Journal of Manufacturing Processes 25 (2017) 262–273

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Low-frequency modulation-assisted drilling of carbon-epoxy composite laminates

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ARTICLE INFO

Article history:
Received 12 August 2016
Received in revised form
10 December 2016
Accepted 11 December 2016

Keywords:
Composites
Laminates
Drilling
Forces
Delamination

ABSTRACT

Carbon fiber-reinforced plastics (CFRPs) have a wide spectrum of industrial applications because of their outstanding multifunctional properties. However, the machining performance of CFRPs is poor which has restricted further expansion of their application range. The damage that is induced during machining is considered as a major hindrance for the applicability of CFRP components for structural applications. In order to mitigate this perplexing challenge, an emerging machining method namely, modulation-assisted machining has been adopted which has not been investigated earlier in context of drilling of CFRP laminates. The drilling performance of the CFRP laminates has been analyzed using both conventional and modulation-assisted drilling techniques. The influence of the feed, frequency of rotation, drill geometry, frequency of modulation, and modulation amplitude on the force and subsequently damage has been experimentally investigated. The results indicate that modulation-assisted drilling technique produces better quality holes than conventional drilling under identical conditions.

1. Introduction

The renowned aerospace companies (Boeing, Airbus etc.) have realized the underlying potential pay-off of composites and have made huge investments for achieving a competitive edge in the global marketplace with the objective of using more volume of composites in aircraft. As a result, Airbus A350XWB and Boeing 787 using composites about 50% of the structural weight [1]. Composite materials such as; CFRPs have outstanding properties including high strength as steel, low density as aluminum, higher stiffness than titanium etc. Thereof, CFRPs are widely used for the development of sophisticated components in automobile, aerospace, biomedical, defense, and sports industries [2]. For instance, the critical load bearing components such as fuselage bulkheads, aircraft skin, stringers, and spars of the commercial aircraft are manufactured using CFRPs [3].

Manufacturing of CFRPs can be broadly ramified into two processes, these are; primary and secondary manufacturing processes. Both manufacturing processes incorporate high degree of automation and therefore, most of the products based on CFRPs can be manufactured to near-net shape products. The primary manufacturing is limited to simpler products with minimum geometrical intricacies. The complex design necessitates the manufacturing of product in multiple parts and then joined them to shape the final product. Machining in general and drilling in particular, thus play a vital rule to determine the structural integrity of the intricate composite product, as it facilitates the assembly operation.

Drilling of CFRPs is different than drilling of metals in a number of ways. The underlying properties of the reinforcement and matrix phase make understanding of material removal mechanism quite complex. The failure of reinforcement and matrix phase that occurs as a result of drilling action has been a research area of paramount importance. The damage of reinforcement and matrix not only influences the hole quality but also affects the long-term performance deterioration of the structure. The research attempts in the area of drilling of composites are majorly focussed on estimation and characterization of the damage. The forces generate during drilling is the major cause of damage which account almost 60% part rejection during quality control test. Surface delamination, burning of the matrix material, fibre pull-out, spalling, and chipping are some of the common forms of damage. The optimization of cutting parameters (feed and speed), selection of the suitable tool geometry and tool material are some of the important methodologies adopted to minimize the material damage during drilling of CFRPs [4–6]. Other methods, those have attained a certain level of success

Abbreviations: amp., amplitude; freq., frequency; CD, conventional drilling; MAD, modulation-assisted drilling.

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http://dx.doi.org/10.1016/j.jmapro.2016.12.009
1526-6125/

for drilling of CFRPs are; high speed drilling [7], orbital drilling [8], drilling with pilot hole [9], use of cutting fluid during drilling [10], vibration-assisted twist drilling [11], rotary ultrasonic machining [12], rotary ultrasonic elliptical machining [13], ultrasonic drilling [14], using of back-up plate during drilling [15], grinding drilling [16] etc.

In the present investigation, an emerging machining technique called; modulation-assisted machining has been applied for drilling of CFRP laminates. The feasibility of the modulation-assisted machining technique for drilling of CFRP laminates has been experimentally investigated and compared with the conventional drilling.

2. The modulation-assisted drilling process

The application of modulation vibration may be bifurcated into two types; velocity-modulation and feed-modulation, as shown in Fig. 1. In the velocity modulation, the tool vibrates in the direction of cutting velocity. But if the modulation is in the direction of tool feed, then it is called feed-modulation. Principally, feed-modulation is specifically adopted during drilling as it improves the drilling efficiency by controlling the chip formation. A few studies are available on feed direction modulation-assisted machining of aluminum, steel, and cast iron [17–20]. But the capability of feed-modulation in the drilling of plastic materials has not been thoroughly investigated. This has motivated the authors to present a work on modulation-assisted drilling of CFRP laminates.

