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Laser Scored Machining of Fiber Reinforced Plastics to Prevent Delamination

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Abstract

Delamination is a major problem in contour milling of fiber reinforced plastics (FRP) causing scrap or rework. Today, delamination avoidance limits overall productivity and tool life. Damage of the top layer of a composite structure is initiated if fibers are not cut during first engagement of the cutting edge, but deflected. Generated cracks propagate due to recurrent contact of fibers with the rotating tool. In contrast, when laser cutting FRP, the heat input often leads to an extensive heat-affected zone (HAZ), particularly in case of large laminate thickness and high energy input. Combination of both processes is a promising approach to overcome the mentioned disadvantages. Experiments indicate that pre-scoring of the top layer is possible with negligible HAZ for FRP materials using proper laser parameters, especially low energy input per unit length. Positioning of the laser scored kerf along the contour to be manufactured by the subsequent milling tool prevents crack propagation along the fiber direction even with a heavily worn milling tool at increased feed rate. Furthermore, laser pre-scoring eliminates protruding fibers and allows for edge chamfering. The process understanding is enhanced using simulation of the laser pre-scoring, particularly considering heat conduction and forced convection, as well as by presenting a model for the mechanism of delamination prevention.

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Keywords: fibre reinforced plastics; contour milling; laser pre-scoring; delamination; heat-affected zone;

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1. Introduction

Carbon fiber reinforced plastics (CFRP) have become a major material for structural elements in modern aircraft design. FRP components usually have to undergo a processing step to obtain their final contour. For this purpose contour milling or laser cutting are two possible processes. Contour milling is well-established for trimming of FRP. Nevertheless, the occurrence of delamination and fiber protrusion limits the tool life and the feed rate significantly and, furthermore, causes expensive rework or even scrap. Laser cutting avoids delamination because it is a thermal and not a mechanical process. However, the key disadvantage of laser cutting FRP is the HAZ, which is mostly considered unacceptable by the aeronautical industry today.

In contour milling, the occurrence of delamination depends to a considerable degree on the fiber orientation angle ϕ and the fiber cutting angle θ [1,2,3,4,5]. A widely used failure criteria for FRP is the *Puck* inter-fiber fracture criteria. It is divided in three different failure modes A, B and C depending on the ratio between normal stress to shear stress in the material [6]. Another significant factor for the quality of the workpiece edge is the wear condition of the tool. The feed force increases significantly with increasing wear, which is accompanied by a greater degree of delamination [3]. Due to the high abrasiveness of the fibers, polycrystalline diamond (PCD) is recommended as a cutting material [3,7]. In full-groove cuts a better edge quality is achieved at the up-milled surface ply [8].

Two different process approaches for laser cutting are available to pursue either high productivity or high quality. Cutting with continuous wave laser systems with a mean power in the kilowatt range allows feed rates above 10 m/min [9,10]. The inherent HAZ and thermal damage of the laminate´s surface at the edge causes a low relevance of laser processing in commercial applications today. Higher cutting quality can be achieved with pulsed laser systems [11]. However, for typical laminates feed rates are limited to about 1 m/min. Concerning the laser wavelength, CO_2 lasers have a much better absorption behavior in FRP than solid state lasers in the range of 1 µm, especially when cutting glass fibers. A first analysis of the kerf building under the influence of the first exposures during laser remote cutting is done by Schmidt-Lehr et al. [12]. A linear relationship between the kerf depth and the number of exposures is found up to a kerf depth of about 6 mm. For continuous wave laser processes a few approaches for numerical process simulation exist [13,14,15]. 3D finite difference or finite element methods are used to predict the temperature field as well as the HAZ or the kerf geometry. Only Liebelt [13] considered all three phenomena for an orthogonal-anisotropic material with a thickness of 0.24 mm. All simulations are based on the numeric solution of the heat transfer equation that considers the isotropic or orthogonal-anisotropic heat conduction. Phase changes of the material are modeled in each study, while Liebelt included the phase changes of the polymer as well as the fiber material. The fiber reinforced material is considered as a continuum in all studies.

The laser scored machining (LSM) process combines laser cutting and milling in a way that promises to overcome the disadvantages of the individual processes. Laser cutting is used to score a kerf into the top layer of the laminate. Due to the small depth of the kerf, the thermal impact on the laminate is greatly reduced, which minimizes the size of the HAZ to an extent that can be considered negligible. In the subsequent milling process, the kerf prevents the occurrence and propagation of delamination.

2. Delamination prevention model

During milling, delamination predominantly occurs in the outside layers of the laminate due to the lack of support. Regarding the effect of scoring, two mechanisms have to be distinguished. The first one is the interruption of delamination propagation at the scored kerf. With the tool proceeding along its feed path, delamination propagates along the fiber direction. In order to interrupt the propagation, the depth of the scored kerf d_k has to be larger than the depth d_d in which the delamination is propagating, Fig. 1a. The second mechanism is the prevention of initial delamination, as shown in Fig. 1b. The cutting edge exerts a force F on the workpiece. When the cutting edge reaches the kerf, the outside layers of the laminate above point e support against the acting force.