A PILOT EXPERIMENTAL RESEARCH ON DRILLING OF CFRP UNDER TENSILE STRESS

D. Poór [1], N. Geier [1], C. Pereszlai [1] and N. Forintos [2]

[1] Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Manufacturing Science and Engineering, Hungary

[2] Budapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Polymer Engineering, Hungary

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Abstract: Carbon fibre reinforced polymer (CFRP) composite materials have excellent specific material properties, these composites are therefore widely used materials in many high-tech sectors. Machining of them is often necessary, however, it is extremely difficult due to the anisotropy, inhomogeneity and abrasive wear effect of carbon fibres. Delamination, uncut fibres, fibre pull-outs and matrix burning are the most common machining-induced defects in CFRP, which has to be controlled and minimised in order to meet the geometrical regulations of designers. The main objective of the present research is to minimise the number of drilling-induced uncut fibres by controlling the stress condition of the CFRP workpiece. The characteristics of uncut fibres were analysed by digital image processing. The influence of the type of drills (an HSS conventional twist drill and a solid carbide brad & spur drill) and of stress conditions (tensile stress on three levels) were analysed on the characteristics of uncut fibres in unidirectional CFRP. A special fixture was designed and manufactured for the drilling experiments. The pilot experimental results show, that the analysed stress condition does not have a significant effect on the circularity error of drilled holes. However, the effect of the stress condition was not clear on the characteristics of uncut fibres.

Introduction

The industrial application of carbon fibre reinforced polymer (CFRP) composites is increasing rapidly, due to the benefits of the mechanical properties of the material. CFRP composites have high strength and stiffness in the fibre direction, furthermore, the strength-mass ratio is also high, it is therefore applied in numerous fields of technology, such as aircraft industry, automotive industry, sports industry and marine industry [1].

Due to the modern and highly automated polymer production technologies, composite products are manufactured close to the final shape by one operation, however, machining is necessary in order to meet assembly requirements, designers' geometrical tolerances or surface roughness criteria [2, 3]. Nevertheless, models and experiences of conventional-machining can not be implemented directly, because of the inhomogeneous and anisotropic nature of fibre reinforced polymers and the carbon fibres' abrasive wear effect on the cutting tool. These structural specialities of composites cause defects on the machined features (e.g.: delamination, uncut fibres, fibre pull-outs, matrix burning, micro-cracking) and are they, therefore, considered as difficult-to-cut materials [4]. This research focuses on the analysis of the characteristics of uncut fibres.

Klocke et al. [5] analysed the influence of different fibre cutting angles on the cutting mechanisms in fibre reinforced polymers (FRP) by orthogonal cutting experiments. They stated, that machining at different fibre cutting angles are causing different mechanical stresses in the fibres, which are connected to the machining failures (e.g. delamination, matrix fracture, fibre pull-out) of the workpiece. They also noted that bending and pressure load are increasing in fibres when the angle between fibre orientation and cutting direction is higher, which is causing fibre breakage. Wang et al. [6] examined the surface cavity defects during CFRP milling. In their publication, they defined four typical material fracture modes: fibre-matrix debonding, bending-induced fibre fracture, shear-induced fibre fracture and compression-induced fibre fracture. Xu et al. [7] investigated the drilling machinability of T800S/250F CFRP laminates. They highlighted, that the burr area in drilled holes is influenced by thrust force during machining. Geier and Szalay [8] compared conventional and helical milling (orbital drilling) technologies of CFRP and they found, that screw pitch has the most significant influence on the drilled hole-quality, followed by the feed rate and by the cutting speed. In addition, they highlighted that these process parameters should be optimised in order to achieve less uncut fibres. In their another publication a digital image processing-based monitoring algorithm was developed, which optimises process parameters between helical milling operations [9]. In that paper they suggested a method to examine and compare defected holes via digital image measurements. Based on experiences of the authors, a novel idea was created: pulling CFRP during drilling produces an augmentation of the rigidity of the carbon fibres, thus a crushing dominated chip removal mechanism (CRM) happens instead of a bending dominated CRM. Therefore, fewer carbon fibres are expected to be bent after machining. By the application of this novel technology, number of uncut fibres could be decreased significantly.

