Wear 338-339 (2015) 11–21

Contents lists available at ScienceDirect

Wear

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

Wear on SiAlON ceramic tools in drilling of aerospace grade CFRP composites

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ARTICLE INFO

Article history:
Received 5 January 2015
Received in revised form
10 May 2015
Accepted 15 May 2015
Available online 22 May 2015

Keywords:
Micro-scale abrasion
Engineering ceramics
Cutting tools
Electron microscopy
Hardness

ABSTRACT

Carbon fiber reinforced polymer (CFRP) composites are difficult to cut materials due to their anisotropic structure and extremely abrasive nature of the carbon fibers. The tool materials used for drilling of CFRP composites are limited; thus there is always a strong demand for new tool materials which can be utilized successfully for the high performance drilling process. In this study, wear behavior of different SiAlON ceramics, which are successfully used for machining of various materials such as gray cast iron, superalloys, etc., on the drilling of CFRP composites was investigated, compared and reported for the first time in the literature. Three different SiAlON-based drilling tools with the same geometry were manufactured and tested on the drilling of aerospace grade CFRP composites and their wear behaviors were compared to that of commercially available WC–Co tools. It was observed that the wear of the SiAlON tools occurs as micro-chipping of the cutting edge in the first few holes; then, severe abrasion takes place with further drilling. While SiAlON with high fracture toughness shows less micro-chipping, which occurs at the initial stage (1–5 holes) of the drilling process, SiAlON with high hardness has the highest abrasion resistance at the later stage. The increase in wear of the cutting edge of the SiAlONs and the WC–Co tools causes an increase in thrust force, and consequently, in peel-up delamination, which are desired to be as low as possible in order to achieve high performance from the drilling tools.

1. Introduction

Drilling is one of the most widely used machining operations to prepare bolted or riveted assemblies in fiber reinforced polymer (FRP) composites. However, drilling of these materials is a challenging process due to their anisotropic structure and their tendency to delamination at the hole entrance and the exit, as well as the abrasive nature of the carbon fibers. Cutting conditions (feedrate, (f) and cutting speed, (ν)), drill geometry and tool wear are the main parameters to be controlled in order to obtain high quality machined holes at minimum cost. Tool wear affects the thrust force which is accepted as the main reason for delamination. Khashaba et al. [1] investigated the influence of tool wear on thrust force, torque and quality of the machined hole during drilling of glass fiber reinforced polymer (GFRP) composite and concluded that the tool wear leads to an increase in the thrust force resulting in micro-cracking and damage in the polymer matrix and diminishes the surface roughness of the hole especially at higher cutting speeds and feedrates. Therefore, wear resistance of the tool material should be as high as possible to be able to drill a large number of high quality holes by using a single cutting tool.

In contrast to chip formation in metal cutting, the material is removed by brittle fracture of hard carbon fibers in FRP composite drilling [2]. Since the energy needed to fracture carbon fibers is much lower than that of cutting a metal by shear mechanism, the cutting force and the temperature are much lower in FRP composite drilling than that of metal machining [3,4]. In a recent study, Perez et al. [5] investigated the influence of material properties and cutting speed on heat dissipation in the drilling of CFRP composites using uncoated carbide tools. The temperature around the holes was measured by using thermocouples and infra-red cameras. The authors reported that the maximum temperatures can reach up to 200–250 °C for the cutting speeds of 50–250 m/min [5]. Rawat and Attia [6] also measured the tool temperature by using thermocouples and found the rate of temperature rise as 350° C/s at a spindle speed of 15,000 rpm and feedrate of 200 μm/rev when drilling of CFRP composites with uncoated carbide tools of 5 mm in diameter. Since a steady state could not be reached at high cutting speeds, they used finite element analysis (DEFORM) to predict the steady state cutting temperature and found that the local temperature may exceed 500° C at high speed conditions [6]. It is clear that the machining temperatures reported for the drilling of CFRP

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http://dx.doi.org/10.1016/j.wear.2015.05.009
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composites (200–500 °C) eliminate the possibility of chemical wear which is based on diffusion or dissolution of the tool and workpiece materials in each other. Therefore, the tool wear mechanism is likely to be related to mechanical wear in the drilling of CFRP composites.

The tool wear during drilling of composite laminates are distinctively different from metal cutting due to the anisotropic nature of hard fibers and thermo-mechanical interactions between drilling tool and composite laminates. The cutting edge experiences force fluctuation, and abrasion due to material heterogeneity and hard fibers, respectively. Furthermore, the drill point is under intensive adhesion/sliding contact with the chip and the machined surface. These result in different forms of wear [7]. Hard and abrasive fibers cause severe tool wear and frictional heat, whereas a soft and sticky matrix makes the tool cutting edge dull by clogging [3]. It has been reported in many investigations that the dominant wear mechanism in drilling of FRP composites in case of using uncoated carbide tools, is abrasive wear which is defined as a mechanical wear caused by scratching action of hard fibers embedded in the soft polymer matrix [3,6–8]. Masuda et al. [9] analyzed wear behavior of uncoated carbide tools which were used for machining of sintered carbons and CFRP composites. In spite of the fact that increase in the grain size of the carbide particles reduces the hardness of the tool material, the authors observed an increase in wear resistance of the tools with an increase in grain size. They also suggested that cobalt (Co) content of the carbide tool improves fracture resistance; however, high content of Co promotes detachment of WC grains from the cutting edge [9]. A similar observation was reported by Wang et al. [4], who investigated the wear behavior of uncoated and coated carbide tools used in the drilling of CFRP composites. Rawat and Attia [6] suggested that micro-chipping was the initial tool wear mechanism observed on the rake face along the chisel edge due to high stresses on the sharp cutting edge at the initial stage of the drilling process. In this stage, the tool was directly abraded by its WC grains which are fractured and detached from the cutting edge and the fractured carbon fiber chips in 3-body abrasive mode. They observed that the dominant wear mechanism turned to abrasive wear along the flank face of the carbide tool when the number of the drilled holes was increased [6].

