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Analysis of Material Weakening in CFRP after a Drilling Operation

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Abstract

Drilling Carbon Fibre Reinforced Plastics (CFRP) induces different material defects like delamination, burnt matrix material, rough bore channel surfaces, fibre pull-out and uncut fibres. Intensive research has been conducted to analyse the amount of defects caused, describing the surface and subsurface defects introduced by machining operations [1, 2]. Additionally, the mechanical strength of rivet joints has been analysed intensively [3]. However, the mechanical performance of rivet joints includes many influencing factors as different materials prepared with various machining processes are being joined. The presented study introduces five newly developed test rigs to analyse the mechanical performance of single bores in relation to different drilling and loading conditions. The setups are designed to focus either on the mechanical strength of the bore channel or the drill entrance or exit. The developed test rigs expand the capability to describe the workpiece quality after a drilling operation. The test rigs facilitate an efficient quality evaluation of drilling processes as well as the development of adapted drilling tools.

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Keywords: Drilling; Carbon Fibre Reinforced Plastic; Workpiece quality; Mechanical Load Test

1. Introduction

Carbon Fibre Reinforced Plastics (CFRP) facilitate light-weight construction and hence shows enormous growth rates. CFRP combines high mechanical strength with a low density. Aircraft manufacturers, the automotive, the sports and the wind turbine industries are the main drivers of the development [1]. The anisotropic material requires an adaption of the full process chain starting from the design, manufacturing and machining operation up to quality control. Meanwhile quality control after machining operations is well established for metals and ceramics [2], the quality control for fibre reinforced materials is not yet fully adapted. Extensive research examines the tool wear and resulting work piece quality after drilling operations in CFRP. However, most research focuses on the exit delamination as well as the bore diameter tolerances and the surface roughness [3, 4]. Recent research shows intensive and regular subsurface damages of fibres after machining operations. Bend or broken fibres regularly appear for specific fibre orientations [1, 5, 6]. An evaluation regarding the influence of induced material defects on the workpiece material strength is of high interest. Most material testing in the field of CFRP manufacturing for aircrafts includes two plates riveted together [7]. Tension and shear forces of the connection are being evaluated. The multiple workpieces and materials result in a high number of influencing factors. Additionally, the specimen preparation requires a countersinking operation and qualified connection technology. The established test standards cause a high complexity that is only required for the evaluation of assembled workpieces and specimens. A complexity reduction to a single plate results in a testing with more defined and reproducible material loading conditions. This enables efficient and significant material testing analyses for the development and evaluation of drill designs and process parameters for machining fibre reinforced plastics. The presented study examines different setups for testing the material weakening of CFRP material after a drilling operation. The study focuses on a reduction of the influencing factors to the single CFRP plate.

2. Induced defects and related loading cases

Drilling CFRP causes various material defects. The areas of defects induced can be divided into three locations: The bore

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entrance, the bore channel and the bore exit. As shown in previous work [6], the bore entrance and exit delamination include a maximum of 3 layers for woven or 5 layers for unidirectional CFRP material on each side. Meanwhile, modern drilling tools cause hardly any entrance delamination, exit delaminations keep being a regularly occurring effect after drilling operations without glass fibre deck layers. A wide range of delamination descriptions can be found in literature, most researchers use a twofold way to describe delamination defects. One aspect describes the size of the defect [8], either comparing the largest radius of delamination to the radius of the bore or by a comparison between the surface area of the delamination and the surface area of the bore. The second aspect categorizes the type of delamination [3], three types being distinguished, see Fig. 1 [3, 8]:

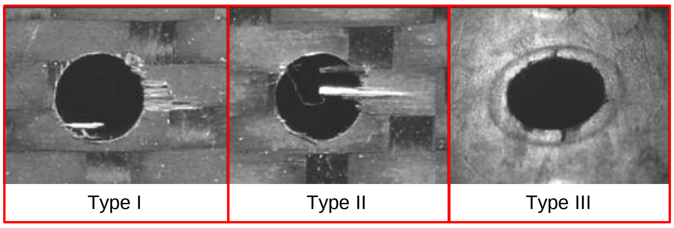

Fig. 1: Types of delamination.

