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Machining strategies for hole making in composites with minimal workpiece damage by directing the process forces inwards

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1. Introduction

The utilization of fiber reinforced plastics (FRP) has increased significantly over the last decades. Today many applications for FRP are found in aerospace and automobile industries as well as in the naval or sporting goods sector. Due to requirements for appropriate material properties for different regions various materials are used. This makes joining operations like composite to metal necessary. Many of these joining techniques such as riveting, screwing or pinning require pre-manufactured holes. Mechanical drilling and milling operations are still widely used although they weaken the workpieces by cutting the fibers. If the machining process leads to additional damage the resulting part's strength may be even worse.

A lot of research has been done on the problems related to the mechanical drilling of FRP. The heterogeneous structure of the workpiece with significantly different mechanical properties of fiber and matrix material leads to problems concerning the machining quality of the holes. Additionally the very abrasive fibers cause extensive tool wear which leads to even worse drilling qualities. König and Graß (1989) define damage such as delamination, chipping or spalling as real damage because of their permanent nature whereas uncut fibers or burrs may be removed by subsequent processes. Delamination is regarded as the most critical damage because the generated interlaminar cracks weaken the structure significantly. Hocheng and Dharan (1990) distinguished between delamination at the entry side of the tool (peel-up) and delamination at the exit side (push-out) (see Fig. 2). Generally push-out delamination is more extensive and thus has to be considered more dangerous than peel-up delamination.

2. Drilling fiber reinforced plastics

Different approaches described in literature are dealing with decreasing the thrust forces which are acting on the outer layers and thus causing critical damage. They range from adapted feed controls, the use of special drill bit geometries, back-up plates which support the outer layers to three-axial milling strategies such as circular milling.

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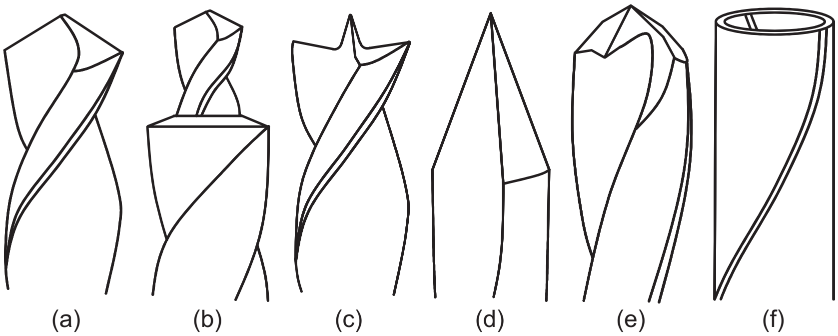

Fig. 1. Schematic of special drill bit geometries used for drilling of fiber reinforced composites: (a) standard twist drill; (b) step drill; (c) candle stick drill; (d) dagger drill; (f) multi-faceted drill; (e) core drill.

2.1. Uniaxial drilling

Hocheng and Dharan (1990) showed that especially the axially acting thrust force influences delamination at the tool exit. Jain and Yang (1991) presented a correlation between feed rate and exit side delamination following Hocheng and Dharan's results. The tool geometry probably has the greatest significance for the direction and absolute value of the thrust forces. Considering the fact that standard twist drills generate 65–75% of their thrust force through the chisel edge, it is comprehensible that good quality machining is possible with special tools which avoid these problems.

A variety of special drill bit geometries has been designed and investigated in recent years. Hocheng and Tsao (2003) presented models for critical thrust force (onset of delamination) for saw, candle stick, core, and step drills. It was found that core drills offer the highest threshold values for critical thrust forces (Hocheng and Tsao, 2006). Bhatnagar et al. (2004) obtained less damage when machining glass fiber reinforced plastic (GFRP) laminates with step drills and facetted drills as compared to twist drills. Many of these special drill bit geometries are commercially available today. Fig. 1 shows some of them schematically.

2.2. Three-axial milling strategies

Changing the machining strategy from conventional uniaxial drilling to multi-axial milling methods for hole making has certain advantages; generally at the cost of higher process complexity and increased machining time. The most published method is circular milling where the tool travels along a helical path through the workpiece.

Park et al. (1995) described an improved quality of the holes with less delamination or fuzzing for circular milling ('helical feed method') of carbon fiber reinforced plastic (CFRP) laminates with a metal bonded diamond core drill. Persson et al. (1997) employed circular milling ('KTH method') to CFRP laminates and achieved better results than with special drill bit geometries such as dagger drills and multi-facetted drills. Yagishita (2007) compared circular milling to conventional drilling with diamond coated drill bits and even vibration-assisted drilling. Better geometrical machining qualities (roundness vs. tool wear) could be obtained by circular milling. Circular milling is especially advantageous for machining compounds as the machining parameters might be adapted during the process to the particular material system. Denkena et al. (2003) compared drilling and circular milling strategies for aluminum–CFRP compounds; Jansen (2003) and Brinksmeier et al. (2005) investigated circular milling to machine aluminum–titanium–CFRP compounds.

