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Rigorous treatment of dry cutting of FRP – Interface consumption concept: A review

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ABSTRACT

The meticulous analysis of the most met mechanisms involved when cutting fiber reinforced polymers (FRP) has a pivotal role in improving part availability, informing the processes used and preventing catastrophic results. So far, the terminology used for qualifying the phenomena encountered when cutting FRP still remains frequently inspired from single phase alloys while observable mechanisms are often strikingly different. This is the main reason that motivates this study to elucidate proper FRP mechanisms against other alloys i.e. metals. After criticizing the most common operations of the open literature by examining the interactions experimentally revealed for given tool–material pairs, the material removal process versus composite type, tool type and operating conditions is addressed. A special focus is put on correlating the material removal mechanisms with the material removal "*volume*" frequently qualified as a "*chip*," through interface consumption concept. The material separation mechanisms and morphology of the produced "*chip*" are discussed in details versus both fiber orientation and cutting variables. Based on the fundamental inspections of experimental studies, the wear land and mechanisms are properly classified versus the tool grade. While experimental trials seem to be challenging, the analytical and numerical approaches show ability to access some cutting outputs although with several limitations. The macro- as well as micromechanical models were built focusing on how to manage the numerical inputs for predicting at best the cutting behavior. Modeling of the fiber–matrix interface and tool–material contact were closely discussed.

1. Introduction

Within the last 1980s, the use of fiber reinforced polymers (FRPs) in the field of aerospace, aeronautical, shipbuilding and automotive industry has significantly increased. Their enhanced mechanical and structural properties made them an ideal substitute for metals. They gathered their popularity due to their high specific stiffness and strength combined with a good fatigue endurance and resistance to corrosion.

Components made of polymer matrix composites are mostly produced in near-net-shape. However, secondary manufacturing processes such as machining are often required for imparting the dimensional tolerances and assembly of composite parts. While machining mechanisms of FRP significantly differ from those of single phase alloys, standard techniques and tools used for traditional metals still remain employed for machining of composites. The behavior of FRP is particularly anisotropic and heterogeneous since it depends on the intrinsic properties and volume fractions of both matrix and reinforcement.

The low thermal conductivity, inherent heterogeneity and anisotropic nature make of each cutting operation a critical task. Fiber pullout, matrix burning and delamination are generally encountered during processing. These mechanisms are obviously coupled with subsurface damage and poor surface finish together with excessive tool wear.

Although a lot of researches were carried out in order to unravel various effects of the geometrical process parameters on the machining behavior, the quantum of published investigations is insignificant and many queries in process still remain under-explored when compared to metal machining. Both analytical approaches and experimental ones have been conducted to understand the material removal process and machining response of FRP. Within the past decade, the finite element method (FEM) has been widely adopted to model the chip formation and to predict the induced damage and generated forces.

This paper presents a review of researches which have been focused on the cutting mechanisms of FRP. As the material removal process of polymeric composites does not lead all the time to a separation of a continuous volume, the concept of "*chip*" as

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Nomenclature

a_p	depth of cut
b	width of cut
d_f	fiber radius
f	feed rate
l_c	chip length
r_e	nose radius of cutting tool
t	part thickness
t_c	chip thickness
A_0	undeformed chip area
E	Young's modulus in transverse direction of fibers
F_c	cutting component of forces
F_t	thrust component of forces
G_{LT}	shear modulus along the fibers
P	indentation component of force, exerted perpendicularly to the fiber axis
S^{shear}	critical lateral force associated with matrix shearing
S^{bend}	critical lateral force associated with fiber bending
V_c	cutting speed
α	relief (clearance) angle
β	friction angle
γ	rake angle
δ	resultant load angle
λ	cutting inclination angle
η_{RVE}	cumber of representative volume elements
θ	fiber orientation
ϑ_f	fiber volume fraction
μ	friction coefficient
ν	Poisson's ratio
τ	shear strength
φ	shear angle

typically observed in single phase materials will be addressed with great vigilance. In the first part, the experimental investigations of drilling, milling and turning were discussed. The cutting mechanisms and experiment set-up were analyzed in details. In the second part, focus was put on the theoretical foundation and fundamental numerical perspectives on cutting of polymer composites.