Type I delamination describes missing fibres in the deck layer. Type II delamination is uncut fibres reaching into the bore and partly being separated from the lower layers around the bore. Type III delamination describes the separation of full layers. Any mechanical test rig evaluating the weakening due to delamination needs to focus the applied forces on the transition area between bore wall and specimen surface.

Analysing the bore wall quality is a well-established process in the field of metal machining. Measurement of surface roughness, penetration testing and form and position tolerance are well defined processes [2]. In the field of CFRP machining, surface roughness as well as form and position tolerance measurement are standard procedures. Nevertheless, dependent on the fibre orientation, subsurface damages can occur [1, 6].

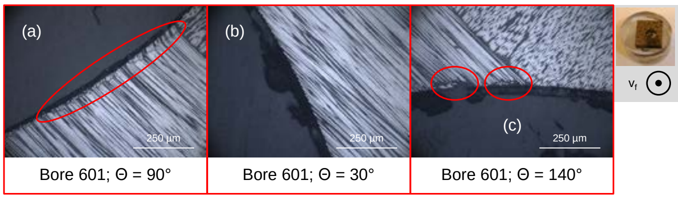

Fig. 2: Subsurface damages for different fibre orientations Θ [6].

Fig. 2 shows a microsection of a CFRP bore location. The drilling operation was performed using a spiral drill with Ø 6.35 mm in 8 mm thick CFRP material and a tool life travel path of 4.8 m. The angle Θ is defined as the angle between the cutting velocity and the fibre orientation. The dark grey area is the bore filled with epoxy, the white lines are polished fibres. For Θ = 90° a subsurface fibre breakage in a depth of 50-100 µm can often be observed. State of the art analysing methods as introduced above cannot detect this kind of damage. The machined area with Θ = 30° shows a fault free subsurface area as well as a smooth surface. The area of Θ = 150° shows a saw tooth shaped surface without any subsurface damages. The results are in good agreement with Rentsch et al. [1]. Testing the residual strength of the bore wall requires radial forces alongside the bore wall. A saw tooth profile reduces the contact area and in result the stiffness in the tests. Broken or bend fibres are expected to reduce the material stiffness as well.

3. Test rig setup

A total of six test rigs have been designed or tested to determine the residual strength of the workpiece after a drilling operation. The test rigs aim to fulfil the following criteria:

- Reliable analysis of the mechanical strength of the bore wall and/or exit
- Good differentiation between different bore qualities
- Good repeatability
- Little time consumption

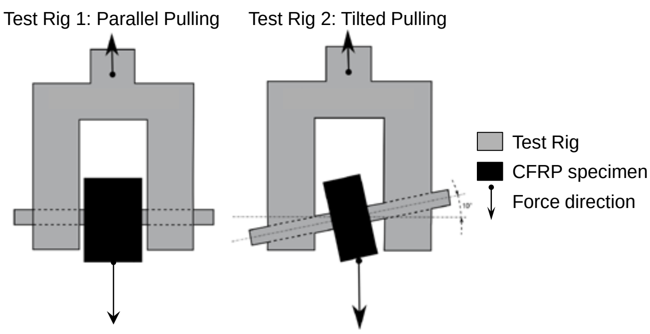

Fig. 3: Test setups 1 and 2 for residual strength test of the bore channel after a drilling operation.

All test rigs are conducted using a Schenck static materials testing machine modified and modernised by Zwick/Roell. The maximum testing force is F_{max} = 250 kN. All bores previously inserted for this study are of a diameter of 6.35 mm, the thickness of the CFRP material is 8 mm. Unidirectional (UD) and woven (MD) CFRP material have been tested. Both types of CFRP are widely used in the aircraft industry, being M21/34%/UD194/IMA-12K as unidirectional material and M21/35%/370H5/AS4C-6K as woven CFRP, both from Hexcel®. Test setups no. 1 and 2, Fig. 3, consist of two symmetrical chucks with one on display each. The CFRP specimen is positioned in between the chucks. A hardened steel pin of Ø 6 mm is mounted into the bores of the specimen. The CFRP specimen is designed as a chain link, shown in Fig. 4.