2.3. Auxiliary devices

A pragmatic means to help reducing workpiece damage at the exit side is a back-up plate. Tsao and Hocheng (2005) described the influence of back-up plates on hole quality analytically and proved experimentally that holes with less damage could be obtained while enabling higher critical feed rates. Ramkumar et al. (2004), Arul et al. (2006) and Babitsky et al. (2007) described the positive effect of superimposed ultrasonic vibrations when drilling GFRP laminates. Forces, tool wear and delamination could be reduced.

2.4. Influence of damage on workpiece strength

Drilling itself decreases workpiece strength because fibers are cut. Additional workpiece damage might weaken the material further. Persson et al. (1997) described a fatigue strength loss of 27% for drilled (dagger drill, facetted drill) CFRP specimens compared to specimens which have been machined by circular milling. Langella and Durante (2008) obtain a reduced tensile strength (15–25%) for GFRP specimens machined with twist drills compared to specimens with holes that have been shaped during the composite manufacturing. Srinivasa Rao et al. (2008) present a correlation between the maximum damage diameter and the workpiece's notched tensile strength – a higher degree of damage consequently reducing strength.

2.5. Conclusion to existing work

The common goal of the strategies described before is the reduction of (axially acting) process forces either by means of tool geometry or process strategy. No work has been published this far, that not just tries to reduce, but to actively direct process forces during hole making in a way that causes no critical loadings. The approach however is not new. For edge trimming of composites or in the wood cutting industry tools with opposite helical or angled cutting edges are used to direct resulting machining forces toward the center of the workpiece and thus reduce chipping, spalling and delamination (Dennis, 1991).

The idea behind the process strategies presented in this article is to direct the resulting process forces toward the center of the workpiece at both the entry and the exit side using standard milling tools. Thus, the most critical regions of the workpiece are machined in a way in which the workpiece acts as its own back-up plate. Theoretically these strategies should result in less damage compared to conventional machining. Fig. 2 qualitatively depicts the desirable direction for the resulting process forces (axial component only).

Process strategies which may reduce machining damage offer the potential of better machining qualities and thus higher workpiece strength after machining. On the other hand this potential advantage may be used to extend tool life, as wear usually causes

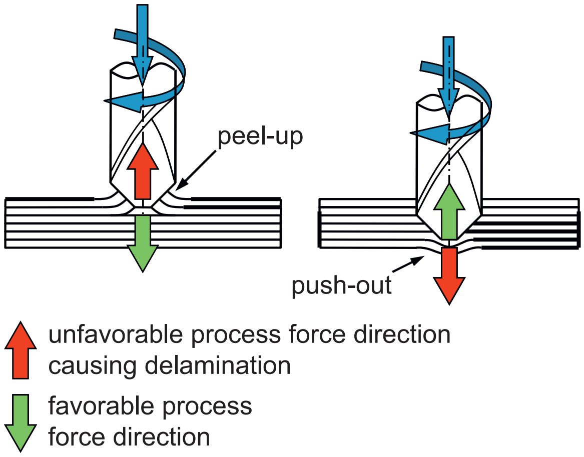

Fig. 2. Schematic of delamination mechanisms (peel-up and push-out) as well as the favorable axial process force direction.

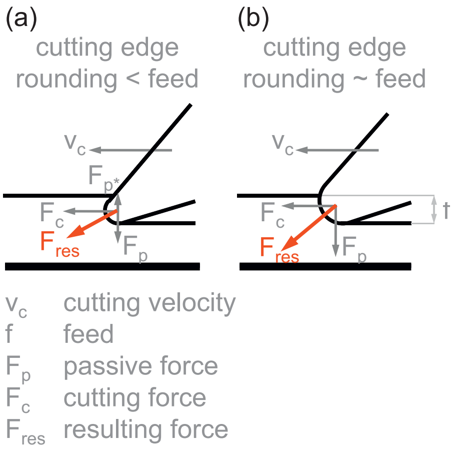

Fig. 3. Influence of the tool's micro-geometry on the resulting process force: cutting edge rounding smaller than feed (a) and cutting edge rounding equal to feed (b).

higher machining forces, which is less critical when they are directed in a way the workpiece can withstand better. Industrial relevance will be given if the increased process complexity can be compensated by the advantages. The focus of this article however lies on the theoretical transfer of the suggested approach on the two described strategies and their subsequent experimental assessment to determine their general feasibility.

3. Damage reduction by directing the process forces toward the center of the workpiece

The basic assumption, which the presented process strategies are based on, is that the generated workpiece damage is a result of only the absolute value and direction of the resulting process force vector together with the respective workpiece strength. In order to minimize resulting damage the acting forces have to be kept below the workpiece's strength. However, since composites are anisotropic material strength is dependent on the direction in which the forces are acting.