2. Experimental approaches: operations addressed

Since 1980, many experimental investigations on machining of FRP have been performed. Most of the conducted studies were focused on the combined influence of fiber orientation, tool geometry and operating conditions on cutting forces, material removal mechanisms, surface morphology and induced damages.

Machining of FRP is achieved by conventional and non-conventional material removal techniques. Conventional methods are mostly drilling, milling and turning, however, non-conventional processes are water-jet, laser beam and ultrasonic machining. Conventional machining consists of engaging a rigid cutting tool in a less rigid material. The relative movement between the tool and the workpiece causes a material removal resulting in a new surface and released volume. The surface profile and the shape of the removed volume mainly depend on kinematics relations between the tool and the workpiece. Different machining processes were therefore classified with respect to geometrical configuration. This review was restricted to drilling, milling and turning operations.

2.1. Orthogonal cutting

Orthogonal cutting assumption is a particular configuration of cutting geometry [1,2]. It is satisfied if the tool edge is perpendicular to the direction of the cutting speed vector. In orthogonal cutting configuration (OCC), the operation is reduced to a 2D problem. This simplifies the investigation of the material removal process and the analysis of cutting variables such as the shape and size of the produced chip, the developed forces, the induced damage, the heat generation, the shear stress and strain, and the tool–material interfacial conditions.

In practice, orthogonal cutting is rarely used. However, this operation reflects different physical phenomena commonly present during 3D machining operations. This explains the large number of researches using this assumption for investigating cutting behavior of FRP materials. Koplev [3] has early used quasi-static orthogonal cutting tests involving carbon/epoxy composites versus HSS single edge tool with rake angle (γ) of 0° and relief angle (α) of 15° (Fig. 1). The work can be considered among the first attempts that discussed the chip size and fracture with regard to fiber orientation. An investigation has also been conducted by Takeyama et al. [4] to survey the cutting behavior of FRP materials with a fiber volume fraction of approximately 59.7%. The high speed photographs gathered during tests demonstrated the sensitivity of the chip formation mechanisms to the fiber orientation. Increase in the rake angle seems to further acting on cutting behavior with high fiber orientation range ($\theta \geq 45°$). Since then, large researches have been published; Table 1 summarizes the experimental investigations that have been conducted on this topic with special reference to the operating conditions used.

The cutting conditions considered [3,5–7,9–13] are commonly far below those used in practice. Most of the works used monoblock uncoated inserts with cutting speeds typically low ($0.24 \leq V_c \leq 14$ m min^{-1}). Nonetheless, the tests conducted in these researches provided valuable information on the nature of chip formation. Recently, Ben Soussia et al. [14] investigated the machinability of glass/epoxy composite with CVD monolayer (polycrystalline diamond) and CVD multilayers (Ti(C,N)/Al_2O_3/TiN) coated inserts. Multilayer coating showed better ability to dissipate the thermo-mechanical cutting energy due to the good adhesion of the coating layer to the substrate. The performance of PVD and CVD multilayer coatings to dry cutting fiber reinforced polymers has also been discussed as to both unidirectional CFRP and GFRP [15]. Regular inspections of the worn face of the two insert types demonstrated that the failure of first-deposited coating layer commonly marks a drastic change in the cutting behavior.

2.2. Turning

In the case of turning, the dimensions of the produced chips primarily depend on the feed rate and the depth of the cut, whereas the surface roughness is mainly affected by the feed rate and the tool radius. Over recent years, several researches have been carried out on turning of FRP. Most of those were focused on the different aspects of tool wear mechanics and the tool geometry optimization in order to ensure a cutting process involving improved energy consumption, reduced wear and better surface finish [16–33].

Santhanakrishnan et al. [17,18] carried out face turning trials on CFRP, GFRP and AFRP to study the chip formation process, the