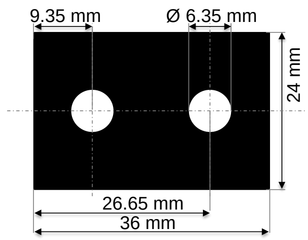

Fig. 4: Design of CFRP specimen for test setups 1 and 2.

A pretesting force of F_{pt} = 40 N is applied, the test is conducted with a velocity of v_{test} = 0.05 mm/s. In test setup no. 1 the load direction is perpendicular to the axis of the drilling tool before. The load is being introduced on the full length of the bore wall equally. The pin for test setup no. 2 is mounted with a tilt of 10°. The setup enables to focus the load on either the entrance or the exit side. Setup no. 2 corresponds with the real situation that a radial force will be introduced from one side of a bold, screw or pin, resulting in a shear force load on the workpiece.

Test setups 3 and 4 as displayed in Fig. 5, induce the test force mainly on the area of the drill entrance or exit as chosen. Both setups have a pin of Ø = 6 mm inside the bore for a good centricity. For test no. 3 the pin opens to a conical head with an opening angle of 100°. For test setup 4 the 6 mm pin is followed by a circular plane of Ø = 10.4 mm. Test setup 3 measures the resistance of the CFRP material against a bore expansion in the area of a possible entrance or exit delamination. Test setup 4 measures the mechanical strength of the CFRP material in axial direction. The force is induced in the area of a possible delamination as well. The specimen size is 24 x 24 mm^2 with the bore inserted centrally. A pretesting force of F_{pt} = 50 N is applied, the test is conducted with a velocity of v_{test} = 0.02 mm/s.

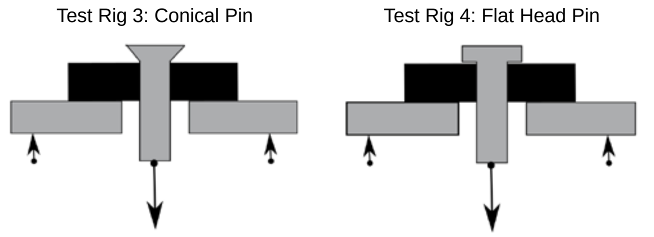

Fig. 5: Test setups 3 and 4 for residual strength test of the bore exit after a drilling operation.

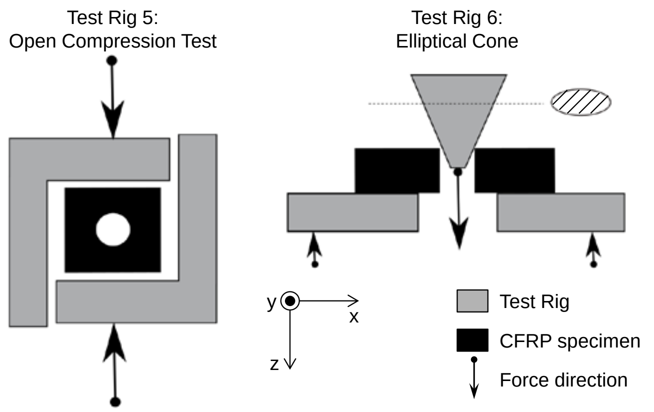

Fig. 6: Test setups 5 and 6 for mechanical strength of drilled CFRP specimens.

Tab. 1: Specifications of used drill models

Modell	Internal Name	Design	Point Angle	Rake Angle	Clearance Angle	Special
M1*	HA	Spiral drill	130°	23°	11°	Sec. Coating
M2	DA	Spiral drill	130°	5°	17°	Sec. Coating
M3*	PA	Spiral drill	98°	23°	25°	
M4*	D0	Spiral drill	130°	5°	17°	
M5*	C0	Ball end mill	----	14°	25°	
M6	H0	Spiral drill	130°	23°	11°	
M7	E0	Spiral drill	96°	N/A	N/A	
M8	Ef	Spiral drill	96°	N/A	N/A	Corner clip
M9	SA	Spiral drill	91°	20°	24°	Corner clip

