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Drilling of Fiber Metal Laminates for Aerospace Applications: Experimental Evaluation of Surface Treatment Effects on Adhesive Strength and Hole Quality

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Abstract. Drilling of Fiber Metal Laminates (FMLs) is a very important manufacturing operation, as the metal-composite layered structure tends to undergo delamination, burrs, and dimensional errors. Although to date research work has mainly focused on cutting conditions, drilling tools, and lubrication methods for improved performance, the role of surface engineering on metal sheets prior to laminate fabrication has not received significant consideration. In this study, the effect of the variation of feed rate values during the drilling operation of FMLs with laser-textured titanium sheets is examined. Specifically, prior to FML consolidation, a unidirectional pattern with spacing characteristics of 200 µm was created on the titanium sheets; then, drilling tests using twist drill bits were carried out at a fixed cutting speed while varying the feed rate on two levels. The results show that a higher feed rate value induces both greater thrust force – and therefore improved adhesion resistance at the interface between the various materials of the multilayer – and a deterioration in the surface quality of the hole, increasing the occurrence of fiber pull-out and metal transfer phenomena.

Introduction

Fiber Metal Laminates (FMLs) are multilayered structures alternating aluminum or titanium alloys laminates and fiber-reinforced polymer composites, featuring well-designed hybrid properties from both components. FMLs are extensively employed as aerospace structural components because of their enhanced fatigue life, versatility, crack tolerance, and high strength-to-weight ratio relative to conventional metallic alloys and fiber-reinforced composites. Nevertheless, inherent heterogeneity, anisotropy, complexity, as well as difficulties in precise control of machining processing make FMLs difficult to handle. Given the applications for which FMLs are intended in the aerospace sector, drilling is one of the main machining operations they undergo. Thus, considerable work has been carried out to improve their machinability.

Damage induced by drilling has long been regarded as a critical issue related to composite materials. In this context, initial investigations focused on the mechanisms of surface integrity deterioration due to phenomena as delamination, fiber pull-out, matrix failure, and thermal damage, which may lead to a serious reduction of the sample mechanical performance and fatigue life [1]. In carbon fiber reinforced polymers (CFRP) laminates, it was found that thrust force predominantly influences delamination initiation, with a strong impact deriving from cutting speed, feed rate, and drill geometry [2]. In more recent studies, it was shown that optimizing drill force parameters through higher cutting speeds can lead to a reduction of thrust force and delamination damages as well, while displaying improved accuracy of the resulting hole geometry and surface quality [3].

When drilling hybrid stacks or FMLs, handling difficulties become considerably more complex due to the abrupt change in material properties at the interfaces. Metallic layers typically promote continuous chip formation and burr generation, while composite layers exhibit brittle fracture and powder-like chip morphology. Shyha et al. [4] provided one of the first comprehensive assessments of hole quality in metallic-composite stacks, demonstrating that interface-related damage, burr formation at metallic exits, and dimensional inaccuracies are strongly influenced by stack configuration and tool progression sequence.

Specific attention to FML drilling has increased over the past decade. Giasin et al. [5] developed a three-dimensional finite element model to predict cutting forces during drilling of FMLs and correlated numerical predictions with experimental observations of hole quality. Their results showed good agreement between predicted thrust forces and experimentally observed damage mechanisms, highlighting the importance of modelling approaches for understanding multi-material drilling behaviour. In a complementary experimental study, Giasin and Ayvar-Soberanis [6] investigated the effects of minimum quantity lubrication (MQL) and cryogenic cooling on GLARE™ laminates, demonstrating that lubrication strategy significantly affects burr height, surface roughness, and delamination severity, especially at metallic-composite interfaces. The influence of cooling and lubrication strategies has also been explored for composite-titanium stacks. Xu et al. [7] conducted a comparative study on dry and MQL drilling of CFRP/Ti6Al4V stacks using different tool coatings, reporting that MQL can reduce tool wear and improve hole quality, although its effectiveness strongly depends on coating type and cutting parameters.

From a materials perspective, the machining behavior of titanium alloys commonly used in aerospace stacks has been extensively studied. Investigations on Ti6Al4V drilling have shown that high thrust forces, elevated temperatures, and segmented chip formation are inherent challenges that directly influence burr formation and dimensional accuracy [8, 9].

