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Research on milling strategies to reduce delamination damage during machining of holes in CFRP/Ti stack

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ABSTRACT

Helical milling is being adapted to machine holes that facilitate component assembling in the aerospace industry. It is superior to conventional drilling in many ways including low cutting forces, reduced tool wear and improved hole quality. The main objective of this study was to establish a better method of milling holes in CFRP/Ti stack. Four strategies were studied experimentally and the results compared including thrust forces, delamination and temperatures. In the first and second strategies, it was found that composite laminate experience less damage when machined in the configuration CFRP/Ti compared to Ti/CFRP. The third and fourth strategies employed three steps to achieve the required diameter while alternating the composite-metal stack. It was found that a multi-step milling strategy leads to the best quality holes as the subsequent steps eliminate the damage caused by the first step while only utilizing peripheral cutting thus minimum forces. Thrust forces were found to have an almost linear relationship with the feed rates and an inverse relationship with the spindle speeds for all the strategies studied.

1. Introduction

The properties of Carbon Fiber Reinforced Polymer (CFRP) composite material including high strength, low weight, high-temperature tolerance, corrosion resistance and low thermal expansion coefficient makes it the current most attractive material for aircraft structures. An aircraft is a complex machine made up of thousands of components. Joining of these components together require thousands of holes for rivets or bolts. Hole making process is, therefore, an indispensable machining process in the aerospace industry.

Machining of CFRP differs considerably to that of metals due to their heterogeneity and anisotropic behavior [1]. The said behavior of composites poses challenges during machining which lead to several kinds of damages on the composite including delamination, fiber pull-out and matrix cracking [2–4]. Of all the damages, delamination has been considered as the most severe form of damage [5] as it leads to significant reduction in the fatigue strength of the component thus degrading the long-term performance of the component. Different approaches including both experimental and numerical methods have been employed by researchers in understanding damages to composites during machining and particularly hole making. Thrust force has been found to have a linear relationship with delamination damage [6,7]. When the thrust force exceed the inter-laminar strength of the laminates, the layers of the composite separate leading to delamination. Factors contributing to thrust force have been yet been fully understood and this remains an active research in the composites material machining. Several factors have so far been pointed out including tool geometry, feed rate and spindle speed. Some researchers [8,9] conducted experiments to determine the effect of using different tool geometries on the quality of the drilled holes. Their results showed that step drill, compared to other drilling geometries records low thrust forces and subsequently less damage to the composite laminate. When using step drill to drill woven CFRPs, the authors [10] found that though reduction of thrust forces was achieved, delamination was only reduced at low feed rates. The recent work by the authors [11] suggested using dampers to mitigate thrust forces during drilling of holes in composite laminates. Their results showed that dampers reduce thrust forces by about 25% leading to better quality holes. The orientation of fiber angles and the stacking sequence employed in fabricating composite laminates has been found to greatly affect the damage behavior during machining as reported by authors [12] in their work.

Conventional methods of machining CFRP have been studied extensively by dozens of researchers and now the focus is shifting to non-conventional methods. These methods have been proven experimentally that when employed leads to less damage on the composite and increases tool life. Farrukh Makhdum et al. [13,14], in an attempt to

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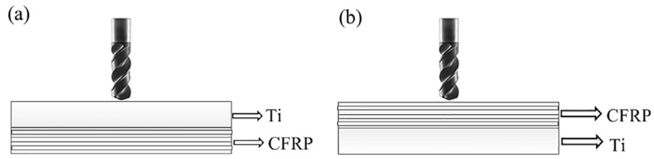

Fig. 1. (a) and (b) showing strategies 1 and 2 respectively of the current work.

reduce the thrust forces and subsequently the damage on the composites during drilling, experimented on ultrasonically assisted drilling (UAD). This method of drilling employs a high frequency (approximately 20 kHz) and low amplitude (< 20 µm) vibrations are superimposed on a drill bit in the axial direction. A thrust force reduction of about 60% and a significant improvement of the drilled hole quality was observed by the authors [15,16] ultrasonically assisted drilling. Helical milling is emerging as an alternative to conventional methods in CFRP hole manufacturing. In helical milling process, the cutting tool proceeds a helical path while it rotates on its own axis. The helical path comprises of both the tangential and the axial directions thus combining frontal and peripheral cutting, therefore, presenting several advantages compared to conventional drilling. The advantages include better heat dissipation, reduction in thermal damage, improved hole quality, reduction in burr formation, improvement in geometrical accuracy and smaller cutting force [17]. Recently, the authors [18] experimented on a two-step technique to reduce delamination damage during milling of large diameter holes in CFRP/Al stack. They found that better hole quality is achieved when the sequence of the stack is beginning with the composite since the metal part will act as a backup plate reducing exit delamination. The helical milling process is suitable for hole generation in difficult to cut materials such as Carbon Fiber Reinforced Polymer (CFRP) composites and Ti-alloys [19–21]. In terms of hole dimension, geometry and roughness, satisfactory results have been obtained when helical milling process is employed for hole generation [22]. It is because of these advantages that helical milling has been labeled as a sustainable hole-making process in difficult to cut materials [23]. The main drawback of helical milling is low productivity since it takes more time to complete machining of a hole when compared to conventional drilling. Since it leads to better hole quality, it is worth the wait during machining. Most machining work is automated these days thanks to the robots which can ensure higher productivity of complex machining processes like helical milling.

