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Evaluation of bore exit quality for fibre reinforced plastics including delamination and uncut fibres

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ABSTRACT

Analyses of the bore exit in Carbon Fibre Reinforced Plastics (CFRP) represent a common method to evaluate workpiece quality non-destructively. The delamination factor F_d, developed by Chen (International Journal of Machine Tools and Manufacture, 37 (1997) 1097) has been established, being a straightforward measureable variable representing the bore quality. Within this paper the advantages and disadvantages of the delamination factor F_d, the adjusted delamination factor F_{da} by Davim et al. (Composites Science and Technology, 67 (2007) 1939) and the equivalent delamination factor F_{ed} by Tsao et al. (The International Journal of Advanced Manufacturing Technology, 59 (2012) 617) as well as the delaminated area A_d at the bore exit are discussed. In unidirectional CFRP material, which tends to show single delaminated fibres, spalling and uncut fibres the commonly used delamination factors F_d, F_{da} and F_{ed} are unsuitable to describe the bore quality.

Five separate damage values combined to a Quality function Q_d are proposed, allowing a reliable evaluation of the machined bore quality especially for unidirectional CFRP. The suitability of Q_d is demonstrated on a drilling series in CFRP and analysed by a robust, operator independent Matlab© tool. In most of the former research, the thrust force increase is used to describe the tool wear. The theoretical critical thrust force of the material determined by Ho-Cheng and Dharan (Journal of Manufacturing Science and Engineering, 112 (1990) 236) as well as Tsao and Hocheng (International Journal of Machine Tools and Manufacture, 43 (2003) 1087) defines the end of tool life time. The presented approach of Q_d offers the possibility to define the expected residual tool life time based on the actual bore exit quality. It contains five bore exit quality factors enabling adaption to different material properties. To proof the applicability, Q_d is compared to the common delamination factors, the progress of tool wear and the thrust force increase which is known to correlate with the bore exit quality in CFRP machining.

Introduction

Challenges in drilling CFRP

Carbon Fibre Reinforced Plastics (CFRP) exhibit excellent stiffness and strength at simultaneously low density. Among other favourable characteristics like excellent fatigue behaviour, composites (CFRP and GFRP) are currently the most commonly used materials in the aerospace industry [6]. Joining different CFRP-components require bores to be drilled into CFRP-material for riveted joint connections. Drilling of CFRP is still challenging on the one hand due to the abrasiveness of the carbon fibres and the heavy wear of the drilling tools and on the other hand due to the inhomogeneous and anisotropic nature of composite materials; Delamination, uncut fibres and fibre pull-outs may occur at the bore entrance or exit [7–18]. Especially in the aviation industry with high safety standards such defects are undesirable, because delamination may be the starting point of a propagating crack (notch effect) [19,20]. It is well known that bore exit delamination has a significantly negative effect on the fatigue life of the final structure, among others analysed by Persson [21] in 1996. Operator independent and preferably automated visual inspection and assessment of delamination becomes more important with the increasing use of CFRP in industry. While quality control for drilling operations is established for metals, full adaption for FRPs has not been conducted yet. Investigations in CFRP machining showed that the bore channel roughness is not suitable to describe the bore quality because cracks may be below the smeared surface [22,23]. Analysing delamination, spalling and uncut fibres describe the bore quality more precisely. Different characterisation and

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Nomenclature

A_d	damaged area around the bore [mm^2]
A_{free}	uncovered bore area [mm^2]
A_{max}	circular area of diameter D_{max} [mm^2]
A_0	circular bore area [mm^2]
$d = 2r$	tool diameter [mm]
$d_{80\%}$	80% of the tool diameter (d) [mm]
D	bore diameter [mm]
D_e	equivalent delamination diameter [mm]
D_{max}	maximum diameter in the damage Zone [mm]
$D_{95\%} = 0.95\,D$	95% of the bore Diameter D [mm]
F_{A-cov}	parameter describing the relative bore area covered with uncut fibres [−]
F_{A-d}	parameter representing the relative damaged area A_d [−]
F_d	delamination factor [−]
F_{da}	adjusted delamination factor [−]
F_{ed}	equivalent delamination factor [−]
$F_{L,95\%}$	relative circumferential length at 95% of D being punctured by fibres [−]
F_{nd}	normalised delamination factor [−]
F_n	factor based on tanh() representing n_{uncut} [−]
GUI	graphical user interface [−]
$L_{95\%}$	complete circumferential length at 95% of D [mm]
n_{uncut}	number of uncut fibres [−]
Q_d	damage value containing various parameters describing bore quality [−]
θ	fibre orientation [deg]
α, β, γ	clearance-, wedge- and rake angle [deg]