Recent works have broadened the focus of FMLs to the exploration of new metallic material systems. In this category, the work of Lizzul et al. [10] analyzed the drilling of magnesium FMLs through hot pressing: the authors observed the importance of surface treatments on metallic layers to the level of interfacial bonding. Although the importance surface modification to the overall performance of laminates has generally been affirmed, the direct relationship of the texturing to the resulting integrity of drilled holes has yet to be made. Indeed, contributions made by the works of Doğan et al. [11] culminated in the compilation of the entire literature relevant to the drilling process of FML stacks through conventional means. Nonetheless, the authors affirmed the challenges experienced despite the research progress made, mainly due to the material variability exposed to the process. Significantly, the challenges have come mainly from the layer surfaces [12].

Though considerable work has been carried out to improve FMLs machinability, very little attention has been paid to the potential role of engineered surface topographies at the metal-composite interface. In fact, a modification in surface roughness necessarily results in different local contact conditions and consequently hot pressing consolidation results, thus influencing key aspects such as forces transmission, drilling-induced damage and hole quality. The present work aims to correlate the application of surface modification techniques – with specific focus on laser texturing – and both the strength of the adhesive bond at the interface between sheet metal and composite layer and the quality of internal hole surface during drilling tests. This is achieved by assessing the evolution of the cutting forces developed during machining as the process parameters vary, and by analyzing the occurrence of phenomena like fiber pull-out, matrix smearing and interface debonding.

Materials and Methods

The samples investigated are FMLs composed of two external Ti6Al4V titanium alloy sheets and a central glass fiber-reinforced thermoplastic composite layer. Each titanium sheet had dimensions of 40mm×160mm and a thickness of 1 mm, while the composite core consisted of a 1 mm-thick glass fiber-reinforced polyamide 6 prepreg PA6-GFRP (Tepex® 102-RG600 (2)/47% Type B). The characteristics of the prepreg assembly are reported in Table 1, while the mechanical properties of the both the metal and composite layers are listed in Table 2.

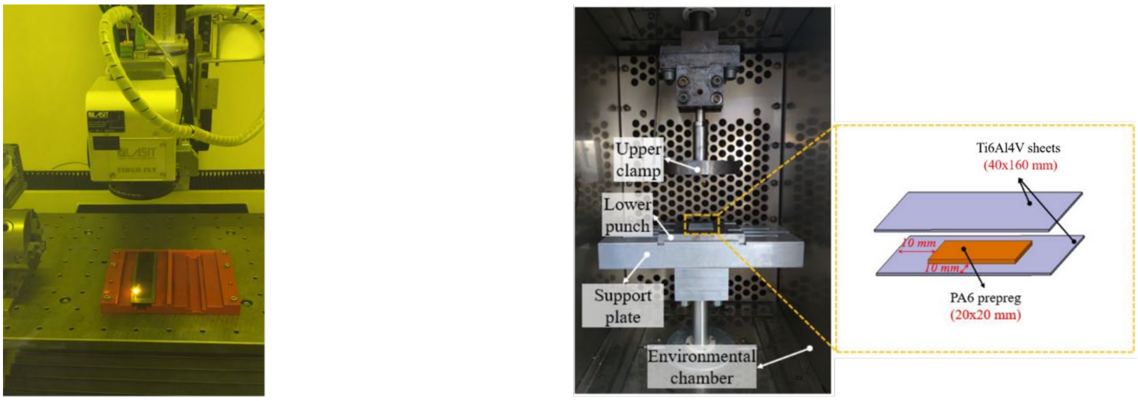
Table 1. PA6-GFRP composition characteristics.

Layup	Characteristics
Matrix	Polyamide 6 [-NH(CH2)5CO-]$_n$ Melting point: 220°C
Reinforcement	E-Glass roving Weaving style: Twill 2/2 Area weight (dry fabric): 600 g/m^3 Yarn count: 1200 tex Weight rate: 50% Fiber content: 47%
Laminate density	1.8 g/cm^3

Table 2. Mechanical properties of Ti6Al4V and PA6-GFRP.