The use of composites in conjunction with other materials to form a multi-material stack such as CFRP/Ti or CFRP/Al in the aerospace industry is a common practice nowadays thanks to its superior mechanical properties. Although milling has been found to be a better alternative to conventional hole making in these materials, it does not completely eliminate delamination. This necessitates further research to understand various variables and methods of the process that contribute to delamination damage. The present work employs helical milling process to manufacture holes in CFRP/Ti stack. In this work, four milling strategies are studied in order to establish a method that leads to less damage on the stack during hole manufacturing. The first and the second strategies compare the effect of stack order on the quality of the holes manufactured. In this case, Ti/CFRP stack is considered for the first case and then CFRP/Ti for the second case. A 12 mm diameter hole is manufactured in a single step for the first and the second strategy. The third and fourth strategies employ a three-step process to achieve the 12 mm diameter hole on the stack. For the third strategy, in the first step, an 8 mm diameter hole is machined while the stack order is CFRP/Ti. In order to eliminate the damage caused by the first step, in the second step, the stack is flipped so that the order is now Ti/CFRP and 10 mm diameter is machined. Finally, in the third step, the stack order is changed to CFRP/Ti and the target 12 mm diameter hole is machined. The fourth strategy is the same as the third except for the stack order where it starts with Ti/CFRP. In brief, the first two strategies bring a comparison of stack order whereas the last two compares stack order when different steps are employed to achieve the final hole diameter. The milling strategies studied are illustrated in Figs. 1–3 respectively shown below.

2. Helical milling

The helical milling process is composed of three simultaneous movements of the milling tool. Firstly, the spindle rotation brings about the rotation of the tool about its own axis then the revolution about the center of the machined hole and lastly the linear movement along with the axis direction of the machined hole. The helical movement of the tool is brought about by the combination of the last two movements (revolution and linear movement). Whereas the helical milling process is achieved by three kinds of movements as already stated, the cutting is divided into two: the peripheral cutting and the axial cutting [23]. The revolution of the milling tool around the machined hole axis brings about the tangential feed (peripheral cutting) while the linear motion along the axis of the machined hole brings about axial feed (axial cutting). Illustration of helical milling as given by the authors [24] is shown in Fig. 4 below.

Unlike in the conventional milling where the diameter of the hole is determined by the milling tool, it is determined by the eccentricity between the axis of the tool and the axis of the machined hole in the case of helical milling [25]. This is one of the many advantages of helical milling as it allows for the attainment of holes with varying diameters without changing the milling tool thus reducing tool inventory.

In order to illustrate the helical milling process, it is very important to standardize the nomenclature of the helical milling parameters [26] as there are several different definitions in literature making it difficult to understand the calculations and to apply the optimal milling parameters achieved in the investigations. First of all, description of the motion of the tool will require two sets of coordinate systems as explained by the authors [27,28]. An X, Y, Z World Coordinate System (WCS) fixed to the workpiece and an x, y, z Local Coordinate System (LCS) fixed to the cutting tool. B. Denkena et al. [29] did a great work in analyzing the kinematics of helical milling process. The parameters to be considered include the diameter of the bore, cutting speed, the

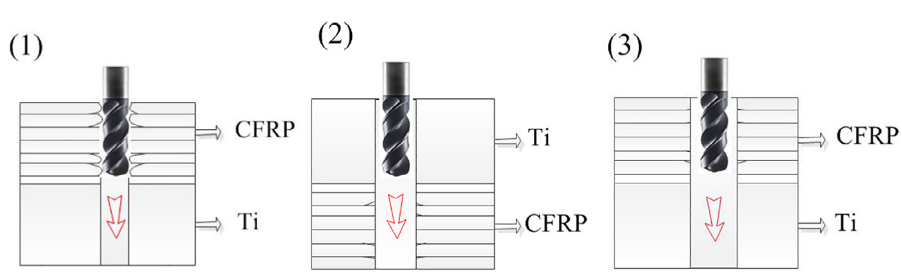

Fig. 2. (1), (2) and (3) showing steps 1, 2 and 3 respectively of strategy 3 of the current work.

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