Test setup 5, Fig. 6, is the “Open Compression Test” equivalent to ASTM D7137. The load is induced over the full bore wall length for test setup 5. Test setup 6 contains a pin of conical and elliptical shape which is inserted into the bore of the CFRP specimen. The semi-axes are in a length ratio of 11 to 6.7. The semi-major axis starts with r_a = 3 mm, the semi-minor axis starts with r_b = 1.83 mm. The cone possesses an opening angle of 3° for each flank. The full length of the cone is 50 mm with a maximum semi-major radius of r_a = 5.5 mm. Test setup 6 induces the forces alongside the bore channel with a focus on the bore edge. Similar to setup 3, the setup 6 leads to a bore expansion but with a preferred direction due to the elliptical shape of the pin. Different load directions, e.g. for anisotropic specimens, can easily be tested. The specimen is 24 x 24 mm^2 with the bore inserted centrally. A pretesting force of F_{pt} = 50 N is applied, the test is conducted with a velocity of v_{test} = 0.04 mm/s. For all setups a load-displacement curve is being recorded.

Nine different drill designs have been used, see Tab. 1. All drills are solid carbide drills with a nano-crystalline diamond coating. The workpiece quality of the drill designs marked with an asterisk (*) have already been analysed in [6]. The drill models M1 and M6 as well as M2 and M4 differ only in the type of nano-crystalline diamond coating.

4. Results

The recording of the load-displacement curve is started when the pretesting force has been established. The pretesting force reduces errors due to jigging.

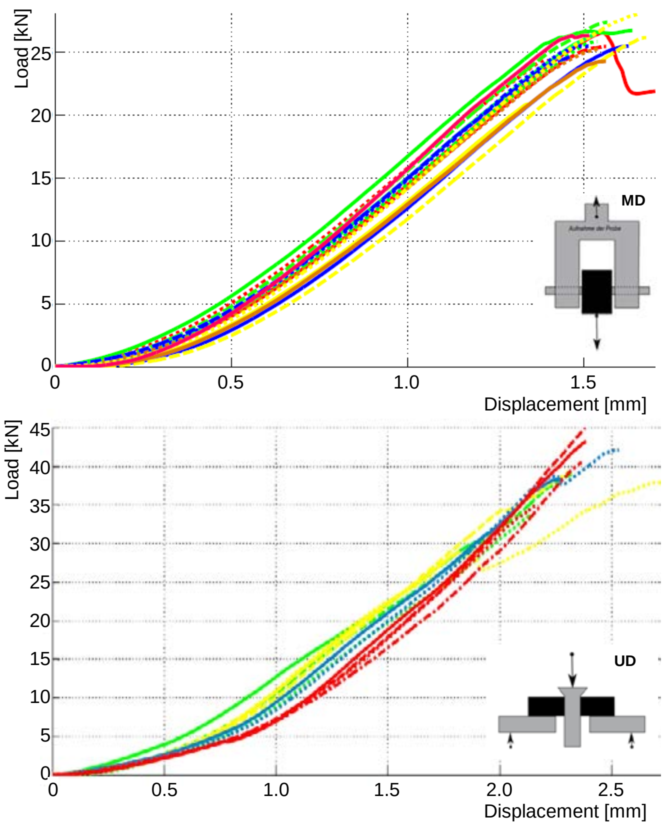

Fig. 7: Exemplary load-displacement graphs for test setup 1 with woven and test setup 3 with unidirectional CFRP.

Fig. 7 shows two sample results from the test setup 1 testing woven CFRP and test setup 3 testing unidirectional CFRP. Each colour represents a different model of drill design that generated the bores. The design of the line indicates the amount of bores already drilled with the tool. Each curve shows an increasing gradient at the beginning, a quasi-linear area for about 25-75% of the maximum load and a maximum force. Test setup 4, the flat head pin provided only load-displacement curves of very low explanatory power, the test setup is therefore further disregarded.