Some general points have to be considered: (a) composite parts generally have a small thickness compared to their outer dimensions (sheets). Also, (b) the reinforcement fibers are positioned within the workpiece's plane and (c) can only carry significant loads which are acting in that direction. (d) Force components acting perpendicular to the workpiece's plane have to be absorbed by the rather weak matrix material. Taking into account (a)–(d) it is comprehensible that the most critical conditions are those of forces that are acting perpendicular to the workpiece surface and which are directed outwards and acting on the unsupported outer layers. The composite's strength in this case is not much more than the strength of the matrix material. Unfortunately those critical force components cannot be eliminated completely at the tool's exit side during drilling operations as the tool has to penetrate the workpiece somehow. It is however possible to reduce the negative effect by first penetrating the workpiece with a certain degree of allowable damage and subsequently removing the generated damage by machining the hole in a way that directs process forces inwards, toward the center of the workpiece. The outer layers' resistance toward this load is higher as the workpiece acts as its own back-up and supports the outer layers.

The basic idea of process strategies which allow directing the process forces toward the center of the workpiece at entry and exit of the tool have been described for an uniaxial drilling processes as well as three-axial and five-axial milling processes (Schulze and Becke, 2009). In general the resulting force direction which acts on the workpiece is comprised of the cutting force, the passive force and the feed force. Per definition the cutting force F_c acts in direction of the cutting velocity; for rotating tools consequently tangentially. Accordingly the feed force F_f is acting in direction of the feed velocity. The passive force F_p contains all the force components which are influenced by the tool's micro- and macro-geometry and tend to push the tool away from the workpiece's cut surface. The micro-geometry describes the geometry of the cutting edge itself (e.g. rounding, chamfer); the macro-geometry describes the tools greater geometric characteristics (e.g. number of teeth, spiral angle, cutting edge angles). Fig. 3 depicts schematically the influence of a greater cutting edge rounding (change of the micro-geometry) on the resulting forces. With increasing cutting edge radius the passive force increases, too. Taking into account that cutting edge rounding is one of the major wear effects when machining composites (Faraz et al., 2009) it becomes understandable why for example thrust forces increase when drilling composites with increasing tool wear.

In order to direct process forces in the desired direction it is therefore necessary to define the tool's movement (tool path and feed) with regard to its geometry. Two milling processes which promise advantages regarding decreased workpiece damage are presented in detail and evaluated experimentally in this article: a three-axial combined process consisting of circular and spiral milling and the five-axial milling process of wobble milling.

3.1. *Combined process of circular and spiral milling*

The combined process of circular and spiral milling is comprised of three steps (Fig. 4): (1) a conventional circular milling at the entry-side with the outer diameter equal to the finished hole (d_{hole}), (2) circular milling through the workpiece with $d_{\text{m}} < d_{\text{hole}}$ and (3) spiral- with subsequent circular milling to finish the hole at the exit side ($d_{\text{m}} \rightarrow d_{\text{hole}}$). Key parameters are the tool's cutting edge rounding together with axial feed during the first process step and the tool's spiral angle during the third process step. An axial feed which is smaller than the cutting edge rounding causes a resultant force which is directed down during machining the top layers. During the second step the tool penetrates the workpiece along the helical tool path (circular milling) which may cause a certain degree of damage at the tool's exit. This damage however is removed during the next step. The tool increases its circular diameter along a spiral until the nominal diameter is reached and the hole is finished with a circular movement. By using a fluted end mill the resultant process force is acting up toward the center of the workpiece. This strategy is relatively easy to implement and not much more complex than conventional circular milling.

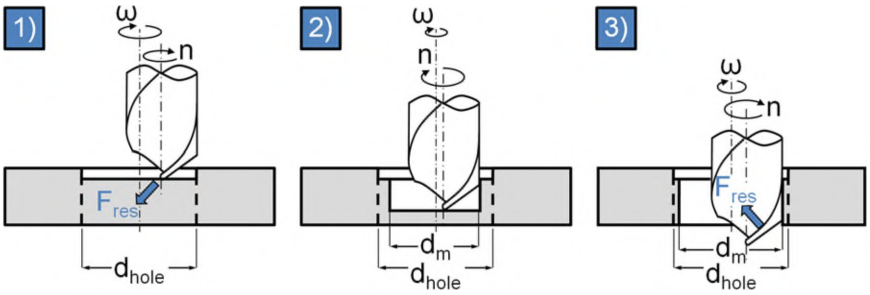

Fig. 4. Process steps and qualitative force direction of the combined circular and spiral milling process.

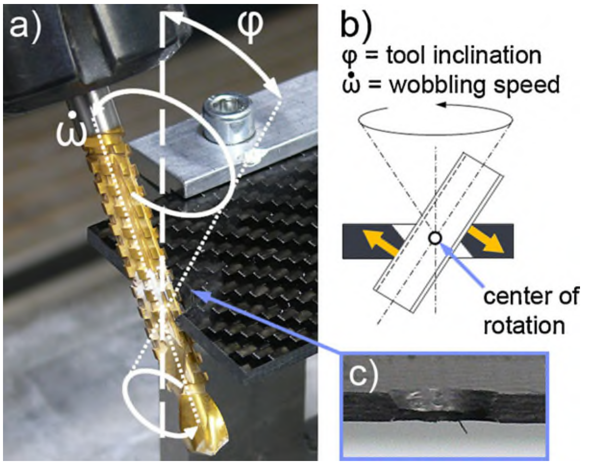

Fig. 5. Basic kinematics of wobble milling (a and b), double cone geometry of the hole after wobble milling (c).

