REVIEW ARTICLE

A Review on the Machinability of Aerospace-Grade CFRP/Titanium Stacks

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DOI: 10.5185/amlett.2021.011591

Multilayer stacks constituted by carbon fiber reinforced polymers (CFRPs) and titanium (Ti) alloys are advanced structural materials being extensively used in the modern aerospace industry in view of their superior properties and functionality. Prior to the final industrial applications, CFRP/Ti stacks have to be machined into desired shapes with qualified surface quality. However, these multilayer materials possess rather poor machinability due to the disparate natures of constituted phases. The present review aims to report on the recent advancements and achievements in the machining of CFRP/Ti stacks by emphasizing the key challenges and difficulties faced by the manufacturing community to achieve the high-quality drilling of the stack materials. A careful discussion on the machinability aspects of the aerospace-grade stacks in terms of chip separation mechanisms, cutting forces, machining temperatures and surface quality attributes was made following a detailed literature survey. The work summarizes the current research progress in the subject area of composite/titanium machining and highlights the future research directions. It will help both academic scholars and industrial engineers specializing in the fields of machining multilayer composite-metallic stacks.

Introduction

In recent decades, the emergence of carbon fiber reinforced polymers (CFRPs) has greatly revolutionized the material distribution in the engineering fields. This can be seen by their huge applications covering a variety of industries such as aircraft, spacecraft, automobile, marine, chemical processing equipment, and sporting goods [**1**]. The CFRP composites are advanced structural materials exhibiting superior mechanical/physical properties involving high specific strength, high specific stiffness, excellent corrosion resistance, *etc*. [**1-6**]. However, despite their attractive applications, CFRP composites are often employed in conjunction with titanium alloys to form hybrid structures for the aerospace applications [**7-9**]. This is due to the low heat resistance capability and the high-temperature sensitivity of the fibrous composites, which cannot be applied to structures subjected to high-temperature working conditions. Titanium alloys are lightweight and superior metallic materials possessing high mechanical properties and excellent thermal behavior, being also the promising materials for the aerospace applications.

Multilayer sandwiches made of CFRP composites and titanium alloys are advanced structural materials combining the merits of both the material phases while their individual weaknesses are significantly avoided [**10-12**]. Although the introduction of titanium alloys can alleviate the weakness of the composite phase, the machinability of the stacked composite/titanium material system is further degraded [**13-15**]. The reason lies in the different properties and machining characteristics of the CFRP and titanium alloy. For instance, the anisotropic architecture and high abrasiveness of the fibrous composites often lead to severe hole damage and excessive drill wear [**2,16-19**], while the titanium alloys show poor thermal conductivity, high hardness and low elastic modulus [**20-25**], resulting in high cutting forces, excessive machining temperatures and catastrophic tool failures like microchipping or edge fracture. As such, machining of these multilayer stacks with desired quality has been a challenging task in the modern aerospace community. Particular issues arise from the inferior surface quality leading to the large proportion of part rejections and the rapid tool wear leading to the short tool life as well as high costs [**26-30**].

Since the CFRP/Ti stacks are often used for the fabrication of structural components, mechanical drilling becomes a compulsory manufacturing operation to create boreholes for riveting and bolting connections. However, the inherent poor machinability of the composite/titanium stacks has greatly restricted their industrial applications, and the drilling operation becomes rather challenging particularly when high surface quality and dimensional accuracy are demanded. Even though great endeavors have been made to investigate the fundamental mechanisms of cutting CFRP/Ti stacks covering a variety of machinability inputs [**9-11,13,15,26-48**], the knowledge obtained is still very limited and cannot be fully transplanted to the precision machining of the hybrid composite materials.

To realize the high-quality manufacturing of CFRP/Ti stacks, there is a critical need to understand the cutting mechanisms associated with the chip removal of the bi-material system as well as the defect formation modes. The present work thus aims to highlight the chip separation mechanisms of the composite/titanium stacks and review the recent research advances in the machining of the hybrid composite structures. A particular focus is placed on the discussion of the machinability characteristics of the CFRP/Ti stacks with respect to the cutting forces, machining temperatures and surface quality attributes. The review work intends to summarize the key findings obtained in the fields of stacks machining and to point out the potential directions of perspective investigations. The results discussed in this paper help to provide some technical guidance for the modern manufacturing engineers when dealing with the machining of composite/titanium stacks.

