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Influence of clamping systems during drilling carbon fiber reinforced plastics

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Abstract

During post processing of carbon fiber reinforced plastics, drilling is one of the mostly used machining processes. With increasing complexity of components the requirements on the clamping systems are rising. This paper shows the investigation of drilling tests for different types of clamping positions which are examined regarding their influence on the resulting workpiece quality. The clamping of the planar specimens was realized by 3 and 4 points and by a ring clamping system with variable distances from the drill axis to the fixed points. During the experiments the process forces were measured and the resulting delamination and fiber pullouts at the workpiece surface were determined. The results demonstrate that the distance from the drill axis to the fixed points has a significant influence on the process forces and the achievable workpiece quality.

Keywords: Fiber reinforced plastic; Machining; Drilling; Clamping systems

1. Introduction

In the last few years the amount of applications for using carbon fiber reinforced plastics (CFRP) has continuously increased. Due to their high specific strength and stiffness many new applications are feasible e.g. in the automotive industry. CFRP are mostly manufactured near net shape. But caused by the manufacturing processes a post processing of the workpieces is necessary, too. Mainly used manufacturing processes are milling of the workpiece edges or drilling holes into the workpiece for subsequent assembly processes [1]. A main advantage of the CFRP is the high potential of a load optimized design, leading to less weight, higher stiffness and strength of the workpieces in comparison to steel or aluminum workpieces with same characteristics.

To support the propagation of the CFRP a high knowledge of the manufacturing processes is necessary to avoid damages at the surfaces. For drilling fiber reinforced plastics (FRP) delamination occurs mostly at the top layers of the workpiece material. Delamination at the initial process side is called ‘peel up’ and at the exit side ‘push out’ delamination [2-3].

Another advantage of the CFRP is the possiblity to create complex 3D shapes. For machining, mainly drilling, it is necessary to fix the workpieces during the machining process [4]. However special clamping devices induce high costs which lead to a reduction of the profitability, especially for workpieces with a high complexity and a small number of production units. As a consequence of this CFRP have not been used for such kind of workpieces. Therefore a good understanding of the influence of clamping devices and their impact on the manufacturing process is essential to support the propagation of these materials.

The influence of the clamping device on the achievable workpiece quality is not fundamentally investigated yet. With increasing distance between the point of drilling and the clamping positions the surface damages like delamination, fiber pullouts and spallings are increasing [4]. Sadat developed a clamping device to avoid delamination at the entrance of the drilling tool.

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To avoid surface damages at the exit side a backside plate was used [5]. Other investigations examine the influence of backside supports to the resulting push out delamination [6]. Tsao and Hocheng investigated a mechanical model for accruing delamination with and without backup at the exit side for a core drill and a saw drill [7]. In this paper, different clamping systems are examined and their influence on the machining quality of the surface layers was considered.

2. Experiments

2.1. Experimental setup and scope

To investigate the influence of the workpiece fixation several clamping systems were developed. First, different clamping systems with a punctate fixation were designed. Moreover flexible four- and three-point fixations were used (Fig. 1). In the experiments the length of l_x, l_y and l_{max} were varied.

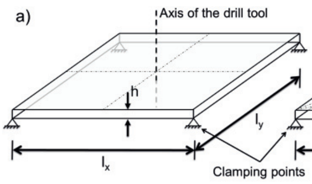

Fig. 1. (a) four point fixation device; (b) three point fixation device

The clamping was realized with a small circular contact face at the edges of the rectangular test plate. The length l_x and l_y was varied from 40 mm to 180 mm. Caused by the variation of this contact length different clamping conditions were generated. For the three point clamping device the clamping points were also varied according to the four point clamping device.

A further clamping device was developed which enables a planar clamping of the test plate (Fig. 2). This is named ring clamping device. The drill axis is located in the middle of the test sample for all devices. The ring clamping experiments were carried out with different diameters of the clamping plates.

