hole-making of Ti6Al4V alloy. Int J Adv Manuf Technol 79:1017–1026. https://doi.org/10.1007/s00170-015-6890-z
20. Zitoune R, Krishnaraj V, Collombet F (2010) Study of drilling of composite material and aluminium stack. Compos Struct 92:1246–1255. https://doi.org/10.1016/j.compstruct.2009.10.010
21. Santos MC, Machado AR, Sales WF, Barrozo MAS, Ezugwu EO (2016) Machining of aluminum alloys: a review. Int J Adv Manuf Technol 86:3067–3080. https://doi.org/10.1007/s00170-016-8431-9
22. Stephenson DA, Agapiou JS (2005) Metal cutting theory and practice. Taylor & Francis
23. Pardo A, Majeed M, Heinemann R (2020) Process signals characterisation to enable adaptive drilling of aerospace stacks. Procedia CIRP 88:479–484. https://doi.org/10.1016/j.procir.2020.05.083
24. Jallageas J, Ayfre M, Cherif M, K’nevez JY, Cahuc O (2016) Self-adjusting cutting parameter technique for drilling multi-stacked material. SAE Int J Mater Manuf 9:24–30. https://doi.org/10.4271/2015-01-2502
25. Smith Advanced Metals AMS QQA 200/3 2024 n.d. http://www.smithadvanced.com/pdf/200-3_2024_AMI.pdf [Accessed March 2022]
26. NeoNickel Ti 6Al-4V (Grade 5) n.d. https://www.neonickel.com/generate-alloy-pdf/?id=177 [Accessed March 2022]
27. Parida AK (2018) Simulation and experimental investigation of drilling of Ti-6Al-4V alloy. Int J Light Mater Manuf 1:197–205. https://doi.org/10.1016/jijklmm.2018.07.001
28. Lazoglu I, Poulachon G, Ramirez C, Akmal M, Marcon B, Rossi F et al (2017) Thermal analysis in Ti-6Al-4V drilling. CIRP Ann 66:105–108. https://doi.org/10.1016/j.cirp.2017.04.020
29. Rana A, Dongre G, Joshi SS (2019) Analytical modeling of exit Burr in drilling of Ti6Al4V alloy. Sadhana - Acad Proc Eng Sci 44:1–19. https://doi.org/10.1007/s12046-019-1114-0
30. Iyer R, Koshy P, Ng E (2007) Helical milling: An enabling technology for hard machining precision holes in AISI D2 tool steel. Int J Mach Tools Manuf 47:205–210. https://doi.org/10.1016/j.ijmachttools.2006.04.006
31. Aamir M, Tolouei-Rad M, Giasin K, Vafadar A (2020) Feasibility of tool configuration and the effect of tool material and tool geometry in multi-hole simultaneous drilling of Al2024. Int J Adv Manuf Technol 111:861–879. https://doi.org/10.1007/s00170-020-06151-7
32. Maňkova I, Vrabel M, Kandráč L (2019) Evaluation of chip morphology when drilling titanium alloy. Cut Tools Technol Syst 134–42. https://doi.org/10.20998/2078-7405.2019.91.13
33. Zhu Z, Guo K, Sun J, Li J, Liu Y, Chen L et al (2018) Evolution of 3D chip morphology and phase transformation in dry drilling Ti6Al4V alloys. J Manuf Process 34:531–539. https://doi.org/10.1016/j.jmapro.2018.07.001
34. Gonsalves JA, Nayak SN, Bolar G (2020) Experimental investigation on the performance of helical milling for hole processing in AZ31 magnesium alloy. J King Saud Univ - Eng Sci. https://doi.org/10.1016/j.jksues.2020.10.004
35. Xu X, Zhang J, Liu H, He Y, Zhao W (2019) Grain refinement mechanism under high strain-rate deformation in machined surface during high speed machining Ti6Al4V. Mater Sci Eng A 752:167–179. https://doi.org/10.1016/j.msea.2019.03.011
36. Ulutan D, Ozel T (2011) Machining induced surface integrity in titanium and nickel alloys: A review. Int J Mach Tools Manuf 51:250–280. https://doi.org/10.1016/j.ijmachttools.2010.11.003
37. Eynian M, Das K, Wretland A (2017) Effect of tool wear on quality in drilling of titanium alloy Ti6Al4V, Part I: Cutting Forces, Burr Formation, Surface Quality and Defects. High Speed Mach 3:1–10. https://doi.org/10.1515/hsm-2017-0001
38. Bosheh SS, Mativenga PT (2006) White layer formation in hard turning of H13 tool steel at high cutting speeds using CBN tooling. Int J Mach Tools Manuf 46:225–233. https://doi.org/10.1016/j.ijmachttools.2005.04.009

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