Key challenges and difficulties

Machining of multilayer CFRP/Ti stacks is facing significant challenges in the current manufacturing community due to the anisotropic machinability and heterogeneous structure of the sandwich materials. Particular issues are resulting from the inappropriate selection of cutting parameters, cutting tools and the limitations of present machining methods. As the multilayer stacks are made of two different material layers possessing different machining behaviors, the optimal cutting parameters suitable for one type of the material phase may differ for the other material. This leads to the difficulty in selecting more appropriate process parameters. To solve this problem, the current machinists have to make a compromise selection for the cutting parameters. Additionally, machining CFRP/Ti stacks entails rapid tool wear and short tool life due to the combined wear effects of each stacked phase. To date, most of the existing tool materials and geometries seem incapable of withstanding the harsh mechanical/thermal conditions encountered in the stacks machining. The inappropriate use of cutting parameters and tool types is the key cause of a large proportion of stack part rejections, being the key challenge to be resolved in both academia and industry. Finally, the most-used twisting drilling method has been proved ineffective to create high-quality holes for CFRP/Ti stacks due to its non-optimal tool design and poor chip evacuation ability, which increases the risk of part rejections and tool failure. To solve the aforementioned challenges and difficulties, there is a critical need to understand the machinability behaviors of the composite-metallic materials. The following sections are then organized to discuss the stack machinability in detail.

Chip separation mechanisms

Chip separation signifies the removal mode of workpiece layers subjected to a specific machining operation. It takes place due to the mechanical/thermal sliding and contact between the work materials and the cutting tools. It is the key source of formation of various cutting-induced phenomena such as the cutting forces, machining temperatures, surface morphologies as well as the resulting tool wear. Since the multilayer CFRP/Ti stacks are sandwiched by two types of completely different materials involving both fibrous composites and metallic alloys, the chip separation mode becomes rather complicated due to the interrelated cutting features of the interface zone. This means that the machining mechanisms of the stacks cannot be simply considered as the combination of the chip removal modes for the individual composite and titanium phases, particularly for the drilling operation.

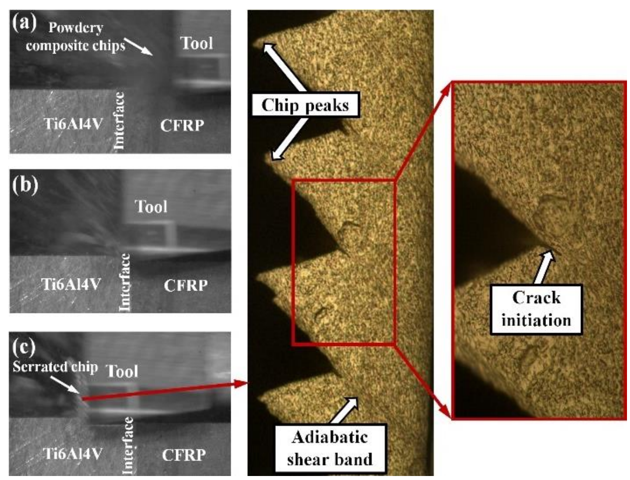

Fig. 1. High-speed camera images of the 0° CFRP/Ti chip separation under the CFRP → Ti cutting sequence: (a) the CFRP phase cutting, (b) the interface cutting and (c) the Ti phase cutting [**15**].