Ti6Al4V		PA6-GFRP	
Elastic modulus	110 GPa	Tensile modulus	18 GPa
Shear modulus	41.35 GPa	Flexural modulus	16 GPa
Poisson's ratio	0.33	Strain at break	2.3%
Yield strength 0.2%	1090 MPa	Flexural strength	300 MPa
Ultimate tensile strength	1120 MPa	Ultimate tensile strength	380 MPa

Prior to laminate consolidation, the titanium sheets were cleaned in an acetone ultrasonic bath and then textured using an air-cooled ytterbium fiber laser system (Lasit Compact Mark G8 – Fig. 1a). Based on preliminary studies [13], a laser power of 40 W and a speed of 50 mm/sec were selected as process parameters. The applied texture consisted of unidirectional features aligned parallel to the minor dimension of the Ti6Al4V sheets and spaced 200 µm apart. After texturization, each component was hot-pressed to form the FML specimens (Fig. 1b), producing titanium-composite-titanium sandwich structures with controlled interfacial bonding.



a) b)

Fig. 1. a) Laser texturing experimental setup; b) hot pressing schematic representation based on [14].

Drilling experiments were carried out on a CNC Mazak Nexus 410 vertical machining center; Fig. 2a illustrates the experimental set-up and the clamping configuration. The specimens were placed inside a support that allowed stable positioning during the test, so as to avoid excessive vibrations and possible displacements of the specimen itself. This support was in turn secured with screws to a 3-components piezoelectric dynamometer (Kistler© 9257), which was connected to a charge amplifier (Kistler© LabAmp 5167A) and used to acquire signals related to the forces generated on the sample during drilling. The thrust force F_z was selected the main variable of interest for the purposes of the analysis; it was measured at a sampling rate of 2.5kHz. Data acquisition and elaboration were carried out via the DynoWare™ software.

All tests were performed using a solid carbide drill (Sandvik Coromant CoroDrill® 863.1-0635-026A1-OS H10F) with a nominal diameter of 6.35 mm and a 135° point angle, designed to optimize GFRP drilling. Fig. 2b shows the geometry of the drilling tool; images were acquired via Leica Stereo Microscope MS5. Due to the intrinsic complexity of the multi-material system under investigation, given the tool manufacturer's recommendations to identify a stable processing window to avoid premature tool failure or excessive damage, and based on information gathered from literature, a cutting speed of 15 m/min was fixed as driving process parameter, while two feed rate values of 0.06 mm/rev and 0.10 mm/rev were varied during the experimental campaign. Given the localized nature of the drilling operations, a minimum quantity lubrication (MQL) strategy was chosen as most suitable. For each combination of process parameters, 5 repetitions were performed in order to allow for adequate statistical analysis of the results, for a total of 10 drilling operations. To prevent any effect of tool wear, each FML was drilled with a fresh drill bit.

a) b)

Fig. 2. a) Drilling experimental setup; b) drill bit geometry.

Drilled FMLs samples were sectioned using a Struers Labotom-5 precision metallographic saw. The internal surface of the holes was analyzed using both a Leica Stereo Microscope MS5 and an optical microscope (Leica DFC320). The surface integrity evaluation took into account aspects such as surface finish, smearing, fiber pull-out, material residues and delamination.