The main objective of the present research work is to investigate whether the pulling of CFRP composites could be a proper technology to minimise the number of uncut fibres.

Experimental setup and methods

Experimental setup

Hand-laminated and epoxy-based unidirectional carbon fibre reinforced polymer (UD-CFRP) specimens (of 3 mm thickness with additional glass fibre reinforced epoxy matrix laminated bonded end tabs, designed based on the standard of EN 527-4:1997 type 3 specimen) were drilled with two types of drilling tools. A solid carbide Ø10 THOMAS 23C103100 brad & spur drill (Fig. 1 (a)) and an HSS Ø9.5 conventional twist drill (Fig. 1 (b)) were used during the experiments. The helix angle of the brad & spur tool is 30° and it has a special W-shape point, which geometry can result in better machining performances on laminates [10]. The HSS twist drill was used to get reference measuring points from a not laminates-specified drilling tool.

Fig. 1 Cutting tools used in the pilot experiments: (a) a brad & spur drill and (b) a conventional twist drill

The experiments were carried out on a Kondia B640 CNC vertical machining centre with no coolant and a Nilfisk GB733 industrial vacuum cleaner was applied. Tensile stress conditions of the CFRP were set up by an upgraded machine vice as a special fixture. The original jaws were replaced with individually manufactured ones; bolts were used to transmit the force from the fixture to the specimen. The machine vice was operated inversely to pull the CFRP workpieces. The magnitude of the tensile stress of the specimens was monitored using KMT-LIAS-06-3-350-5E strain gauges. The signals of the gauges were processed by a Hottinger Baldwin Messtechnik Spider 8 processor. A DeltaTron 4518-001 accelerometer was connected to a National Instruments USB-4431 vibration device. The experimental setup is shown in Fig. 2.

Uncut fibres were detected by a Dino-Lite AM4013MT digital microscope and the circularity error of drilled holes were tested with a Zeiss UMC 850 coordinate measuring machine (with 720 planned measuring points, a cutting wavelength of UPR 50 Gaussian filter, a speed of the touch probe of 1 mm/s).

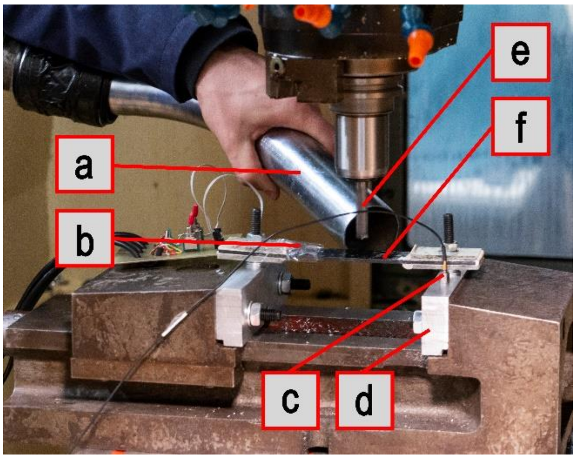

Fig. 2 Experimental setup: (a) vacuum cleaner (b) strain gauge (c) accelerometer (d) fixture jaw (e) drilling tool (f) UD-CFRP specimen

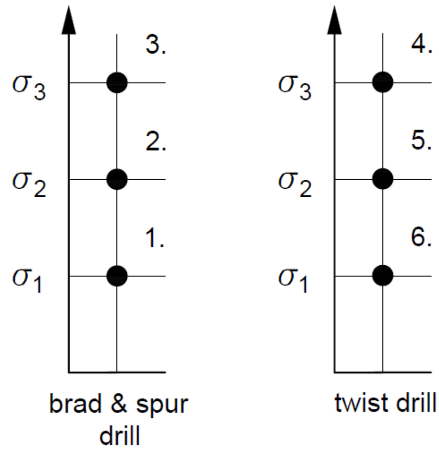

Fig. 3 Schematic drawing of the experimental strategy

The machining parameters and the factorial levels of the experiment were specified based on a previous research work [4] and tool-catalogue recommendations. Three levels of the tensile stressed condition were designed. The minimal level was set to zero (non-pulled CFRP) and the maximal level was set to 80% of the ultimate tensile strength. The maximal value was calculated as the minimum of four tensile testing specimens' ultimate tensile strengths. The experimental design matrix is can be seen in Table 1. The experimental strategy can be seen in Fig. 3.