3.2. *Wobble milling*

The process strategy of the five-axial wobble milling is comprised of three steps: (1) the pre-drilling of a starter hole which causes a certain degree of damage, (2) the rotation of the tilted tool (inclination angle φ) around the center of the hole which is the actual wobble milling and (3) the final machining of the uncut material with the vertical tool in a spiral and circular movement. Fig. 5a shows the tool during the second process step. By tilting the tool the resulting process forces (both F_c and F_p) can be directed toward the center of the workpiece. Both of the outer layers of the workpiece are machined at the same time at opposite points. Those are the regions which are most susceptible to damaging. The resulting cross section of the hole has the shape of a double cone (Fig. 5c). It needs to be pointed out, that the speed of the wobble rotation is much smaller than the spindle speed ($\dot{\omega} << \dot{\Omega}$) and the direction of the wobbling is clockwise when looking toward the spindle.

To further specify the amount of process force which may be directed toward the center of the workpiece a simplified calculation based only on the theoretical force direction is presented. The left schematic in Fig. 6 shows the tilted tool in contact with the workpiece. The plane of the cutting edge trajectory for a point at the circumference of the tool is highlighted and the path of the tool inside the workpiece is shown as well. The right part of Fig. 6 depicts the top view on the plane of the cutting edge trajectory and illustrates the changing vectors for the forces F_c and F_p. Introducing the angle Ω for the rotational position of the cutting edge and φ for the inclination angle, it is straight forward to derive correlations (Eqs. (1) and (2)) between the axial (z-direction) force components and the process angles.

$$F_{c,z} = -\sin \Omega \cdot \sin \varphi \qquad (1)$$

$$F_{p,z} = -\cos \Omega \cdot \sin \varphi \qquad (2)$$

The cutting edge enters the workpiece from the bottom and moves upwards until it reaches the top position at $\Omega = 0^\circ$. Taking into account the fact that while the tool rotates the superimposed wobble motion moves it radially, the cutting edge exits the workpiece at approximately that point. Its rotation down from $\Omega = 0^\circ$ to $\Omega = 180^\circ$ (with the respective cutting force vector pointing down as well) occurs outside the workpiece. Fig. 7 shows plots of the cutting force ratios for F_c and F_p which are directed toward the center of the workpiece. The ratios are defined as the respective force component acting in z-direction ($F_{c,z}$ and $F_{p,z}$) divided by the absolute force (F_c and F_p). The passive force ratio increases until it reaches its maximum at the tool's exit, the cutting force ratio decreases constantly until it is zero (parallel to the workpiece plane) at the tool's

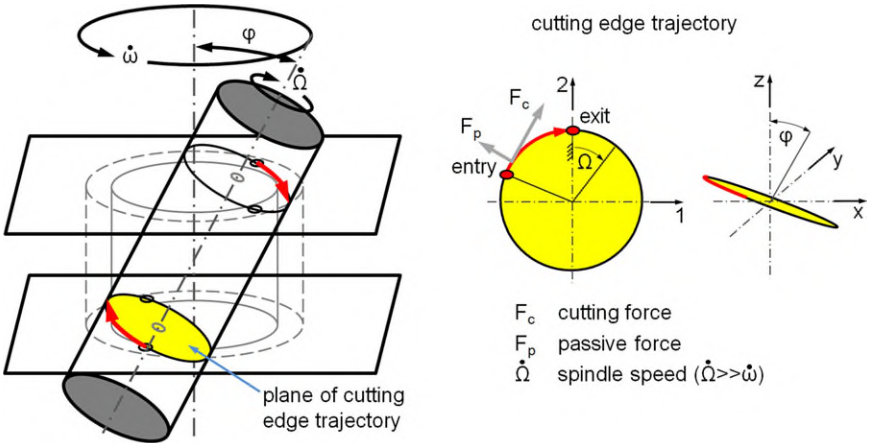

Fig. 6. Schematic of tilted tool and the direction of the process forces F_c and F_p according to the rotational position of the tool.

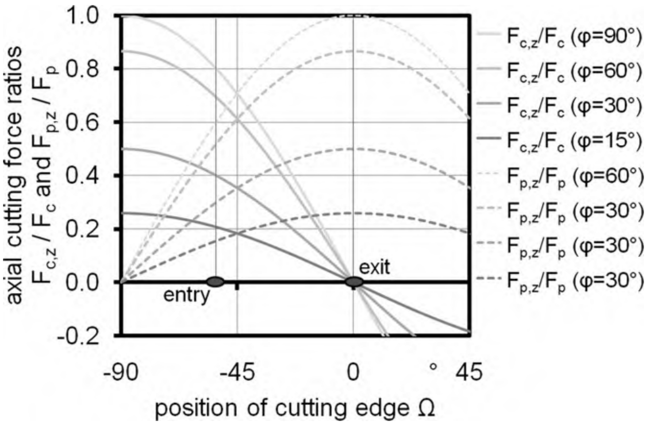

Fig. 7. Axially acting cutting force ratios for cutting force F_c and passive force F_p.

exit. However, both ratios $F_{c,z}/F_c$ and $F_{p,z}/F_p$ are positive during the time the cutting edge is in contact with the workpiece. That leads to a resulting process force that is constantly directed towards the center of the workpiece. The plots further show that the amount of force acting in z-direction increases with the tool's angle of inclination. Hence, machining with a maximal inclined tool is theoretically desirable.