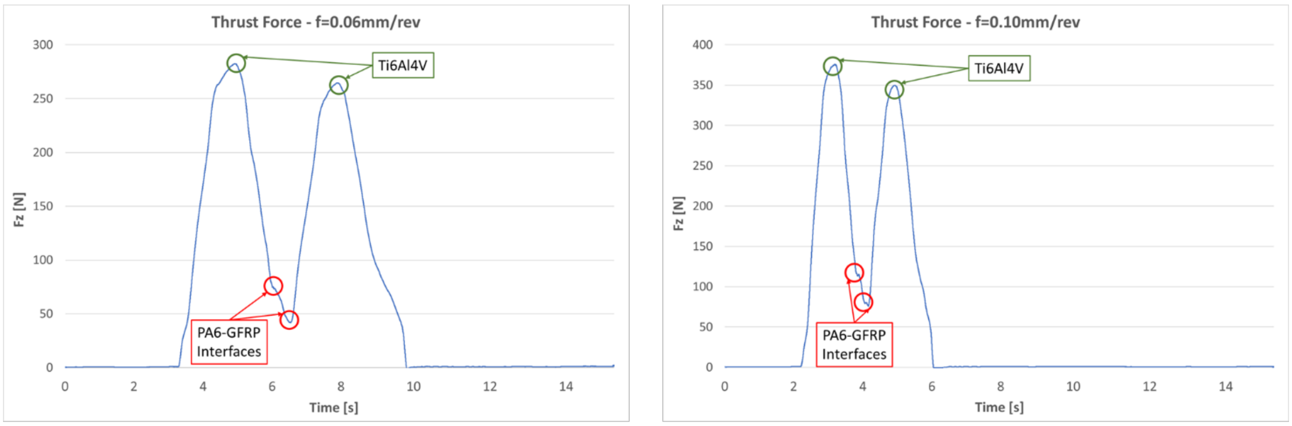
Results and Discussion

Fig. 3 shows the representative trends in the evolution of the thrust force generated during the drilling process for both combinations of process parameters used – the data was first cleaned of noise resulting from signal acquisition. In both cases, three clearly defined regions can be identified.

When the tool comes into contact with the external titanium surface of the FML, a rapid increase in thrust force occurs, as it reaches its maximum value, thus indicating complete penetration into the layer. This peak reflects the high mechanical strength and low thermal conductivity of the material, which result in considerable friction and, indeed, high thrust force.

Then, a sudden decrease in force is recorded: this can be attributed to the fact that the titanium sheet has been perforated and therefore the tool comes into contact with the PA6-GFRP layer. This material not only has a significantly lower strength than titanium, but also exhibits brittle deformation and fracture behavior due to the presence of glass fibers. It is interesting to note that the Ti6Al4V/PA6-GFRP and PA6-GFRP/Ti6Al4V interface regions can be identified by slight fluctuations in the measured force values. These variations are primarily due to the transition of the drill bit from the metal material to a completely different one, as well as to aspects such as the presence of fibers, their orientation within the matrix and the alternating cutting action of fiber and matrix.

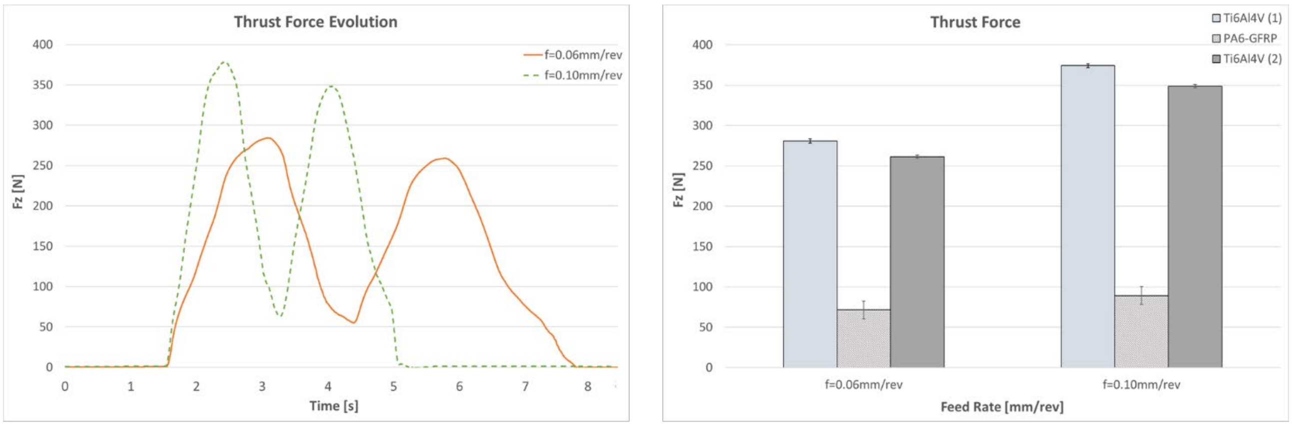
Finally, when the tool completes its engagement into the polymer layer to encounter the second titanium layer, a further increase in the thrust force occurs. Here, the peak force reached when the titanium layer is completely drilled through is lower than the previous one: this decrease is to be ascribed to both the tool, since the drilling of the two previous layers caused an increase in temperature and the possible onset of wear, and to the sample, as its overall flexural strength is reduced from the first layer to the last one. As the force value decays to zero, the FML has been completely drilled through.



a) b)

Fig. 3. Thrust force evolution for different feed rate values: a) f=0.06 mm/rev; b) f=0.10 mm/rev.