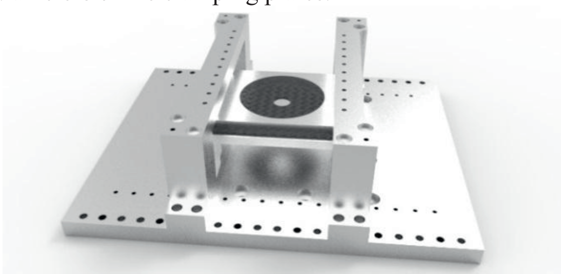

Fig. 2. Ring clamping device

Increasing tool wear at the cutting edge has also a big influence on the arising damage around the borehole [8]. To eliminate the influence of cutting tool wear reference drills were carried out, by drilling in a reference plate between each drilling process at the clamping device setup. The reference plate was clamped in an ideal way to avoid workpiece deflection and vibrations. Therefore the setup for the reference drillings can be considered as an ideal clamping system with a nearly infinite stiffness. The accruing damage at the reference drilling delivers the influence of tool wear. Thus the difference of the resulting damages between investigated clamping device and reference drilling delivers the direct influence of the clamping system to the originating surface damage. A further advantage of this testing procedure is to compare the variation of the clamping device with an ideal clamping system.

2.2. Material data and process parameters

The used sample material in these experiments is a carbon fiber composite based on an epoxy matrix. The type of the fibers is T620SC 24 K 50C produced by the Toray company. The material consists of eight plies with biaxial textiles. The fiber orientation was quasi-isotropic (0°/90° and +45°/-45°). With the stack up and the epoxy matrix flat plates were pressed with the resin transfer molding process. The plates have the dimensions 860 mm x 510 mm x 2.5 mm. The sample material was cut out of thin plates. The dimensions of the sample material depend on the type of clamping device which is used. The Young's modulus of the composite is 46100 MPa.

The drilling tool was made of cemented carbide with a diameter of 10 mm according to DIN 6539 (see table 1).

Table 1. Drill tool used in the experiments

Parameter	Drill tool
Diameter	10 mm
Helix angle	30°
Point angle	118°
Number of teeth	2

The drill speed was fixed to *n = 3000 rpm* and the feed rate was fixed to $v_f = 300$ *mm/min*. All experiments were executed on a machining center from Heller type MC-16. The axial process forces and torque were measured with a Kistler multicomponent dynamometer type 9215A.

2.3. Measurement of surface damages

Caused by the drilling process, surface damages occur around the borehole. The damages are mostly in form of delamination, fiber pull outs and spallings [2], [8-11]. They are influenced by the clamping system, process parameters and the tool wear [2-3], [12-13]. To quantify the damages optical photographies of the top layers were taken after the drilling process. Afterwards the pictures were analyzed with a self-developed software tool to capture the damage area [14]. To assess the damages like delamination, fiber pullouts or spallings, the damage factor was determined according to Eq. (1).

$$F_D = \frac{A_D}{A} \tag{1}$$

The delamination factor is defined as the ratio of delaminated area (A_D) to the area of the ideal hole (A) [15-16].

2.4. Static material behavior

To describe the static material behavior e.g. a deflection caused by a load it is necessary to consider the geometrical form of the workpiece. For rectangular plane plates which are stressed by a distributed load Ashby calculated the deflection b by using Eq. (2) [17].

$$b = \frac{5Fl_y^3}{32El_x h^3} \tag{2}$$

In this equation F is the area force, E the young's modulus, h the thickness, l_x the width and l_y the length of the workpiece. For annularly plane plates the deflection b of a workpiece is calculated by using Eq. (3) [18].

$$b = \frac{Fr^2}{16\pi K}\frac{3+\mu}{1+\mu} \tag{3}$$

In this equation F is the force and μ the poisson's ratio. The plate stiffness K is defined by

$$K = \frac{Eh^3}{12(1-\mu^2)} \tag{4}$$

with the Young's modulus E, the thickness h and the poisson's ratio μ.

3. Results

3.1. Machining Quality

The results of the experiments show a dependency between the adjustment of the clamping system and the processing quality of the workpiece at the surface layers. Therefore, the damaged areas at the top and bottom side of the workpieces were detected and the damage factor determined, Eq. (1).

Figure 3 shows the damaged area at the bottom side of a reference drilling (Fig. 3a) and the damaged area of a fixing situation caused by a clamping system with a 4-point fixation at the distances $l_x = 40\ mm$ and $l_y = 180\ mm$ (Fig. 3b). The damaged area of the reference drilling is only small-sized, since less delamination occurs around the outer edge of the borehole. In contrary to this, the damage of the borehole which was drilled by using the 4-point fixation is significantly higher and was dominated by delamination, fiber pullouts and spallings.