The maximal possible angle of inclination φ_{max} is a function of the geometrical properties tool radius r_t, hole radius r_h and workpiece thickness t (Eq. (3)). It decreases for the machining of thicker plates, smaller holes and with increasing tool diameters. φ_{max} is also the only angle at which both (top and bottom) edges of the hole are machined simultaneously. For any angle smaller than φ_{max} both sides have to be machined separately. The center point of tool rotation (intersection of tool axis and hole axis) has to be moved down to machine the top edge of the hole and down to machine the bottom edge respectively.

$$\varphi_{\max} = \cos^{-1}\left(\frac{r_t}{\sqrt{(t^2/4)+r_h^2}}\right) - \tan^{-1}\left(\frac{t}{2r_h}\right) \quad (3)$$

4. Experimental setup

The two presented strategies have been compared to the reference process of conventional circular milling to evaluate their potential advantages. The resulting damage at the workpiece was assessed after machining. As the focus of the proposed strategies lies on minimizing damage like delamination or spalling, which occur at the outer layers, surface damage is the major criterion to evaluate the differences between the strategies.

4.1. Machining experiments

The machining experiments have been conducted on a three-axial machining center for circular milling and the combined process (Hüller Hille Specht Z 500 T) and a five-axial machining center for wobble milling (Fidia D218). Fig. 8 shows the setup of the three-axial milling processes; the set-up of the five-axial milling is shown in Fig. 5a. Programming of the tool path has been done manually by standard NC-code. The wobble movement which requires multiple axes to interpolate simultaneously can be programmed by simply setting a fixed RTCP (rotation tool center point) and rotating the C-axis. However, the coordinates of the RTCP have to be determined to be exactly the intersection point of the hole center axis and the workpiece center plane.

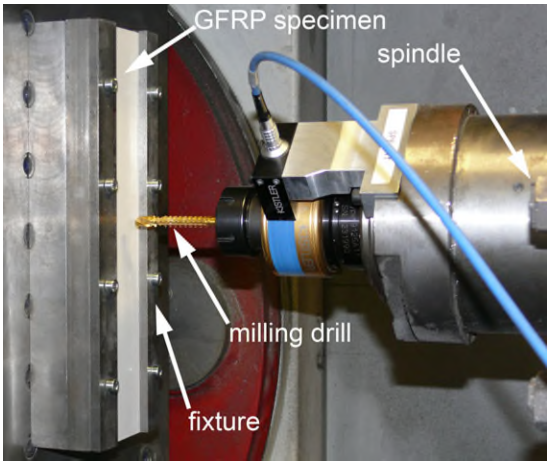

Fig. 8. Experimental setup for the three-axial processes showing the spindle with the tool as well as the clamped specimen.

Table 1
Composition of GFRP (SMC) specimen material.

Resin	Unsaturated polyester
Filler	Chalk
Fiber	Chopped glass Length: approx. 25 mm Diameter: 15 μm 22.3 vol.%

4.1.1. Workpiece material and tools

The material used for the drilling experiments presented in this article was a short glass fiber reinforced plastic obtained through a sheet molding compounding (SMC) process with subsequently pressing the prepregs into plates with dimensions of 400 × 400 mm^2 and a thickness of 3 mm. As typical for SMC processes, the orientation and distribution of the short chopped fibers was random. The plates were cut later into specimens with dimensions of 300 × 50 mm^2 and clamped as shown in Fig. 8 in a fixture to reduce elastic deformations during the machining. The basic material properties are given in Table 1.

4.1.2. Tooling

Two types of high speed steel (HSS) tools were chosen primarily because of their geometry and price: an 8 mm standard three fluted end mill for circular milling and the combined process; an 8 mm milling drill for wobble milling. The end mill's spiral angle was 40°; the milling drill's spiral angle was 0° to eliminate its effect. The front of the milling drill was a standard twist drill which was used for pre-drilling the holes before the wobble milling process step. Since HSS is generally not a good choice to machine composites, the tools were replaced frequently to compensate for the inevitable tool wear after the cutting edge radius had grown approximately 5 μm. To reduce the impact of this effect, the process parameters have been varied in random sequence. Thus tool wear should only increase the variance rather than influence the trends significantly. Table 2 gives an overview of the used tools.

Table 2
Tool properties.