To understand the effect of feed rate variation on thrust force, Fig. 4a shows the two typical trends analyzed above superimposed on the same graph; Fig. 4b shows the average thrust force values at the peaks identified for the two Ti6Al4V layers and the valley corresponding to the composite layer. In particular, given the variability of the thrust force in the PA6-GFRP layer between the two interfaces, the average force measured at the interfaces was taken as a reference value to describe the behavior of the material. It can be highlighted that, as the feed value increases, there is a 30% rise in thrust force: this effect is a direct consequence of the higher material strength, which in turn is attributable to an increase in strain rate. This effect is particularly significant for the PA6-GFRP layer, as it can be considered related to the mechanical strength of the FMLs interfaces, thus implying an increase in resistance to delamination when drilling at higher feed rates.



a) b)

Fig. 4. a) Comparison of thrust force evolution for both feed rate values; b) maximum Ti6Al4V and mean PA6-GFRP thrust force values.

In terms of hole quality assessment, Fig. 5 shows the hole cross sections as the feed rate varies. Specifically, images captured using a stereo microscope (Fig. 5a,b) and an optical microscope (Fig. 5c,d) are shown.

When using a feed rate *f=0.06mm/rev*, the surfaces in the Ti6Al4V layers show regular and relatively uniform circumferential streaks, indicating a stable cutting process and low roughness; only limited localized plastic adhesion phenomena are observed, compatible with moderate built-up edge (BUE) formation, yet without obvious signs of tearing or smearing. Near the tool exit zone, grooves are probably caused by chips getting stuck in the hole before being ejected, so that the tool rotation left such pattern on the metal surface. The PA6-GFRP layer has a fairly homogeneous surface: the glass fibers emerge regularly and are sharply cut, while only near the interface with the metal layer a reduced fiber pull-out and a slight presence of smeared metal material can be noticed (Fig. 5c). On the other hand, the absence of cavities or voids suggests a limited damage and the absence of debonding.

As the feed rate increases, there is an overall deterioration in surface quality. In fact, in the Ti6Al4V layers, the streaks are more pronounced and less uniform, consistent with an increase in cutting forces, chip thickness and BUE instability. In the composite layer, the surface is more irregular, with less clear fibers cut, an increase in extraction or fraying phenomena, and the presence of more consistent plasticized metal residues, located not only at the interface, but also in the central portion of the layer (Fig. 5d). This phenomenon is likely to be favored by the increase in temperature and contact pressures that develop at a higher feed rate. However, no debonding or delamination phenomena are observed in this case either.

Overall, an increase in feed rate leads to increased roughness and irregularity in the metal layers and a higher level of damage to the composite layer. These findings indicate that, under the conditions examined, the lower feed rate ensures better surface integrity of the hole in the multilayer laminate, reducing both damage to the GFRP and metal transfer phenomena.