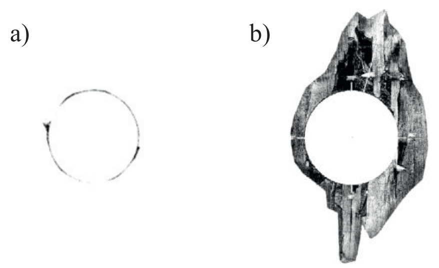

Fig. 3: Damaged area of a reference hole (a) and of a fixing situation due to 4 points (b)

Figure 4 shows the delamination factor determined for drillings at the top of the workpieces which were realized by using the 4-point clamping system. The occurring damages can be separated into three sections: In the first section (l_y less or equal *80 mm*) the damage is small and despite of increasing l_y nearly constant. In the second section (l_y between *80 mm* and *120 mm*) the damaged area increases. If l_y is larger than *120 mm* the damaged areas grow with increasing distances.

The curve progression of the damaged areas at the bottom side of the workpieces corresponds approximately to the damaged areas at the top side, see Fig. 5. Equivalent to the bottom side, the progression of the damage can be split in three sections. However, the damaged areas at the bottom side are continuously wider, especially for l_y larger than *100 mm*. In the third section, the damaged areas increase, too (l_y is larger than *120 mm*).

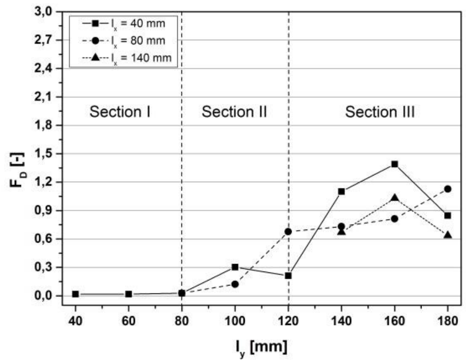

Fig. 4: Damage factor at the upper surface layer for different fixation adjustments (4 points)

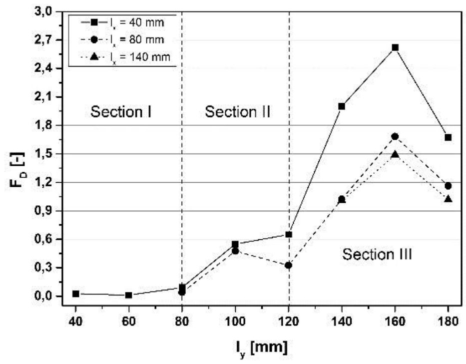

Fig. 5: Damage factor on the bottom side for different fixation adjustments (4 points)

The figures 6 and 7 show the curve progression for the damage factor at the top and the bottom side of the drillings due to the 3-point and the ring clamping system. According to the damage factors of the 4-point clamping system, the damaged area on the top side is smaller than the damage located at the bottom side. Furthermore, by using a ring clamping system no significant increase of the damage factor with a growing diameter could be observed. Additionally there is a significant increase of the damage factor for l_{max} greater than *75 mm* for the 3-point clamping system.

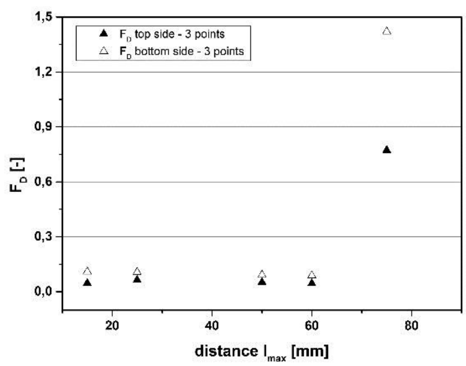

Fig. 6: Damage factor of the drillings for the 3-point fixation (top and bottom side)