	End mill	Milling drill
Material	HSS-E	HSS (TiN coating)
Diameter	8 mm	8 mm
Spiral angle λ	40°	0°
Cutting edge radius r_β (new)	~15 μm	~18 μm
Cutting edge radius r_β (used)	~20 μm	~25 μm

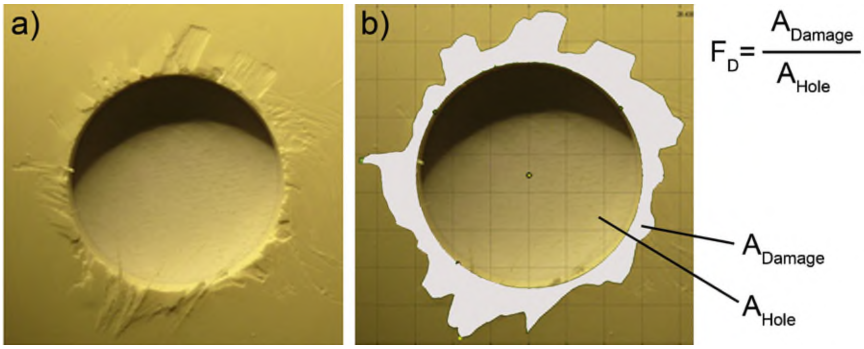

Fig. 9. Exit side damage: original photograph (a) and marked damage area (b).

4.1.3. Process parameters

The range of process parameter used to evaluate the different process strategies is given in Table 3. Beside the cutting velocity, which has been varied in 3 steps, tool feed, depth of cut, and tool inclination angle have been varied. As changing the feed also changed the cutting conditions at the cutting edge, tool feed (tangential) and depth of cut (axial) have been varied in at least 4 steps. Each parameter combination has been used. The maximum inclination angle of 35.67° has been determined for a workpiece thickness of 3 mm, tool diameter of 8 mm and hole diameter of 12 mm according to Eq. (3).

4.2. Damage evaluation

There are different possibilities to evaluate process induced surface damage at the workpiece. Conventional microscopy or high resolution photographs with subsequent image processing may be used to obtain information about the surface damage. According to the proposal of Mohan et al. (2007) and Jin et al. (2008) the total damaged area is measured and divided by the area of the hole to obtain a dimensionless delamination factor F_D. This ratio was chosen over the length ratio (Chen, 1996) of the maximum damage diameter divided by the hole diameter because of the specimens' material characteristics. The damage pattern of the short fiber reinforced polyester tends to be inhomogeneous. The pullout of some fibers from the surface would result in disproportional large damage ratios if only the maximum diameter would be evaluated. Fig. 9 shows pictures of exit side damage before and after the damage has been marked and the area calculated.

The procedure to determine the surface damage included photographing the drill holes perpendicular to the specimen surface using a high-resolution digital camera and a suitable lighting setup. The images were then imported into a programmed MATLAB tool to determine the visible damage manually and calculate its total area automatically. A measure which has been placed on the surface of the specimen has been used to scale the images.

In addition to the surface damage, micro-computer tomography (CT) scans (Yxlon Y.CT Precision) have been obtained to analyze qualitatively the structure of the machined surfaces inside the hole. The measurements have been taken at 70 kV tube voltage with a flat panel detector. A selection of cylindrical samples (hole diameter = 10 mm) has been prepared for the different machining strategies as well as conventional drilling using twist drills. After machining they were scanned using an industrial micro-CT system with an acceleration voltage of 120 kV and a resolution of 12 μm due to the geometric setup. The resulting 3D images have been transformed into a cylindrical coordinate system after the central axis has been determined using further image processing steps (Ibáñez et al., 2005). Accessing the surface condition is accomplished by finding the surface points in radial direction and visualizing them as a surface (Fig. 10).

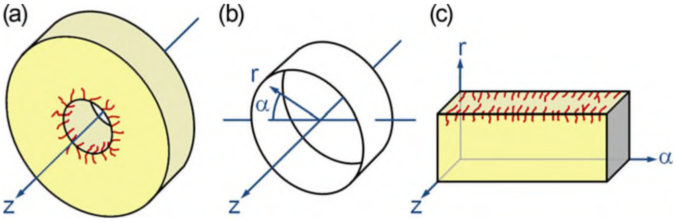

Fig. 10. Image processing steps for 3D CT scans; drilling axis and sample geometry (a), cylindrical coordinate system to scan the hole surface (b) and cylindrical surface plot (c).

5. Experimental results and discussion

5.1. Results of the 3-axial machining processes

To compare the surface damage resulting from the three-axial processes, the delamination factor F_D was analyzed in combination with feed rate f and depth of cut a_p. Fig. 11 shows plots of F_D for circular milling and the combined process vs. the respective feed rates for entry and exit side. The data show a strong variance for the same set of process parameters due to the material's random fiber distribution. However, trends can be recognized and comparison between the process strategies is possible as the difference in F_D is significant. A strong correlation exists between feed rate (Fig. 12a1–a3) and surface damage for both strategies: the degree of damage increasing with higher feed rates. The data shows this trend with regard to the mean values as well as difference between maximum and minimum values, meaning that an increase in feed (and thus machining force) results in a less stable process with a much higher possible damages.