Accordingly the load-displacement curve of each test setup is analysed extracting three measurement values as shown in Fig. 8. The first value, displacement at 5kN, d_5, indicates the resistance of the material against first material displacements. The value is measured as stiffness [kN/mm]. The second measured value is the gradient m over the quasi-linear range. The value m [kN/mm] describes the resistance of the CFRP material against major displacement around the bore or delamination. The chosen bandwidth of the force depends on the characteristics of the test setup. The third measured value describes the maximum force F_{max} the specimen achieved during the test. The measurement of the maximum force requires a full destruction of the specimen. Evaluation of the test setup showed a full destruction only occurring for test setups 1 and 5.

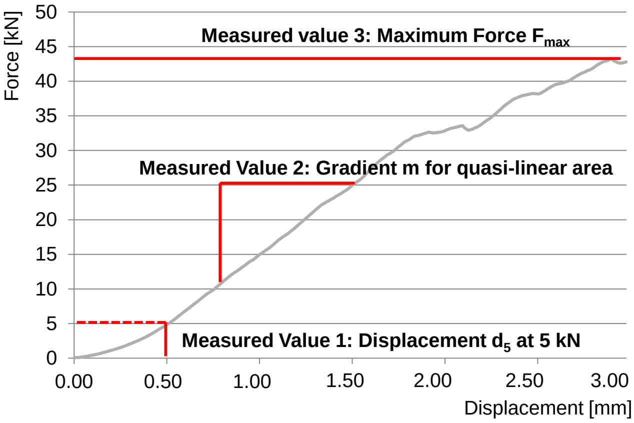

Fig. 8: Analyse scheme for load-displacement curve.

The measurement values of each test rig setup are subsequently standardized using equation (1). The achieved material strength values of each specimen can hence be plotted relative to the strongest specimen.

$$M_{Ni} = \frac{M_i}{M_{i\,max}} \quad (1)$$

The different measured values are added up for each test series according to:

$$L_{Bi} = \sum_{j=1}^{f} a_j \cdot M_{Ni} \quad f \ldots .2,3 \quad \sum_{a_j} = 1 \quad (2)$$

Every measured value weighted the same, f being 3 for setups 1 and 5 in all other cases being 2 as the maximum force F_{max} being only measured for the test setups 1 and 5.

	1 Pull straight			2 Pull inclined			3 Pin conical			5 Open Comp		
Drill M1 / HA	93%			69%			89%			93%		
	100	86	94	86	52		86	91		100	80	97
	25.41	0.540	26.3	11.56	1.261		18.32	0.507		116.5	0.131	60.64
Total Feed M1							1.2 m					
Drill M2 / DA	84%			79%			92%			86%		
	89	76	87	78	79		100	85		99	58	100
	22.73	0.612	24.26	10.49	0.824		21.37	0.548		114.94	0.181	62.21
Total Feed M2	4.8 m						2.0 m					
Drill M3 / PA	86%			83%			91%			97%		
	92	74	91	78	87		96	87		98	100	93
	23.36	0.631	25.44	10.42	0.749		20.48	0.535		114.03	0.105	57.95
Total Feed M3	1.2 m			1.2 m			1.2 m			8.0 m		
Drill M4 / D0	92%			84%			96%			94%		
	96	81	100	82	87		93	99		97	89	96
	22.78	0.600	20.85	10.96	0.751		19.85	0.467		113.1	0.119	59.71
Drill M5 / C0	96%			100%			92%			/		
	94	100	95	100	100		93	92				
	23.82	0.466	26.69	13.41	0.655		19.96	0.508				
Drill M6 / H0	/			83%			/			90%		
				80	87					96	82	93
				10.73	0.757					116.34	0.140	61.21
Total Feed M6										2.0 m		

50-84% 85%-94% 95%-100%

Fig. 9: Sample results of the mechanical strengths for six different drill designs.

