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Machining of carbon fiber reinforced plastics: Influence of tool geometry and fiber orientation on the machining forces

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ABSTRACT

Tools optimized for machining carbon fiber reinforced plastics (CFRP) belong to the key enablers for the application of CFRP in many areas such as aerospace or automobile industry. Conventional tool designs do not consider the differing machining behavior of CFRP compared to metals. This leads to short tool lifetime and limited workpiece quality. The presented study introduces fundamental tool-geometry analyses based on orthogonal cutting of unidirectional CFRP-material. Within an extensive experiment series process-forces (i), abrasive tool-wear (ii), workpiece damages (iii) and delamination (iv) are evaluated depending on different tool geometries and fiber-orientations. In conclusion, workpiece damages and tool lifetime can be linked to tool characteristics.

Introduction

High performance engineering components made of carbon fiber reinforced plastics (CFRP) are often produced near net shape. They still need to be machined to reach a certain precision e.g. for assembly [1,2]. Turning, milling and drilling, well known from metal machining, also belong to the frequently used machining processes for CFRP parts. CFRP differ from metals as any plastic deformation is absent; the material is anisotropic and inhomogeneous [3]. The understanding of chip formation, tool wear and process-parameters are not directly transferable.

The civil aircraft industry, which currently benefits most from the low weight, high strength and corrosion resistance of the material, is the main driver for the development of carbon fiber production and processing [4]. In state-of-the-art airplanes like the Boeing 787 or the Airbus A350 about 50 wt.% are contributed by CFRP [5]. It is expected that CFRP-production driven by the automotive industry will reach production stage in the next few years [6].

CFRP machining is of utter importance for starting serial production of high precision CFRP components [6]. The intensive abrasive tool wear due to the high strength of carbon fibers represents a challenge for tool life time [5]. Toward the end of the tool life more damages are induced into the workpiece [7]. Former papers put effort into the research of detecting workpiece damages caused by CFRP machining. The most critical damages are thermal overload of polymeric material, chatter marks, delamination, fiber fracture and fiber pull-out as described in [5,8–10]. Further studies show that the tool life time depends on the tool geometry, coating and process parameters [11,12]. The experiments underlying these papers focus on the influence of the tool geometry on the workpiece quality. The analyzed parameters are cutting forces, workpiece roughness, fiber fractures and delamination damages at the edge of the workpieces.

In the 1970th Everstine and Rogers [13] describe the deforming process during CFRP machining mathematically. In the early 1980s Koplev et al. [14] start to machine CFRP experimentally. They state that chip formation and defects substantially depend on the fiber orientation. Furthermore it is found that the feed force directly correlates with the tool wear. In 1988 Santhanakrishnan et al. [15] analyze the wear of carbide-tools machining CFRP and Kevlar Fiber Reinforced Plastics (KFRP) in detail. In the middle of the 1990s Rummenhöller [16] investigates extensive experiments of orthogonal cutting tests with CFRP. In his work he validates the results of Koplev [14] about carbon fibers having a greater impact on the machining results than the matrix material. Depending on the load case different fracture morphologies appear. Rummenhöller [16] proposes a case distinctive for fiber orientations (i) $0 < \Theta < 90^\circ$ and (ii) $\Theta > 90^\circ$. Bending and compression of the fibers appear additionally to the already mentioned brittle fracture. For the case of $\Theta = 90^\circ$ the fibers are mostly loaded in bending and compression which leads to strong tool wear and poor workpiece surface. For a

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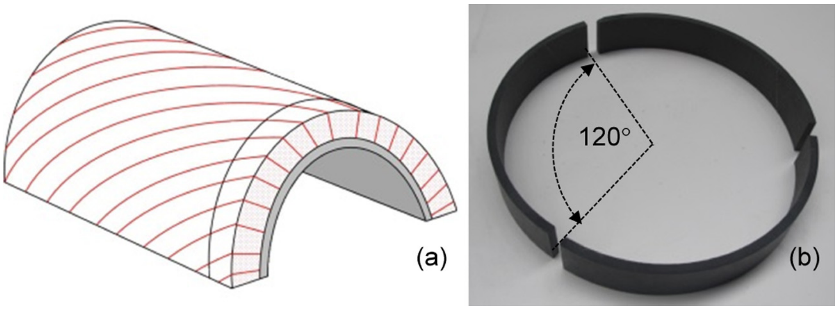

Fig. 1. Primary CFRP material (a) and ring manufactured by water jet machining (b).