To understand the operating cutting mechanisms of CFRP/Ti stacks, Xu and his co-authors [**15,29,46,49-53**] have sought to utilize the orthogonal cutting method to inspect the chip separation modes governing the machining of these composite-metallic stacks. In their work, both the experimental observations and the numerical simulations were adopted to reveal the underlying mechanisms of the stack chip formation process. The orthogonal cutting mode typically represents the simplest way to identify the fundamental cutting phenomena of a complicated machining process such as drilling or milling. In one of Xu's experimental studies, the high-speed CCD camera was used to document the *in-situ* chip removal process of the CFRP/Ti stacks. **Fig. 1** shows the dynamic chip separation process of the CFRP/Ti stacks under the orthogonal cutting configuration [**15**]. It is clear that the entire cutting process for the CFRP/Ti stacks can be divided into three stages involving the composite cutting, the interface machining and the titanium cutting. As the cutting edge attacks the composite phase, powdery chips are produced from the tool rake face due to the brittle-fracture dominated chip separation mode of the CFRP material. It should be noted that the specific chip separation mode of a CFRP composite may greatly depend on the fiber orientation of the material. For details concerning the varying chip removal mechanisms of unidirectional CFRPs having different fiber orientations, readers are directed to the relevant references [**54-60**]. When the tool cuts across the interface region, a rapid transition of the chip separation mode from brittle fracture to elastoplastic deformation takes place, which leads to the change of the chip type during the cutting process. This phenomenon may initiate severe cutting vibrations as well as tool chatters during the stack cutting process, thus increasing the risk of catastrophic failure of tools like micro chipping or edge fracture [**15**]. Finally, when the tool attacks the titanium alloy, serrated and continuous chips are produced flowing along the tool rake face because of the elastoplastic behavior of the metallic phase. It can be expected that large magnitudes of cutting forces are promoted due to the excessive plastic deformability of the metallic alloys.

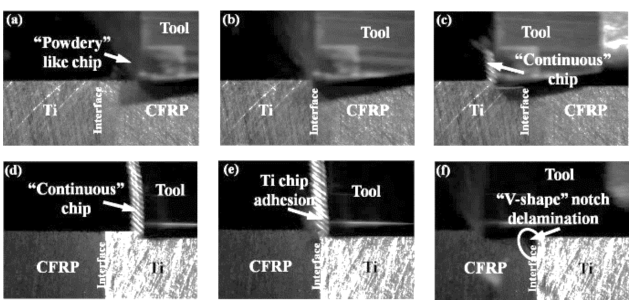

Fig. 2. High-speed camera images showing the chip separation of 45° CFRP/Ti stacks: (a) - (c) the CFRP → Ti cutting sequence and (d) - (f) the Ti → CFRP cutting sequence [**46**].

Most investigations have indicated that the key factors influencing the chip separation of CFRP/Ti stacks include the fiber orientation (layup) of the composite phase and the used cutting sequence strategy. Generally, the fiber orientation affects the chip removal mode of the CFRP phase, while the cutting sequence strategy impacts the entire stack cutting operation mainly due to the presence of the interface zone. Xu and El Mansori [**46**] have stated that during the orthogonal cutting of multilayer CFRP/Ti stacks, the cutting sequence strategy affects the titanium chip evacuation process and thus influences the final machining outputs such as the surface quality of the interface region. As shown in **Fig. 2** [**46**], machining from the composite phase to the titanium phase is favorable for the chip separation of the stack workpieces. However, cutting from the titanium to the CFRP tends to cause severe issues of titanium chip clogging due to the ineffective ejection of the serrated metallic chips. The titanium chips adhering onto the tool rake face lead to severe scratching effects onto the subsequent interface and composite regions. This is clearly evidenced by the formation of the "V-shape" notch delamination at the stack interface zone as depicted in **Fig. 2(f)**.

In general, the drilling mechanisms of CFRP/Ti stacks can be considered as a combination of brittle-fracture and elastoplastic-deformation modes. However, the impact of the cutting sequence strategy on the stack chip removal may change due to the different conditions of the metallic chip evacuation. It is worth mentioning that Brinksmeier and Janssen [**32**] have pointed out that drilling from the CFRP phase to the Ti phase is extremely unfavorable for the improvement of the stack hole quality due to the titanium chip ejection leading to serious erosions onto the composite hole walls as shown schematically in **Fig. 3**. In contrast, cutting from the titanium to the composite is confirmed beneficial for the metallic chip evacuation and hence the improvement of the stack hole quality [**9,29,30**]. However, such findings are contrary to the observation of the stack orthogonal cutting. This is due to the different effects of the cutting sequence on the stack chip evacuation.