Table 3
Summary of the used machining parameters.

	Cutting velocity v_c (m/min)	Feed f (mm)	Depth of cut a_p (mm)	Inclination angle φ (°)
Circular milling	50–150	0.05–1.00	0.05–1.00	–
Combined process (tool entry)		0.05–1.00	0.03–0.10	–
Combined process (tool exit)		0.05–1.00	–	–
Wobble milling		0.03–0.15	–	0–35.67

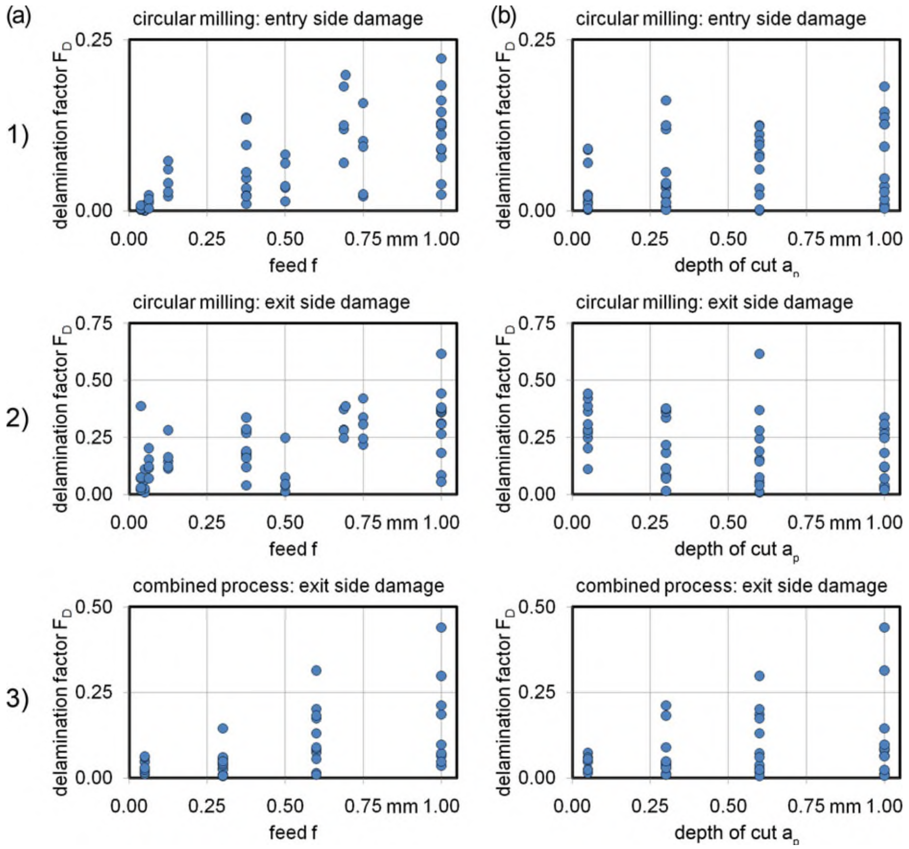

Fig. 11. Data plots showing surface damage vs. tool feed (a1–a3) and depth of cut (b1–b3) for the processes of circular milling (a1, b1, a2, b2) and the combined process (a1, b1, a3, b3).

Regarding the influence of depth of cut a_p, which corresponds to higher axial feed rates, the same trend can be recognized to some extent for entry side damage (both processes, b1) as well as exit side damage of the combined process (b3). However, analyzing exit side damage of conventional circular milling (b2), no damage reduction by small axial feed rates can be recognized. The mean values of F_D even show a slight decrease with increasing depth of cut, which can be explained by the increasing influence of the circumferential cutting edge. The spiraled tool induces forces which are acting opposite to the axial feed direction after the tool tip has penetrated through the workpiece. A correlation between cutting velocity v_c and F_D could not be identified for any process strategy and is thus concluded to be insignificant within the investigated range.

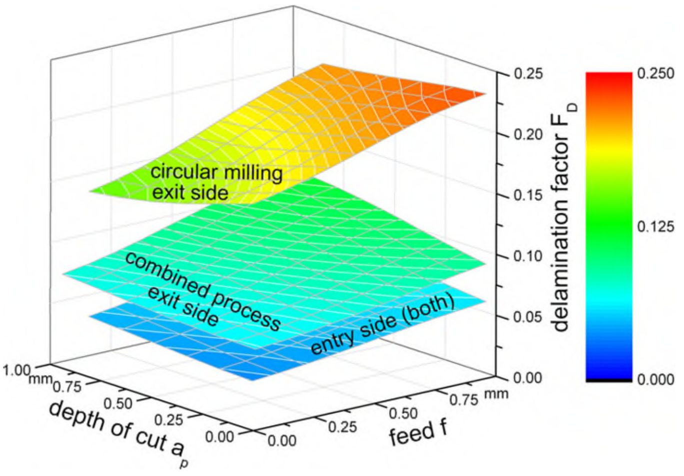

Fig. 12. Comparison of exit side surface damage (weighted mean) of circular milling and the combined process (circular and spiral milling).