Coating of the carbide drills with ultra-hard poly-crystalline diamond (PCD) via chemical vapor deposition route is an efficient way of extending the tool life. Wang et al. [4] investigated the performance of uncoated, diamond coated and AlTiN coated carbide tools on drilling of CFRP composites. They reported that the diamond coated tool did not show a significant wear at the cutting edge after 80 holes, whereas the AlTiN coated tool experienced high wear even worse than uncoated tool due oxidation of AlTiN coating and abrasion by the wear debris. The authors attributed the performances of uncoated and coated carbide tools to the sliding wear of the tool materials which refers to a wear resulting from sliding between two surfaces without formation of a significant chip debris due to abrasive wear [4]. In another study, Wang et al. [10] compared the wear behavior of uncoated, AlTiN coated and nano-composite (AlTiN+Si_3N_4) coated drills on drilling of CFRP, Ti and CFRP/Ti stacks. The authors concluded that the ultra-hard, coated tools have higher tool life in comparison to the uncoated tools due less micro-chipping provided by the coating materials [10]. Iliescu et al. [8] tested uncoated and PCD-coated carbide drills with special geometries on the drilling of CFRP composites and developed a mathematical model to predict the relationship between the cutting parameters and the tool wear. The authors stated that while the wear of the uncoated carbide tool increases linearly with contact length, the wear of the PCD-coated drills is almost constant up to a certain cutting length, after which it increases remarkably as a result of the removal of PCD layer. They also concluded that the life of the coated carbide tools is 5–10 times higher than that of the uncoated counterparts depending on the type and the quality of the coating [8]. Similar wear behavior was also observed by Karpat et al. [11], who investigated the performance of double point angle uncoated and PCD coated carbide drills in CFRP composite drilling.

SiAlONs, which exhibit outstanding mechanical, thermal and chemical properties, are another type of widely used cutting tool materials, especially in turning of gray cast irons and superalloys. Hardness of an α/β-SiAlON increases significantly with increasing α-phase content, which results, on the other hand, in a decrease in fracture toughness. The possibility of altering the α- to β-phase ratio enables one to tailor α/β-SiAlON composition in order to obtain composites with desired properties not only for the cutting tools, but also for the other applications, where the mechanical wear resistance is required at moderate temperatures (<1000 °C) such as attrition milling arms, wire extrusion dies, roll bearings etc. Jones et al. [12] investigated wear behavior of α/β-SiAlON composites with different α to β ratios under dry sliding conditions and suggested that fracture toughness determines the wear rate of the material under heavier loads, whereas hardness is more effective on the lower loads. Reis et al. [13] also studied the wear characteristics of the α-SiAlON which was reinforced with different amounts of β-SiAlON fibers by the pin-on-disk method under dry sliding conditions. The authors observed that the α-SiAlON reinforced with 10–20 wt% β-phase shows higher wear resistance in comparison to single phase SiAlON materials, which indicates importance of toughness. Accordingly, α/β-SiAlON composites are successfully used in metal cutting operations, in which high abrasion and/or chemical wear resistances are required from the tool materials. In these applications, SiAlON ceramics show much better performance than WC–Co especially when the cutting conditions are severe (high cutting speeds and feedrates). On the other hand, our study showed that SiAlON ceramics have substantially higher wear resistance than WC–Co when they are used as rotor pins in an attrition mill in dry grinding of fused alumina. Therefore, investigation of the performance of SiAlON ceramics in the drilling of CFRP composites, where the main wear mechanism appears to be the severe abrasion caused by the fragmented carbon fibers according to the literature findings, and comparison with WC–Co deserves an attention. In fact, drilling of CFRP composites by SiAlON ceramics have been reported for the first time in the literature in our recent study as tool materials for drilling of CFRP composites [14]. In that study, α/β-SiAlON drilling tools with four different sets of common drill geometries were manufactured and the effects of tool geometry on cutting forces and hole quality were investigated. However, a detailed analysis of wear behavior of SiAlON tool materials has not been investigated and reported yet. The objective of this study was to investigate the wear behavior of different SiAlON ceramics tools with varying microstructural characteristics on the drilling of CFRP composites and to compare their performances with a WC–Co tool.

2. Experimental procedure

Three different SiAlON-based materials were designed for manufacturing of drilling tools. The first one was composed of 25 vol% α- and 75 vol% β-SiAlON with a "*z*" value of 0.2 and denoted as 25A. Y_2O_3 and CaO were used in order to stabilize the α-SiAlON phase. Sm_2O_3 was utilized for promoting the formation of more elongated β-SiAlON grains in the microstructure in order to increase crack deflection and bridging capabilities of β-phase. The second composition was obtained by reinforcing the 25A composition with sub-micron SiC particulates (UF 15, HC-Starck, Germany; the specific surface area is 15 m^2/g). 15 wt% of the SiAlON mixture was replaced with the same amount of SiC powder in