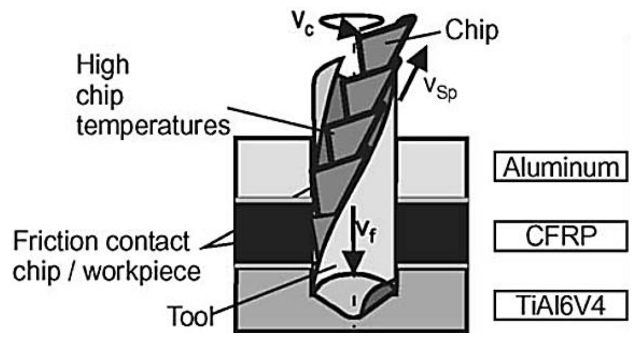

Fig. 3. Schematic diagram showing the problems of the metallic chip ejection [**32**].

Cutting forces

Cutting force signifies the mechanical loads promoted at the tool-chip and tool-work interfaces during the material removal process. It is the critical factor reflecting directly the machinability grade of a workpiece material subjected to various machining processes. Since the cutting forces are the key cause of the formation of the composite delamination damage, they have to be reduced as far as possible during the stacks machining. The factors that influence the machining force levels of the CFRP/Ti stacks include the process parameters, the workpiece constituents, the tool geometries as well as the tool materials.

Machining CFRP/Ti stacks entails different levels of force generation owing to the different machinability behaviors of the stacked constituents. To date, most of the studies dealing with the manufacturing of CFRP/Ti stacks are focused on the analysis of the force signatures and the parametric effects on the force values [**7,9,15,44-46,61,62**]. The key objectives of these studies are to seek the solutions to reduce the cutting forces for CFRP/Ti stacks as far as possible in order to minimize the occurrence of composite delamination damage as well as other cutting-induced defects. Due to the disparate chip separation modes involved, machining the titanium phase produces much higher values of thrust forces than the cutting of the CFRP phase, which has been proved by a variety of experimental investigations. Additionally, process parameters such as the cutting speed and the feed rate are influential factors determining the generation of the stack drilling forces. In most cases, the cutting speed tends to have a negative impact on the development of the drilling forces for the multilayer stacks such that an increase of the cutting speed often leads to a reduction of the drilling forces. On the contrary, an increased feed rate basically leads to the elevation of the drilling forces due to the enlarged uncut chip thickness as the feed rate increases [**9,30**].

Apart from the process parameters, tool conditions such as the tool materials (uncoated tungsten carbide or various types of coatings), tool geometries (point angle, helix angle, flute number, *etc*.), and tool wear extents also affect significantly the generation of drilling forces for the composite/titanium stacks. Such phenomena can be attributed to the change of the tool-chip contact conditions as the tool conditions differ. Advanced tool coatings such as the CVD diamond coating or the PVD TiAlN-coating materials are extensively used for the machining of CFRP/Ti stacks in order to reduce the force values. These tool materials shall possess superior mechanical/physical properties including high hardness, excellent toughness, low friction coefficient and high thermal conductivity.

Lower levels of cutting forces can be produced through the use of specialized cutting tools. These tools are characterized by the modification of tool geometrical features such as the removal of the tool chisel edge zone, the optimization of tool edge angles or the increase of tool flute number. **Fig. 4** shows some of the specialized cutting tools dedicated to the drilling of CFRP/Ti stacks [**44**]. It was found by Alonso *et. al*., [**44**] that the modification of the tool chisel edge as well as the increase of the flute number succeeded in reducing the drilling forces for the hybrid composite stacks.

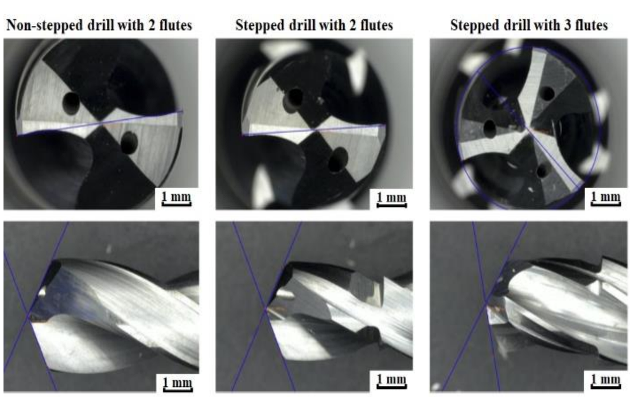

Fig. 4. Some specialized tools designed for the drilling of CFRP/Ti stacks [**44**].