Table 1. Experimental design matrix

Specimen No. [-]	Tool [-]	Feed [mm/rot]	Spindle speed [rot/min]	Cutting speed [m/min]	Tensile stress [MPa]
1	Ø10 brad & spur	0.26	2387	75.0	$\sigma_1 = 0$
2	Ø10 brad & spur	0.26	2387	75.0	$\sigma_2 = 240$
3	Ø10 brad & spur	0.26	2387	75.0	$240 < \sigma_3$
4	Ø9.5 twist drill	0.26	2387	71.2	$\sigma_3 = 298$
5	Ø9.5 twist drill	0.26	2387	71.2	$\sigma_2 = 240$
6	Ø9.5 twist drill	0.26	2387	71.2	$\sigma_1 = 0$

Digital image processing

Images captured by the Dino-Lite digital microscope were processed by the Wolfram Mathematica software with the following different algorithms: the first is an area-comparison based (Fig. 4 (a)), the second is a contour-comparison based (Fig. 4 (b)). Both of the methods examine the drilled holes individually, thus the inaccuracies of measuring device and drilled hole size differences do not affect the result of digital image processing. Schematic illustration of the digital image processing algorithms can be seen in Fig. 4.

The main steps of the area-comparison based algorithm are the following (depicted in Fig. 4 (a)): (i) The pixels of the image are segmented into black and white pixels. (ii) The pixels of the area of the hole excluded the uncut fibres are counted (A_{hole}). (iii) The area of the smallest circumscribed circle is defined ($A_{nominal}$), the difference of the nominal area and the actual area of the hole gives the quantity of burrs. Areal burr factor (B_a) can be expressed by $B_a = (A_{nominal} - A_{hole})/A_{nominal} \cdot 100$, where B_a [%] is the areal burr factor, A_{hole} [pixels] is the number of pixels of actual hole area, $A_{nominal}$ [pixels] is the area of the circumscribed circle.

The steps of the contour-comparison based algorithm are the following (depicted in Fig. 4 (b)): (i) The pixels of the image are segmented into black and white pixels. (ii) The edge is detected and the contour of the drilled hole with uncut fibres is plotted with black colour. The black pixels are counted (C). (iii) The perimeter of the smallest circumscribed circle of the contour is defined (P), from the difference of perimeter (P) and contour (C) conclusions of the number of uncut fibres can be stated. The ratio of ideal circle and burred holes, called contour burr factor (B_c) is expressed by $B_c = (C - P)/C \cdot 100$, where B_c [%] is the contour burr factor, C [pixels] is the number of pixels of contour, P [pixels] is the perimeter of circumscribed circle. B_c is a comparable quantity of the qualities of the drilled holes.

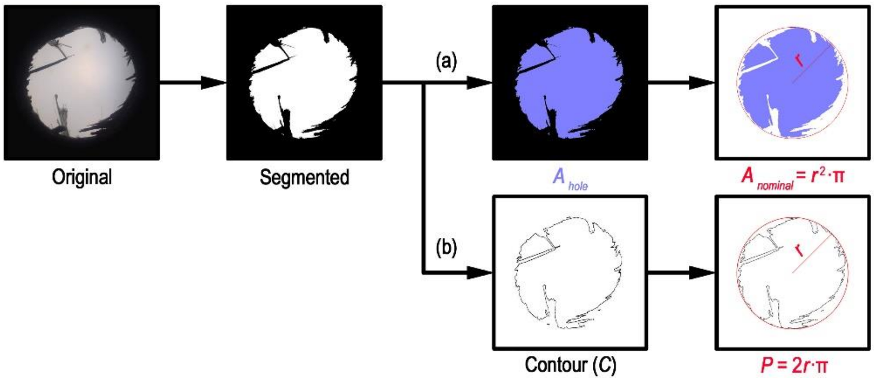

Fig. 4 Main steps of the digital image processing methods: (a) area-comparison based (b) contour-comparison based