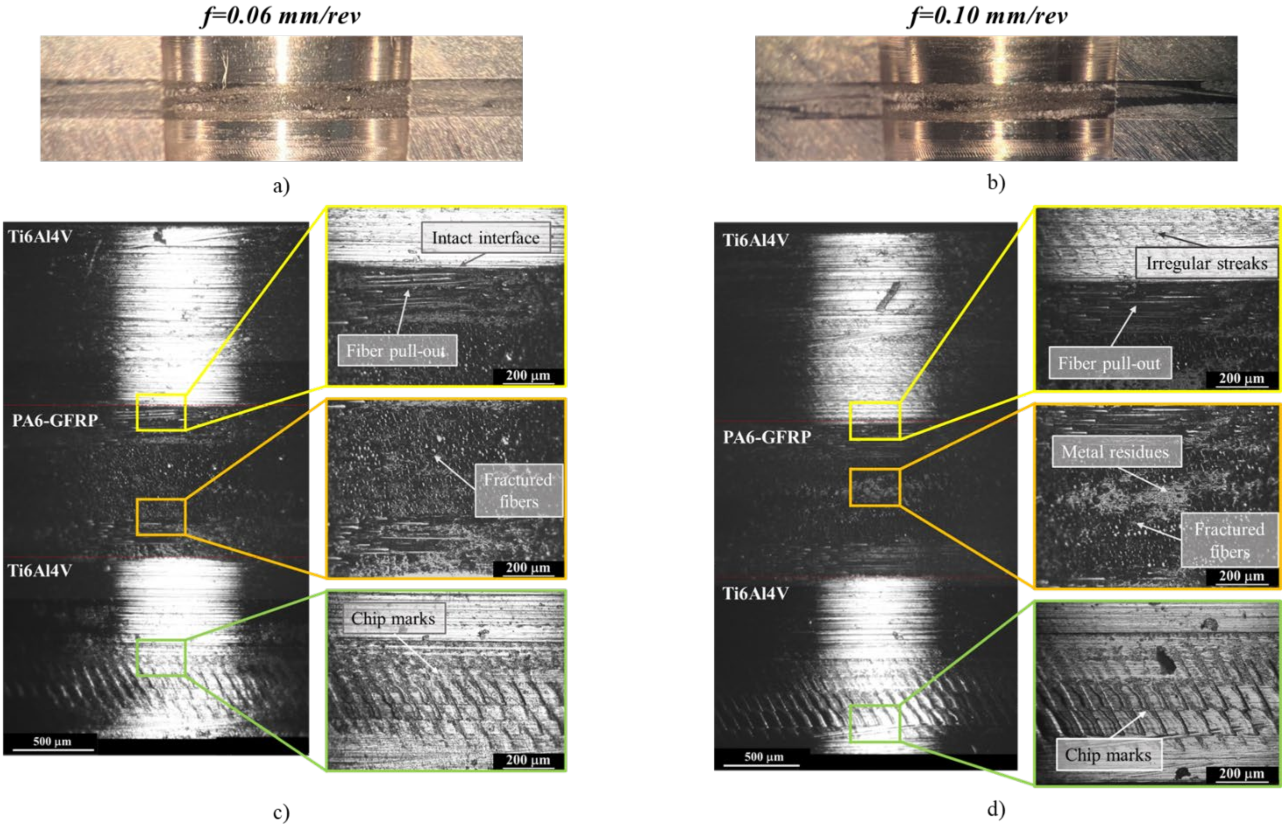


Fig. 5. Hole cross sections of drilled samples at varying feed rate observed via: stereo microscope (a, b); optical microscope (c, d).

Conclusions

This study focused on assessing the strength of the adhesive bond and the hole quality in the drilling process of FMLs structures typically used in the aerospace industry. The main objective was to investigate the influence of surface modification treatments, specifically laser texturing, on these aspects of significant engineering importance, since drilling-induced defects substantially affect the structural integrity and fatigue performance of FMLs.

To this end, Ti6Al4V sheets, which constitute the metallic part of FMLs, were subjected to laser texturing to create a one-dimensional micro-pattern; laser-textured titanium sheets were then consolidated with glass fiber-reinforced PA6 prepreg (PA6-GFRP) through hot pressing to produce aerospace-grade FMLs.

The experimental drilling test campaign allowed to establish how, at a given cutting speed, an increase in feed rate leads to an increase in thrust force, identified here as the main engineering variable since it provides a measure of the adhesive bond strength at the interface between the titanium sheets and the composite core. On the other hand, the evaluation of the surface quality of the inner walls of the holes showed that an increase in feed rate corresponds to an increase in roughness, a greater amount of fiber pull-out and more widespread plasticization of the titanium, resulting in it spreading in different areas of the polymer matrix layer. However, no debonding or delamination phenomena occurred for either feed rate value.

Accordingly, the next steps will aim to further expand this research by introducing new textures to be compared to the one investigated here, analyzing a wider range of feed rate values – in order to identify the delamination limit condition – and introducing a variation in cutting speed as characteristic process parameter. For a more in-depth analysis of the surface quality of the holes made, SEM can be used as reference technique.

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