Finally, the active control of the tool wear progression is another feasible strategy to minimize force development during the stacks machining. It is no doubt that an increased tool extent tends to increase the force generation of a workpiece material irrespective of the applied manufacturing operations due to the loss of edge sharpness and the blunting of cutting tips. This point of view has been extensively confirmed by worldwide scholars involved in the investigations of drilling CFRP/Ti stacks [**10,13,62-64**].

Machining temperatures

Machining temperatures are another vital indicator signifying the machinability grade of the composite/ titanium stacks. They reflect the thermal behavior of a workpiece material, which are produced by the frictional work generated in the chip removal process. The *in-situ* measuring of drilling temperatures is more difficult to implement than the measuring of cutting forces. Currently, the most-used methods for the temperature monitoring include the thermocouple embedded tools and the infrared thermography camera. The former is a direct temperature measuring way, in which the thermocouples are positioned through the coolant holes of the drill bits being close to the tool flank surface (Ref. **Fig. 5** [**30**]), while the latter one is an indirect method which cannot precisely quantify the magnitudes of the actual temperature.

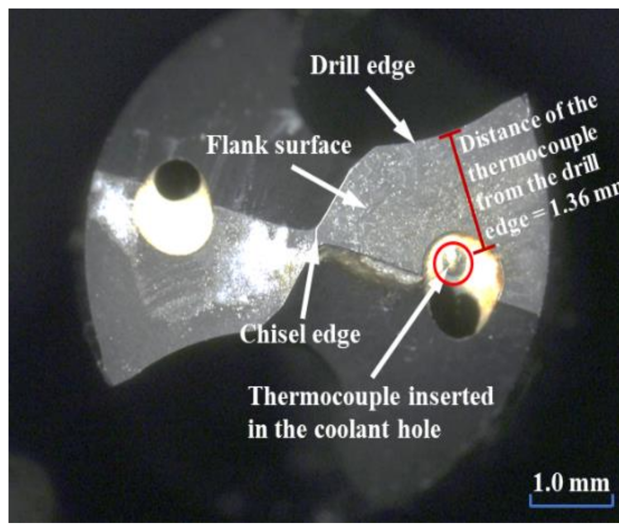

Fig. 5. The thermocouples embedded method for the *in-situ* measurement of drilling temperatures [**30**].

Due to the presence of the metallic phase, machining of CFRP/Ti stacks is likely to generate excessive cutting temperatures, being detrimental to the surface integrity of the cut stack materials. In the stack drilling operation, the high cutting temperatures of tool edges promoted in the titanium machining tend to cause severe thermal softening of the composite phase, increasing the risk of the glass transition of the matrix base [**9,30,32**]. The process parameters affecting the development of drilling temperatures include the cutting speed and the feed rate. Normally, a high cutting speed is favorable for the increase of the drilling temperatures due to the intensified frictional contact between the tool edges and the workpiece materials. In contrast, increasing the feed rate is mainly beneficial for the decrease of the drilling temperatures because of the reduced contact time between the tool and the stack. Apart from the effects of the process parameters, the cutting sequence strategy may affect the evolution of the drilling temperatures for the multilayer stacks. It was reported by Xu *et. al.*, [**30**] that drilling from the CFRP phase to the titanium phase is inclined to generate higher magnitudes of the maximum drilling temperature during the stacks cutting as shown in **Fig. 6**. The phenomenon is attributed to the poor evacuation process of titanium chips as a result of the extended path of the chip ejection channel.

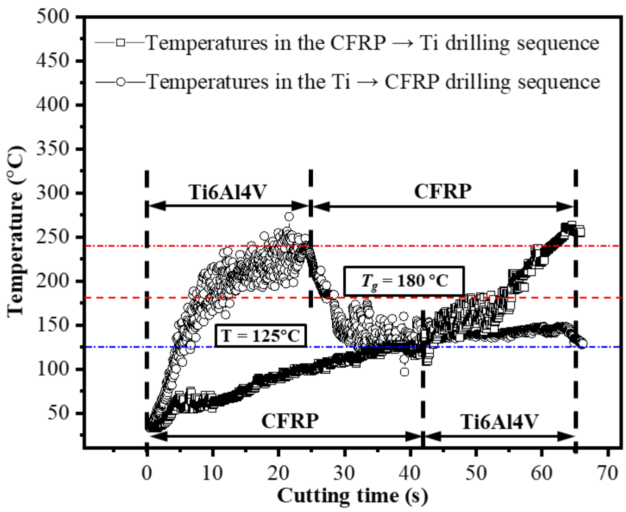

Fig. 6. Effects of different cutting sequences on the evolution of drilling temperatures for the CFRP/Ti stacks [**30**].