Results and discussion

Results of digital image processing

The influence of tensile stress and tool geometry on the characteristics of uncut fibres can be seen in Fig. 5 and Fig. 6. The values of the areal burr factor (B_a) do not show monotone tendencies in both cases of used tools. However, with the twist drill after a small decrease, B_a increases above the level of the non-pulled measurement point. Furthermore, in the case of the brad & spur drill was used, the tendency is the opposite of the twist drill's, as depicted in Fig. 5.

The contour burr factor (B_c) increases at higher tensile stress levels and the process shows a monotone tendency in the case of using the twist drill. Nevertheless, the brad & spur drill resulted (i) a slight decrease of the contour burr factor (B_c) at the highest tensile stress level, compared to the lower tensile stress level, but (ii) the B_c is the smallest in the case of the non-pulled state (σ_1).

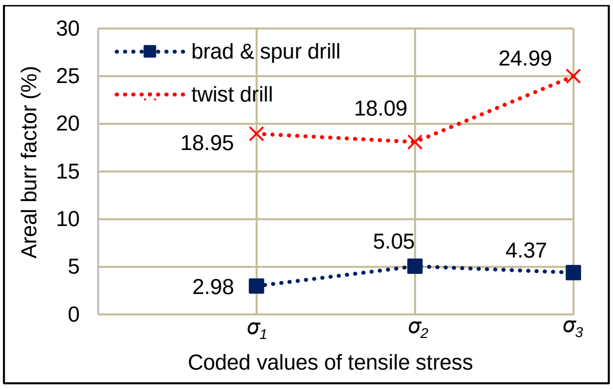

Fig. 5 Influence of tensile stress and tool geometry on areal burr factor

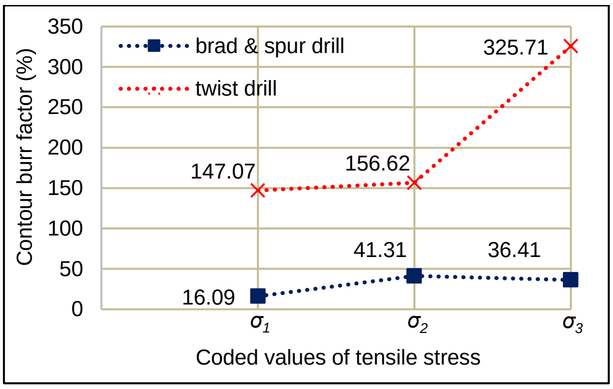

Fig. 6 Influence of tensile stress and tool geometry on contour burr factor

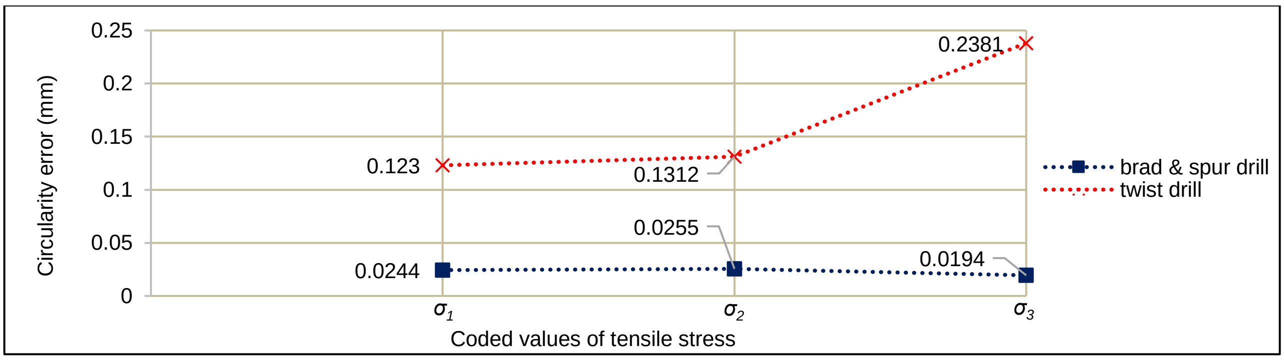

Fig. 7 Influence of tool geometry and tensile stress on circularity error

By the application of both digital image processing methods, the tendencies of measurement points of different tool geometries show dissimilarity. It can also be seen in Fig. 5 and Fig. 6, that the tendencies of using the twist drill differ at different digital image processing algorithms. The tendencies of burr factors calculated at the entry and exit side of the holes are very similar, the entry burrs are therefore analysed in this study.

Results of circularity errors

The results of the coordinate measurements show that the different characteristics of drilling tools resulted in dissimilar tendencies of measured points, as can be seen in Fig. 7. Due to norms of mechanics, an increasing tendency of circularity defect would be expected because of the material's elastic deformation. The coordinate measurement results show that the tensile stress level does not have a significant influence on the circularity error, in the case of the brad & spur drill. However, the results of the drilled holes converge to the expected tendency in the case of the twist drill was used. As the coordinate measurement results present, tool geometry has the most significant influence on the circularity error, followed by tensile stress. Additionally, geometrical form tolerances of drilled holes are between IT7 and IT13. Thus, it can be stated, that this amount of tensile stress (approximately 45% of ultimate tensile strength) has no significant effect on the circularity errors.

Discussion

The possible reason of the differences and the not-monotone tendencies of the results of the different digital image processing algorithms could be found in the measurement uncertainty, which is caused by the low number of experimental runs. The dissimilarity of the results of the different tool geometries examined with coordinate measuring can also be caused by the low number of measurement points' standard deviation. In the future, more repeated experiments should be done in order to calculate experimental error to have further and more accurate results.