fiber orientation of $\Theta = 0^\circ$ the cutting mechanisms are buckling and pealing with advancing crack formations in front of the cutting edge. These cutting mechanisms induce relatively low forces and a good surface quality. CFRP machining with fiber orientations between these two Θ-angles, for example $\Theta = 30^\circ$ or $\Theta = 60^\circ$ causes a mixture of these cutting mechanisms. According to Sheikh-Ahmad [5] tool geometry, besides the temperature in the cutting zone and process parameters, represents the crucial determinant of the CFRP cutting process. In accordance with Davim [17] he defines the most important influential parameters as: tool material, rake angle, cutting edge radius, feed and cutting speed. Sheikh-Ahmad claims that not just metal but also CFRP-material undergoes a change from ductile to brittle when deforming more intensely. The shape and type of resulting chips and the surface quality depends on the process parameters. Increasing the rake angle while decreasing the depth of cut results in larger chips due to less deformation of the material.

Takeyama and Iljima [18] start intensive modeling of CFRP machining processes in 1988. The model includes a shear plane with the angle Φ along which CFRP material shears off. Seven years later Bhatnagar et al. [19] extend this model by showing that the material shears off only along fiber orientation Θ. According to their research $\Phi = \Theta$ applies. Neither Takeyama and Iljima [18] nor Bhatnagar et al. [19] include a cutting edge radius into their models. 2001 Zhang et al. [20] publishes a new model that considers the aforementioned cutting edge radius. The authors take friction into account and divide the tool into the following three separate areas:

- Rake face (area γ).
- Flank face (area α).
- Cutting edge radius (area r).

Their force model is designed for a fiber orientation of $0 \leq \Theta \leq 90^\circ$. The total feed force and cutting force is assumed to result from adding the individual forces in each area. Zhang et al. [20] include a spring-back effect of the fibers with the magnitude of the cutting edge radius. In preparation of actual force calculations the model of Zhang et al. [20] requires experimental determination of shear angle Φ, friction coefficient μ between fibers and tool and a coefficient K. The coefficient K considers the influence of microfractures. The workpiece-tool contact length for fiber orientations between $\Theta = 0^\circ$ and $\Theta = 90^\circ$ is assumed to be about the edge radius. For fiber orientations of $\Theta > 90^\circ$ the spring-back effect is even twice the edge radius.

Experiments

The presented paper serves to increase the understanding of machining CFRP and thus expand tool lifetime and workpiece quality by adjusting the tool macro-geometry. A side effect is to increase the reliability of the machining process. The experiments are conducted in an orthogonal turning process. The workpiece surface quality, occurring defects depending on the tool geometry and the fiber orientation are analyzed.

Test-rig

The test rig setup for the turning tests is implemented on an Okuma LB15-II. The setup allows CFRP machining in an orthogonal cut or turning operation with a constant fiber orientation Θ. The cutting tests can be conducted at cutting velocities between 20 and 500 m/min in an infinite, non-interrupted cut. Half pipe shaped CFRP specimens are of about 1 m in length, a wall thickness of 5 mm and the total pipe diameter is 200 mm. They are manufactures with a single fiber orientation using an autoclave and pre-preg material. Afterwards, these half pipes are cut into 120° segments with 55 mm width using water jet cutting. The primary material with an indicated fiber orientation is shown in Fig. 1a. The segmented ring is shown in Fig. 1b. This test rig setup ensures machining with a single fiber orientation in a continuous cut. A production of full pipes with fibers of infinite length would have required a device for pipe manufacturing which the participating aircraft manufacturer does not possess.

Fig. 2 shows the test rig setup with modified clamping jaws on the hydraulic chuck of the lathe to enlarge the contact area. The setup allows a great variety of cutting speeds and a good observability due to the three segments forming a closed ring when mounted on the machine. Machining is analyzed by a tool-sided dynamometer and high-speed camera recordings. For orthogonal cutting the width of cut is identical to material thickness.

An inner aluminum ring, shown in Fig. 3, keeps the CFRP ring elements from bending due to high clamping forces. Different ring diameters are used for different workpiece diameters.

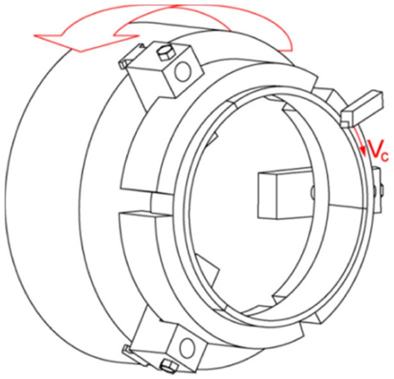

Fig. 2. Test rig setup for orthogonal cutting and turning tests (schematic illustration).

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