To effectively reduce the levels of machining temperatures, the simplest way is to use advanced machining technologies or apply the cutting fluids/lubricants directing into the cutting zones. Some advanced machining methodologies such as the ultrasonic drilling, helical milling (orbital drilling), low-frequency vibration-assisted drilling have been proved capable of reducing the machining temperatures for the CFRP/Ti stacks due to the intermittent contact between the tool edges and the workpiece materials allowing more time for heat dissipation. Moreover, the use of the minimum quantity lubricant (MQL) can benefit the minimization of the drilling temperatures for the composite/titanium stacks owing to the reduced frictional coefficient and the improved heat dissipation ability. Due to the increased awareness of heat-related issues for the drilling of CFRP/Ti stacks, more scientific work is expected to be carried out focusing on the development of advanced cutting methods by also considering the optimization of the cutting environments such as the use of cryogenic conditions.

Surface quality attributes

Since the composite/titanium stacks exhibit anisotropic machining behaviors and heterogeneous structures, it is rather difficult to produce desired surface quality with minimal damage formation. Specifically, mechanical drilling of composite/titanium stacks often leads to several types of quality issues such as serious surface damage/defects and poor surface dimensional accuracy. The issues of surface damage/defects are mainly induced by the thermo-mechanical loads promoted in the stack chip removal process. Generally, the surface damage can be further classified in terms of its distribution area, as shown schematically in **Fig. 7** [**12,35,36**]. For the composite phase, the typical drilling-induced damage includes the deterioration of the composite surfaces, interlaminar delamination, splintering, fiber pullouts, matrix loss, or surface cavities. Amongst these types of defects, interlaminar delamination is the most critical one associated with the drilling thrust force as it is irreparable when occurring, which accounts for 60% of all the composite part rejections. Splintering damage is induced by the overcut of the fiber plies resulting in the surface splitting, while the fiber pullouts are the uncut fibers extruding outside of the composite surface that are not completely sheared by the drill edges during the material removal. With respect to the matrix loss and surface cavities, they are mainly produced in the form of material peeling due to the against fiber cutting angle between the tool edges and the fiber/matrix system while drilling. Apart from the composite damage, the interface represents the weakest zone susceptive to the formation of severe drilling-induced damage. This is due to the rapid transition of the chip separation mode leading to the uneven distribution of mechanical/thermal loads when the tool edges cut across the stack interface zone. The basic damage types for the interface include the surface deterioration because of the severe scratching of the metallic chip ejection and the surface burning due to the excessively high process temperatures occurring at the interface region. The damage modes involved in the titanium phase machining consist of the exit burrs and the surface deterioration.

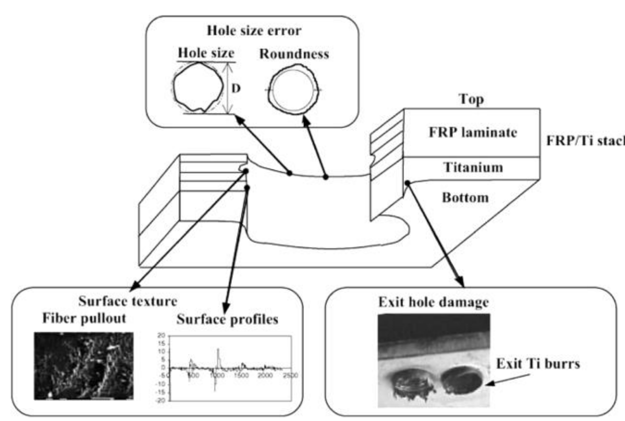

Fig. 7. Schematic diagram showing the drilling-induced defects distribution for the CFRP/Ti stacks [**12,35,36**].