By cause of some unexpected device failures, the maximal designed stress level could not be reached and one of the pull-magnitude could not be measured properly.

The signals of the accelerometer were heavily loaded with noise, thus the results of vibration examination are unclear. This could be explained by the sensor's installation place (the accelerometer was screwed into one of the jaws of the fixture). In the future, it will be placed into the CFRP specimen.

The planned maximal level of tensile stress could not be set, because of the non-proper structure of the fixture. The clearance fit between the bolt and the hole in the jaw caused the bolt to rotate during the unidirectional pull, which bent the specimen. From the theory's perspective, this did not decrease the results' significance, but this caused inaccuracy in the monitoring of the parameters of the experiments.

During the digital image processing, it was experienced, that the opacity of the uncut fibres has an effect on the results of burr factors. This could be explained by the failure of the pixel segmentation: some areas of the uncut fibres (due to the transparency) are as light grey as they are classified to be white pixels after the segmentation. In the future, a novel process should be developed, which allows adjusting the threshold of the segmentation manually. A pilot investigation (which is not discussed in this paper) showed, that this problem affected a 13% difference in B_a and a 3% difference in B_c. This issue requires further examinations.

Future directions regarding this study are the following: experimental setup defects must be solved in order to have significant experimental results, experiments must be repeated with more measuring points and digital image processing algorithms has to be improved to eliminate the effect of the opacity of uncut fibres.

Conclusion

Based on the present study, the following conclusions can be drawn: A special fixture was developed in order to set the designed tensile stress levels of the workpiece. A novel optimisation parameter was introduced, which is based on the comparison of the actual hole contour (included the burrs) and the perimeter of the ideal, non-burred drilled hole.

It was found that the stress level has not a significant effect on the burr factors. However, more numerous experiments are needed in order to increase the significance level of the results. Results show also, that the brad and spur drill produced better quality holes (fewer amount of uncut fibres) than the twist drill. Geometrical form tolerances of drilled holes were between IT7 and IT13, thus it can be stated, that the amount of tensile stress of approximately 45% of ultimate tensile strength has no significant effect on circularity errors. In the future, more experiments are required to examine the effect of tensile stress on the number of uncut fibres, furthermore experimental devices and digital image processing methods need to be upgraded.

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