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Wear patterns and wear mechanisms of cutting tools used during the manufacturing of chopped carbon fiber

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ABSTRACT

Chopping carbon fiber is an efficient way to manufacture short carbon fiber reinforced plastic (SCFRP). Drastic wear of cutting tools during this process has been observed because of the highly abrasive nature of carbon fiber. Wear patterns and wear mechanisms need to be investigated to reduce tool wear and prolong tool life. This paper presents the formation and transition of wear patterns during the chopping process. The chopped rate is less than 95% after 21k cuts; thus, tool specimens and data are collected from the initial 21k cuts. Overall, the wear forms a crescent shape along the tool edge at one cutting position. This wear pattern is due to an uneven wear volume caused by the uneven distribution of filaments in the fibers, which forms an oval profile of the chopped carbon fiber. The oval profile results in more crescent shaped wear, which causes a more uneven filaments distribution, leading to a high wear rate. Conical structures at the ends of the chopped carbon fiber and micro scratches on the tool edge are observed. Thus, the abrasive wear mechanism during chopping is verified. The wear pattern on the tool profile is a combination of cutting edge rounding (CER) and rake face wear. Two wear stages divided by 8k cuts are introduced: the CER wear stage (before) and rake face wear stage (after). In the CER wear stage, the wear rate is basically stable at 32 μm/2k cuts and the wear pattern is an increasing CER up to 20 μm. The rake angle is approximately stable at 79°. In the rake face wear stage, the wear rate begins to increase and the wear pattern transitions from the CER wear to massive rake face wear in which the CER decreases and leans towards the flank face and the rake angle rapidly decreases. The CER decreases to 4 μm, and the rake angle decreases to 14° at the end. The wear pattern includes a groove that appears on the tool rake face in this stage, which is similar to crater wear on the rake face of a traditional turning tool because of the low hardness of the tool interior. Moreover, analytical models based on 3-body abrasive wear theory are developed to explain these wear patterns and wear mechanisms.

1. Introduction

1.1. Cutting sized carbon fiber and its challenges

Short carbon fiber reinforced plastic (SCFRP) combines the advantages of polymers, such as good impact resistance and low weight, with the high stiffness and strength of carbon fibers. They are increasingly used in a wide range of applications, such as in the aerospace, marine, automotive, biomedical science, building and construction industries [1–3]. An efficient method of manufacturing SCFRP parts is to cut carbon fiber into strips that are typically 3 to 50 mm long, embed them into a resin matrix, form short-fiber-reinforced polymers and use traditional methods, such as compression molding, injection molding and extruded molding, for mass production [4].

Carbon fiber exhibits a totally different machining behavior compared to common metals and other materials because of its anisotropy and abrasive nature [5–10]. The challenges of chopping carbon fiber can be categorized into two types: excessive tool wear and workpiece material-related problems [6,9,11–14]. The latter type mainly includes the part shape, chopped rate and surface morphology.

The process of chopping carbon fiber is similar to sheet metal cutting, which involves feeding the tool transversely with pressure on the fiber tow such that filaments in the fiber gradually break until the fiber is fully cut. During the cutting and shortly after the cut off, the chopped carbon fiber end flows over the tool face and rubs the tool, which causes tool wear. In return, tool wear affects the machining shape, chopped rate and surface quality.

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1.2. Research motivation

Many studies have been performed on fiber breakage and chip formation in machining FRP-laminated composites, including drilling, milling and turning. KoPlev et al. [5] was the first to declare that chip formation in machining CFRP is a process of material brittle fracture. Several researchers [7–14] experimentally validated this theory. Karpat et al. [8] studied the milling force of unidirectional carbon fiber reinforced polymer laminates and showed that the milling forces are minimal when the fiber cutting angle is 45°, which is related to fracturing of the fibers. Rahman [10] showed that the chips formed from turning CFRP are discontinuous type chips in a powder or scrap form, and this chip formation mechanism is brittle fracture. Chip formation due to fracture will impact the tool edge and thereby blunt the cutting edge and generate flank wear [15]. In summary, filament fracture will impact the tool edge, which blunts the cutting edge and causes tool wear.

Several studies indicated that the dominant tool wear mode was cutting edge rounding (CER) in machining CFRPs [6–9,13,14,16–24]. Faraz et al. [6] proposed a latent wear characteristic CER as a measure of sharpness/bluntness of uncoated cemented carbide tools when drilling CFRP composite laminates. They experimented with four different types of uncoated cemented carbide drill bits and concluded that the value of the CER constantly increases. Similar wear patterns with uncoated, diamond coated and AlTiN coated carbide drill bits drilling CFRPs were observed by Wang et al. [13,14]. Madhavan et al. [9] found that with increasing wear, the cutting edge radius of the tool tip decreases when drilling CFRP laminated composites. They proposed that the abrasive wear along the flank face (caused by the cut fiber ends rubbing along it) is the dominant wear mode compared to the wear of the cutting edge expected from cutting the fibers. They also proposed a wear fact called a natural wearing radius and proposed that whether a cutting edge is initially prepared with a diameter greater than or smaller than this radius, the worn edge will assume its natural wearing radius. This natural wearing radius is determined by factors such as the fiber diameter, bundle size, fiber adhesion to the matrix material, among others.