Fig. 9 shows sample results for six different drill models. The results from the test setups 1, 2, 3 and 5 are displayed; test setup 6 is very complex in production and was not yet available during this test series. In general one of the first three bores of every drill is analysed, any deviation is displayed in total feed. The two or three values in the three upper boxes indicate one relative measured value each, the left box shows the Displacement d_5, the box in the middle the Gradient m and the box to the right Maximum Force F_{max}. The upper box shows the achieved mean value over the measured values. For a relative strength of 95-100% the specimen is rated good, the box or the number is highlighted green. Measured values between 85 and 94% are rated sufficient and hence highlighted yellow, all worse measured values are highlighted red. The lower three boxes show the absolute values: Displacement at 5 kN (left, [mm]), the gradient m (centre, [kN/mm]) and maximum force (right, [kN]). It can be observed, that test setup 2 leads to the highest variety in the test results. The lowest achieved mean value being 69% of drill model 1, the highest value achieved by drill model 5. For test setup 3 with the conical pin Drill model 1 achieves the lowest value with 89%. For test setup 5, the open compression test, the drill model 2 achieves the lowest mean value of 86%. The test results show in general very poor mechanical strengths of drill models 1 and 2. Drilling with model 5 results in a high mechanical strength of the bore wall as the drill model achieves very good results for the test setups 1, 2 and 3.

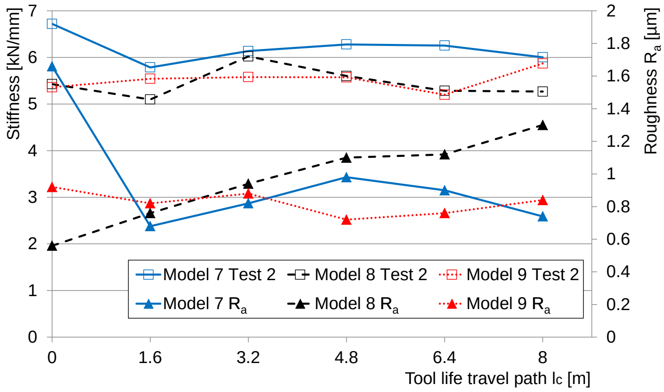

Fig. 10: Mechanical strength for Tilted Pulling Test (Test 2) and roughness of bore wall.

Fig. 10 shows the gradient of the load displacement graphs between 500-1000 N (mechanical strengths) and the bore channel roughness over the tool life travel path. These sample results in Fig. 10 concentrate on the Tilted Pulling Test. First bores drilled with geometry M7 show high bore channel roughness of about 1.65 µm, decreasing to 0.65 µm after 1.6 m tool life travel path followed by a curl between 0.7-1 µm for the remaining tool life time. In this case high roughness does not necessarily lead to lower stiffness of the bore, it is even the other way round: The stiffness of M7 is highest in this sample results between 5900 and 6800 N/mm. While the roughness R_a of drill geometry M8 increases significantly during tool lifetime the mechanical strength of the drilled bores does not change intensively. The stiffness remains between 5 and 6 kN per mm displacement. Stiffness for tool geometry M9 stays in about the same range (5-6 kN/mm) but does not show increasing bore channel roughness, like tool M8. A significant relation between surface roughness and mechanical strength cannot be found.

The sample results of the Conical Pin Tests (Test 3) in Fig. 11 show the mechanical stiffness between 500-1000 N. The stiffness trend differs from the results of the Tilted Pulling Test. The conical test design loads the exit or entrance delamination of a bore. The stiffness starts at 10 or 8.9 N/mm respectively for new tools and decreases to 60% or 80% of the start value at the end of tool life time (8 m). This stiffness reduction represents the increasing amount of delamination due to tool wear.

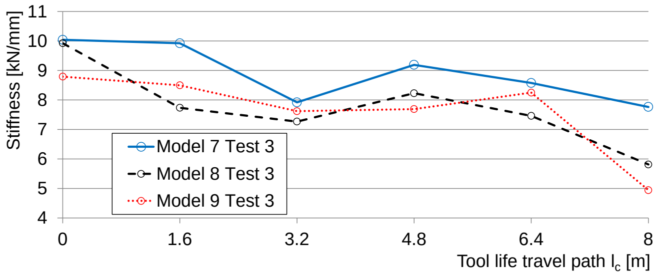

Fig. 11: Exemplary stiffness for Conical Pin Test (Test 3) loaded in reverse feed direction.