In addition to the hole damage, surface dimensional accuracy is of vital importance for the quality of cut stacks. The dimensional accuracy attributes include the hole diameter, cylindricity errors and hole roundness. These attributes affect significantly the assembly performance of cut composite/titanium stacks. Tool geometries/materials and process parameters are the key factors determining the hole dimensional accuracy of machined CFRP/Ti stacks. Besides, the cutting sequence strategy may have an impact on the quality of the composite/titanium stacks.

As shown in **Fig. 8**, the CFRP → Ti drilling induces severe composite surface damage close to the interface zone due to the scratching effects of the titanium chip evacuation [**29**]. By contrast, the interface damage promoted in the Ti → CFRP drilling sequence is limited owing to the avoided effects of the metallic chip ejection. Therefore, to achieve the high-quality drilling of CFRP/Ti stacks, special attention should be paid to the careful selection of the process parameters as well as the cutting sequence strategy.

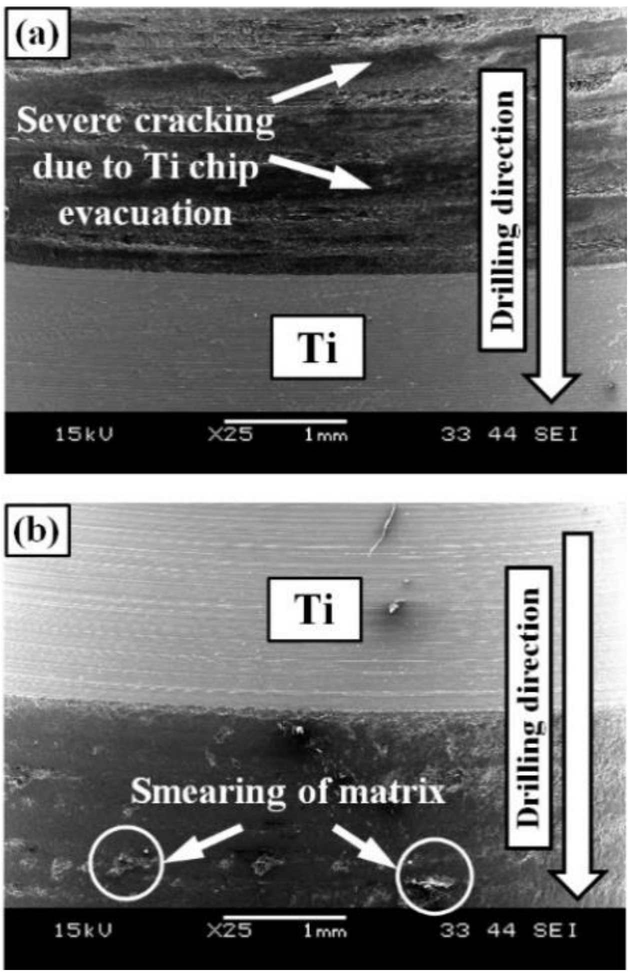

Fig. 8. Effects of different cutting sequence strategies on the hole morphologies of drilled CFRP/Ti stacks: (a) the CFRP → Ti drilling and (b) the Ti → CFRP drilling [**29**].

Conclusions & future perspectives

In the present paper, a comprehensive review focusing on the recent advances in the fields of machining CFRP/Ti stacks was offered with a particular focus on the discussion of the drilling machinability issues of the multilayer stacks. Although scientific studies and advanced manufacturing technologies are continuing to proceed, achieving the high-precision and high-efficiency machining of these composite/titanium stacks still remains the key scientific and technological challenge to be overcome for both academia and industry.

To guide the future research as well as to realize the high-precision machining of CFRP/Ti stacks, more attention should be paid to the following procedures.

- In the first step, the manufacturing sectors have to optimize the tool geometries and coating materials in order to match well the machinability of the aerospace-grade CFRP/Ti stacks.
- Secondly, both the academia and industry need to develop more cost-effective strategies for the high-quality machining of CFRP/Ti stacks.
- Finally, the machinists should seek to apply more advanced manufacturing techniques, *e.g.*, clean manufacturing, green manufacturing, non-traditional machining, for the drilling of CFRP/Ti stacks.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Grant No. 51705319).

Keywords

CFRP/titanium stacks, high-precision machining, machinability characteristics, cutting mechanisms, surface quality.

Received: 21 July 2020
Revised: 23 August 2020
Accepted: 03 September 2020

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