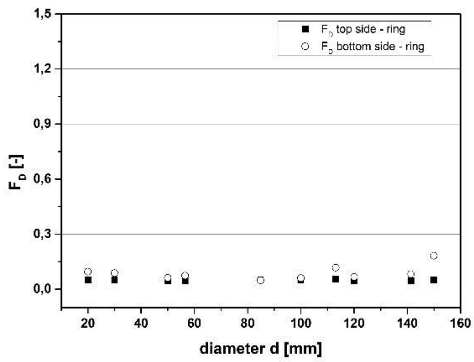

Fig. 7: Damage factor of the drillings for the ring fixation (top and bottom side)

3.2. Cutting Forces

During the experiments axial cutting forces were measured. Thereby, the occurring axial cutting forces can be separated into three sections (analogously to chapter 3.1). Figure 8 (a-c) shows the resulting cutting forces regarding the variation of the clamping systems in comparison to the reference drillings. In Figure 8a the curve progression of the cutting force for the 4-point fixation ($l_x = 40$ *mm*, $l_y = 40$ *mm*) is shown. It is approximately congruent with the cutting force of the reference drilling.

With increasing distance to the fixation points (e.g. $l_x = 80$ *mm*, $l_y = 80$ *mm*) the curve progression of the cutting force differs between the reference drilling and the 4-point fixation (Fig 8b). The maximum force occurs time-delayed. In the third variation the maximum of the cutting force differs significantly from the reference drilling and arises at a later time, too (Fig 8c). Additionally, a negative peak in the force progression occurs ($l_x = 40$ *mm*, $l_y = 180$ *mm*). After that, the cutting force drops to zero while the corresponding force of the reference drilling is still larger than zero. This can be observed because the drilling process has not finished at that time.

4. Discussion

The results show a significant dependence of the machining quality on the clamping system. The high damage factor in the third section (Fig 5) can be explained by the negative force peak (Fig 8c). During the drilling process the thickness of the workpiece is getting thinner. If the remaining material is too thin to resist the process force a breakthrough of the cutting tool occurs [4], [6]. Immense delamination and spalling at the workpiece are a result of this.

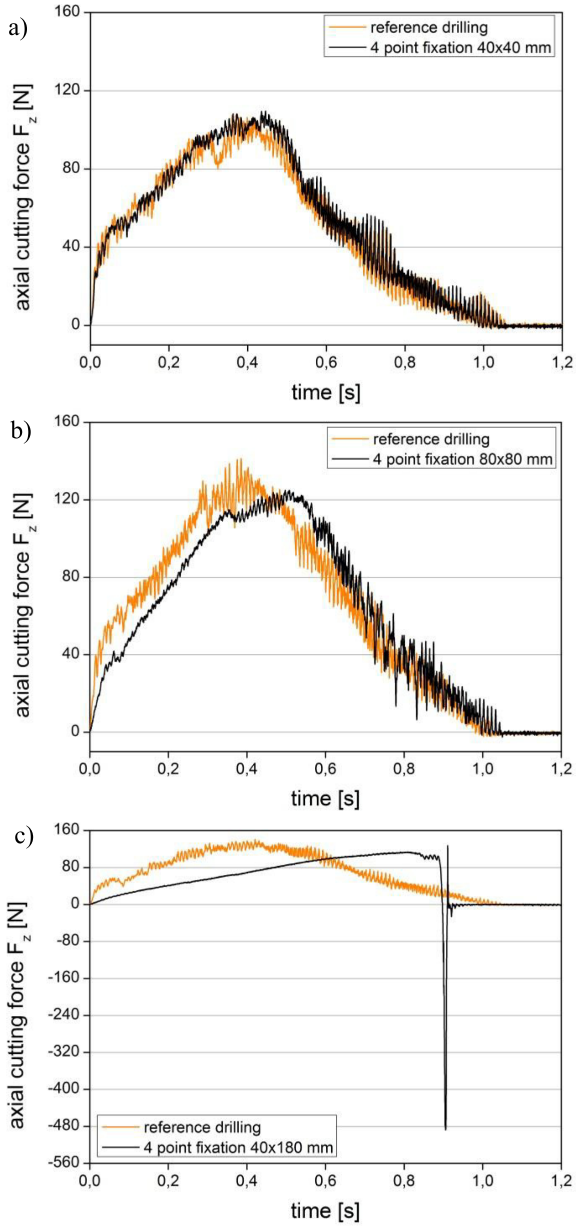

Fig. 8: Axial cutting force of 4 point fixation and reference drilling, 40 x 40 mm (a), 80 x 80 mm (b) and 40 x 180 mm (c)

If the fixation points are close to the drill hole, the fixation is almost ideal located similar to the ideal clamped workpiece in the reference drillings. With increasing distance of the fixing points, the machining quality is decreasing. Additionally the increasing damage with growing distance of the clamping points induces a time-delay of the force maximum between the reference drilling and the 4-point clamping system. This delay can be explained by the deflection of the workpiece. Therefore, the maximal cutting force occurs later than at the reference drilling.