A consequence of the natural wearing radius is that the final wearing radius is determined by the conditions of cutting despite the initial tool conditions. Cutting edge rounding means that during the cutting process, the radius of the tool tip increases and the tool becomes blunt. Two different types of wear patterns have been discovered in the process of drilling CFRP, but the wear patterns and mechanisms in chopping carbon fiber have not been fully described. Summarizing the basic findings of studies regarding chopping carbon fibers, the wear pattern in chopping sized carbon fiber is assumed to be a combination of the CER and rake face wear and wear mechanisms, including fracture impact and abrasive wear. Filaments are cut, which causes an impact because of the fracture (which mainly causes CER wear) and the chopped carbon fiber end rubs along the tool rake face (which mainly causes rake face wear) in the process. Fig. 1 illustrates a new tool bit and the two types of wear patterns: Fig. 1(b) shows the CER wear and Fig. 1(c) shows the rake face wear.

During the process of chopping carbon fibers, the cutting tool is quickly worn because of fracturing and the highly abrasive nature of carbon fibers. Once the tool is ground too much, the fibers will not be fully cut and will form a continuous tow that results in a low chopped rate. This will lead to a screening process, which increases cost and waste. Furthermore, the chopping process has to stop and tools have to be changed. Quick wear will result in frequently changing the cutting tools, which raises the process cost. The wear mechanism needs to be studied to slow tool wear and prolong tool life. With regard to this, the major objectives of this research are given in the next section.

1.3. Research objects

This research develops a knowledge base of the wear patterns and wear mechanisms of a cutting tool used in chopped carbon fiber manufacture by performing the following tasks:

- To predict the wear mechanisms and wear patterns of the cutting tool used in chopping carbon fiber. The wear mechanism combines

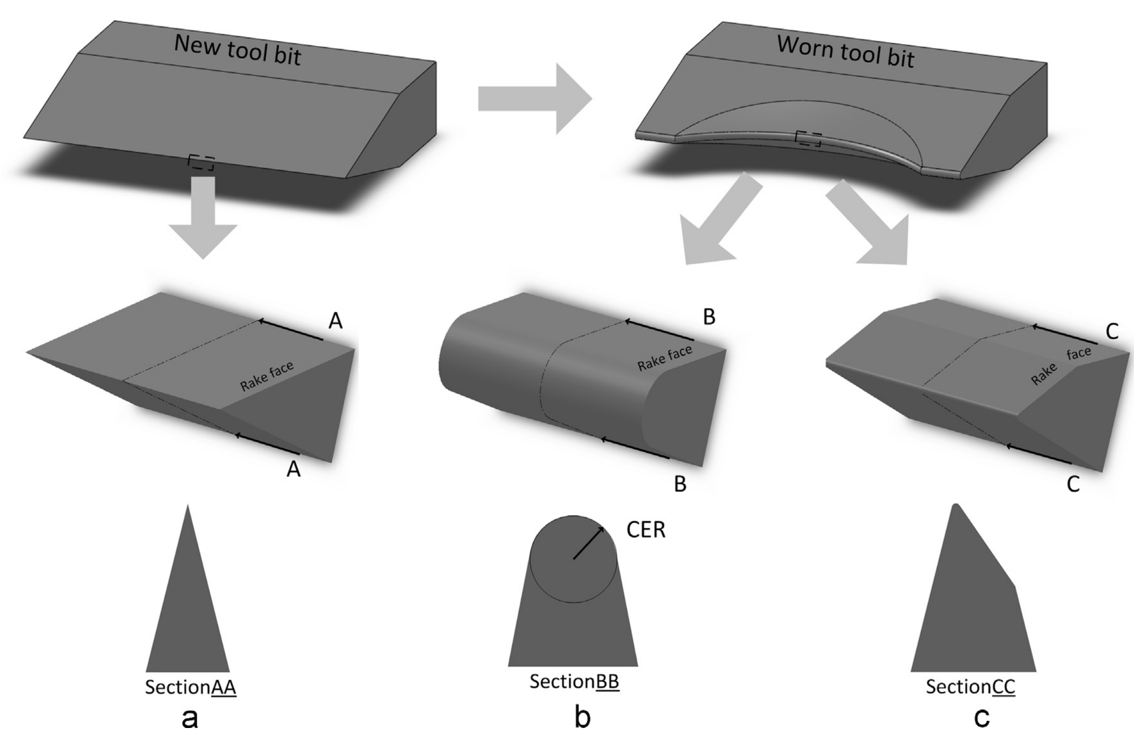

Fig. 1. Cutting tool wear at one cutting position: (a) new cutting edge, (b) cutting edge rounding and (c) rake face wear.