In modulation-assisted drilling, the tool is superimposed by low-frequency (typically <1000 Hz) and high-amplitude (up to 150 μm) modulation vibration. The low-frequency and controlled sinusoidal oscillation is imposed on the drill in a direction parallel to the feed direction of the drill bit causes the formation of shorter chips. The formed chips are substantially shorter than the chips formed during conventional drilling. Furthermore, the thickness of the undeformed chip varies sinusoidally during modulation-assisted drilling whereas the thickness of the undeformed chip is constant during conventional drilling, as depicted in Fig. 2. Also, during drilling, the tool comes in contact with the fiber and matrix at different interval of time as it passes through the composite laminate. At low frequency, the interaction of the tool with the composite constituents is relatively less frequent in comparison to the high-frequency oscillation. Thus, the generated heat is dissipated and chip is ejected from the machining zone with a greater efficiency.

A substantial change in the characteristics of the formed chip and force occurs on the imposition of modulation. This effect is associated with the K and the ratio of f_p to the f_d (where, K = amplitude of modulation, f_p = frequency of modulation, and f_d = frequency of rotation of the drill). For a drill bit consisting of two cutting edges, when f_p/f_d is an even integer or zero, the modulation has no significant effect on the thrust force, torque, and instantaneous chip thickness. Under this condition, the modulation-assisted drilling resembles much like conventional drilling. But when f_p/f_d is an odd integer and $K \geq (feed/rev)/4$, the average drilling forces decrease and the thickness of the chip will vary sinosoidally and will reach zero (during disengagement). This is attributed to the fact that the drill is retrieved from the workpiece during each modulation cycle. Under the similar condition, a large dynamic component of the torque and thrust force is observed. At the same time, the value of thrust force does not go

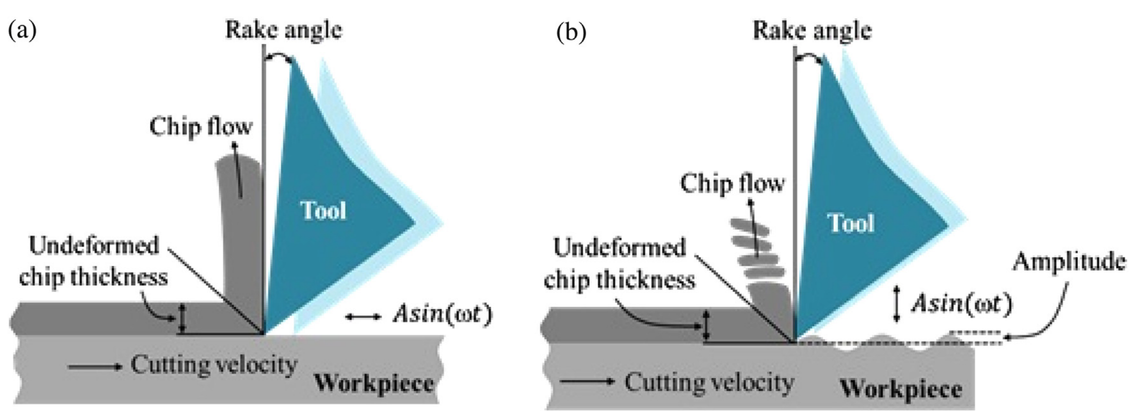

Fig. 1. Variants of modulation-assisted machining; (a) velocity-modulation, and (b) feed-modulation.

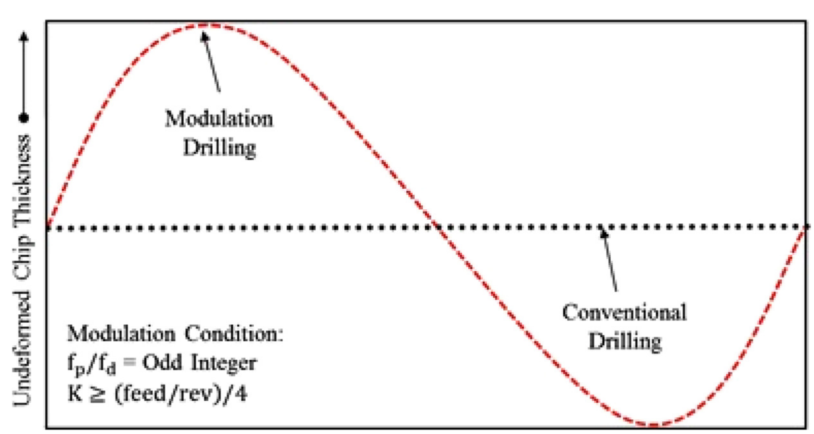

Fig. 2. Variation in undeformed chip thickness.