This bending behavior of the workpieces can be explained by a modification of Eq. (2). A modified approach to describe the deflection b of a rectangular plane plate is shown in Eq. (5).

$$b = K_P \frac{F_z l_y^3}{E l_x h^3} \qquad (5)$$

In this equation F_z is the concentrated axial force and E the Young's modulus. Here h is the thickness, l_x the width and l_y the length of the workpiece.

The factor K_P was implemented for an optimized description of the modelled deflection b and is defined as

$$K_P = K_1 + K_2 l_x \qquad (6)$$

where K_1 and K_2 are constants and l_x the width of the workpiece. To describe the bending behavior for the test setup of the investigations the factor K_1 is *3,688* and K_2 is $0{,}231\ mm^{-1}$ in the case of the 4-point clamping system.

Figure 9 shows the damage factor which depends on the modelled deflection (replacing Eq. (6) in Eq. (5)) for the top side of the workpiece. If the critical deflection is higher than $b = 0.4\ mm$ the damage factor increases at the top side of the workpiece until it stabilizes again at $b > 1.0\ mm$.

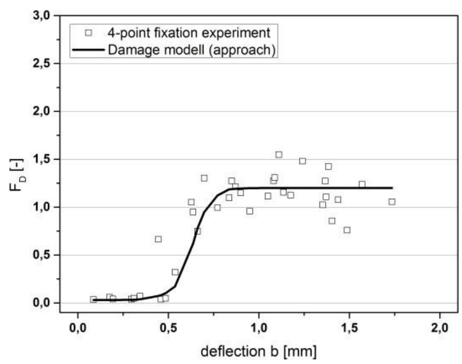

Fig. 9: Damage factor on the top side depending of the deflection of the specimen

At the bottom side the damage factor is increasing at a critical deflection $b = 0.4\ mm$ (see Fig. 10). In comparison to the upper surface layer the results show no stabilization of the damage factor at the bottom side.

In all drilling experiments the maximum force is increasing with an increasing number of bore holes caused by the tool wear. The value of the maximum force of the 4-point clamping system is related to the maximum value of the force during the reference drilling.

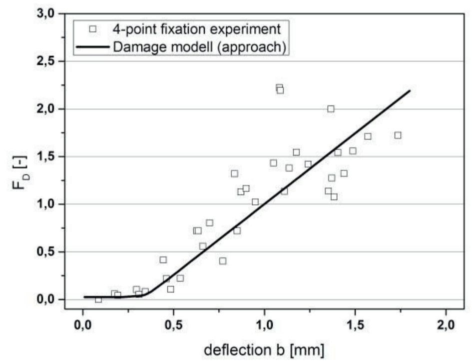

Fig. 10: Damage factor on the bottom side depending on the deflection of the workpiece

5. Conclusion and Outlook

Based on the results of the experiments the following conclusions can be deduced:

- With short distances between the fixation points and the hole center the maximum process force remains constant and the deflection can be determined as time shift of the maximum axial cutting force. Therefore it is possible to predict the deflection by analyzing the force development
- If the distance from the fixation points reaches a critical level, the remaining material of the workpiece fails and the machining quality is decreasing rapidly. The critical level for this workpiece material was observed at a distance of the fixation points which is higher than 80 mm.
- In contrast to the bottom side, the surface damage at the top side stabilizes at a constant level with increasing deflection
- To avoid the breakthrough of the cutting tool the distance of the clamping points must be shorter than a critical value.
- Based on the results of the experiments it will be possible to predict the expected surface damage with a consideration of the clamping system and the process parameters.

In further experiments the deflection will be measured by a modified test stand and the dynamical behavior will be examined. Additional experiments to determine the influence of the clamping system for milling processes are in progress.

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