Sample results for the Elliptical Cone Test (Test 6) and Drill Model 8 are shown in Fig. 12. Test 6 applies the load mostly to the bore wall and less to the bore exit due to the small opening angle of the cone of 3° for each flank. The stiffness has been calculated for an insertion depth of 300-1000 µm and 300-1500 µm of the Elliptical Cone in z-direction. This corresponds with a maximum bore wall widening of 60 µm and 80 µm respectively for each flank. The evaluated maximum bore wall widening has been chosen equivalent to the maximum depth of damages in the bore wall, as could be shown in previous studies [6]. The cone has been induced with two different orientations $\Phi = 0°$ and 90°, which are oriented parallel to the fibre orientation of the first fibre layer. Fig. 12 shows a small reduction in stiffness over tool life time for $\Phi = 0°$. The stiffness over 60 µm bore wall widening reduces about -8.8% over 80 µm about -3.3% during tool life. For $\Phi = 90°$ the CFRP shows a higher stiffness, but also a more intense stiffness reduction of -20.1% (60 µm) and -11.8% (80 µm).

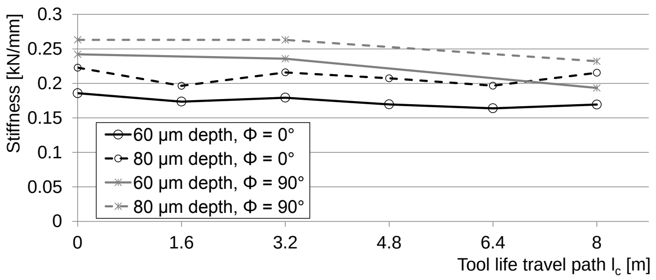

Fig. 12: Exemplary stiffness for Elliptical Cone Test (Test 6) and Drill Model 8 loaded in reverse feed direction.

5. Conclusion

The study shows different test setup designs for the evaluation of material strength in CFRP after a drilling operation. The test series show the mechanical strengths of bores dependent on the used drill model and the tool life time. Test setups 3, 4 and 6 experience a relative movement between CFRP and the penetrating cone element. Although the relative movement is small, the amount of abrasive wear occurring on a test rig made of hardened steel cannot be neglected. In result, the penetrating pistons have been made of tungsten carbide with a nitride or diamond coating. The test setups 2; 3 and 6 deliver the most reliable results. Test setup 2 (Tilted Pulling) focuses the load on the bore channel. The bore wall quality can be analysed reliably using this test setup. Major defects on the surface and up to 100 µm below the surface influence the measuring results. Nevertheless, the production of the test specimens is somewhat unhandy and the results need to be correlated to the wall thickness of the specimen. Test setup 6 (Elliptical Cone) also stresses primarily the bore wall, the bore wall quality can be evaluated comprehensively. Specimen preparation, test conductance and test of different load orientations are more convenient than for test setup 2. Test setup 3 (Conical Pin) evaluates the material weakening due to work piece delamination. In contrast to Test setups 2 and 6, the bore entry or exit quality can be controlled using the test setup. Specimen preparation and test conductance are very efficient. Analyses of the samples after the tests show a penetration of the areas influenced by the drilling process already with small forces of 300-1000 N. the process forces and penetration depths have been adapted in Fig. 10-12. In the previous study surface roughness of a bore wall has already been lined out as a poor indicator for workpiece quality, e.g. induced subsurface damages, after a drilling process [6]. In good agreement, the presented study shows no correlation between surface roughness of the bore and mechanical strength.

Combination of the test setups 3 and 6 enable a very efficient and capable evaluation of the material strength after a drilling process. Bore wall as well as bore entrance and exit can be evaluated. The Elliptical Cone allows an efficient evaluation regarding the stiffness of the bore wall depending on the load direction. Analyses of the stiffness during small displacements or small loads provide the most precise detection of caused defects due to drilling operations.

The methods evaluated provide a valuable addition to the established methods of delamination and bore wall analyses. The shown setups have the potential to increase the efficiency and reliability in the development of optimized tool and process designs for machining fibre reinforced plastics. A subsequent standardisation will allow the application of the test setups 3 and 6 for different diameters.

6. Acknowledgement

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