measurement methods are known in literature to measure uncut fibres and damages around a bore [24]. Nowadays optical measurement devices show accuracies in the range of one micro meter and a better reproducibility than tactile measurement devices [25]. Common measurement methods are 3D-microscopy [26,27], digital image processing [3,7,28,29] or ultrasonic C-Scan [30–33]. Today tool geometries for CFRP machining are well adapted to generate a high bore quality and exhibit better wear resistance using optimised diamond coatings protecting the cutting edge more efficiently [34,35]. Nevertheless some unidirectional CFRP materials, which are more difficult to machine than woven CFRP, still show massive delamination and uncut fibres using conventional drilling. These defects usually become worse with increasing tool wear and thrust force [1,10,22,36], especially if a supporting glass fibre layer at the bore-exit side is absent. Referring to Hocheng and Tsao [5,16,28,33,36] the critical thrust force leading to bore exit delamination is mainly dependent on the feed, the tool diameter and geometry as well as the ply thickness. The lower the critical thrust force, the smaller the process window to achieve a bore of sufficient quality [5].

Research motivation

The most common evaluation criterion for the bore exit quality in drilling CFRP is the delamination factor (F_d), proposed by Chen [1]. The delamination factor F_d is calculated by the ratio of the maximum diameter D_{max} in the damaged zone to the bore diameter D:

$$F_d = \frac{D_{max}}{D}, \quad F_d \in [1; \infty] \tag{1}$$

The delamination factor represents a good approach to quickly assess the maximum extent of delamination at bore entrance and exit possessing a regular pattern, especially in GFRP or woven CFRP. Most researchers use this delamination factor due to the fast and easy determination of F_d. For example Davim and Reis [37,43] considered the delamination factor F_d to analyse the effect of different drill geometries on the magnitude of delamination around the bore. Arul et al. [30] considered a delamination factor, calculating the ratio of D_{max} and the tool diameter d instead of the bore diameter D, studying the effect of axial vibration assisted drilling on the bore exit quality in woven glass fibre reinforced plastics (GFRP). Due to elastic deformation and springback effects the bore diameter in FRP is smaller than the tool diameter, which was detected by several authors [24,29,38]. Hocheng and Tsao [31] use the reciprocal value (ratio of tool diameter d and D_{max}) to describe the influence of different tool geometries on critical thrust force at the onset of delamination. The effects are described mathematically as well as experimentally.

Capello [39] investigates the effect of support structures underneath the workpiece when drilling CFRP. The amount of delamination at the bore exit with and without backing was characterised by the delaminated area around the bore A_d and not just by the maximum damaged diameter D_{max}. The damaged area A_d around a bore is more difficult to assess but machining CFRP shows irregular defects like spalling, cracks and delamination, which are hard to depict with only one diameter [2]. Fig. 1 shows two bore exits schematically with the same delamination factor F_d

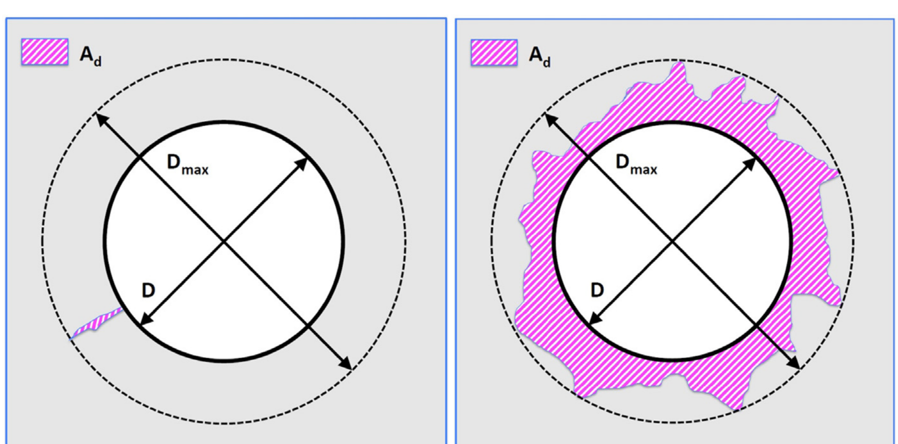

Fig. 1. Example for identical delamination factor F_d, but a difference in the delaminated area A_d.