A direct strategy comparison is given in the 3D-plot of Fig. 12 in the form of weighted mean for F_D vs. f and a_p. The data shows especially that exit side damage is significantly lower for the combined process strategy as compared to conventional circular milling. Hence, directing process forces toward the center of the workpiece helps reducing process damage when machining composites. Exit side damage of the combined process is still higher than entry side damage. This suggests that damage which is generated when the tool penetrates the exit side are not removed completely by the subsequent spiral milling but propagated by the machining. The fact that F_D increases with feed rate and depth of cut suggests that the degree of penetration damage and the way it is removed influences final hole quality.

5.2. *Results of wobble milling*

Following the results of five-axial wobble milling are presented. The experiments showed that the major influencing factor on surface damage was given by the angle of inclination. No influence could be determined for feed rate and cutting velocity within the investigated ranges. However, it needs to be mentioned that feed velocities were limited by the limits of the machining center's axes. During wobble milling the spindle has to travel on a relatively large circular path (interpolated by *x*- and *y*-axis) and simultaneously rotate the *b*- and *c*-axis to generate the desired tool motion. With increasing angles the length of that circular path increases, which limited the maximum possible feed rate to approximately 0.15 mm at the tool. By plotting F_D over the angle of inclination φ (Fig. 13), the data show decreasing damage with increasing inclination angle and

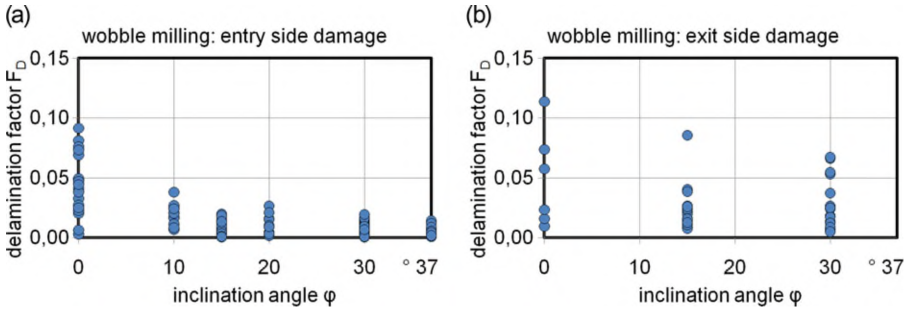

Fig. 13. Data plots showing surface damage vs. tool inclination for the process of wobble milling for the entry side (a) and the exit side (b).

thus increasing ratio of process forces which are directed toward the center of the workpiece.

Comparison of entry and exit side damage in Fig. 14 (weighted mean for F_D vs. f and φ) shows the relatively strong influence φ has, as well as the non-existing influence of f. It also shows higher damage at the exit side which suggests that the damage generated by pre-drilling is not removed completely by the subsequent wobble milling. Otherwise entry and exit side would have to show nearly identical results. However, comparing the absolute values for F_D of wobble milling with the three-axial process strategies, wobble milling shows significantly lower mean damage over the complete investigated range.

5.3. *Qualitative CT-scans*

The 3D-data acquired by micro-CT have been used to compare the machined hole surfaces of the different machining methods to each other. Results are visualized in a cylindrical coordinate system where damage and roughness are reflected in the height profile. Comparison of the profiles of the different methods show considerable damage and roughness in the drilling hole of the spiral drilling process while circular and wobble milling show a relatively smooth surface profile. The image of the spiral drilling process also shows the occurrence of striations. This effect cannot be found in the other machining methods.

Considering the damage introduced at the entry and exit side of the tool, characterization using optical measurements to determine the delamination factor can be supported. Fiber pull-out or spalling of material is predominantly observed at the edges of the drilling hole. The depth characteristics of such effects are furthermore decreased by using the circular or wobble milling strategies. Fig. 15 shows the CT-scans of a hole machined by conventional drilling (a) as well as wobble milling (b).

5.4. *Practicability of the new strategies*

Both presented strategies show promising machining results compared to the reference process of circular milling. The degree of surface damage can be reduced by machining strategies that direct process forces inwards. Also, no negative effect on the quality of the drill hole wall can be recognized. Achievable geometric tolerances are no different to those of circular milling. They are basically only dependent on the used machine tool (static and dynamic stiffness) and its controllers.

Within the field of parameters which has been investigated (and the machine tool used) the drill holes do show the problem of non-circularity at higher feed velocities for both of the three-axial machining processes. These errors were as big as 0.2 mm for a feed velocity of 3000 mm/min due to the used machine tool and the high alternating accelerations of the axes necessary to obtain the helical tool movement. Generally the hole diameter decreases with increasing feed velocities, which however can be compensated. None of the machined holes by wobble milling showed the problem of non-circularity as the necessary accelerations are much smaller than with circular milling.

Both of the new strategies do have a higher process complexity than conventional machining methods such as uniaxial drilling or circular milling. As for the combined process, this increase in complexity is marginal and easily implemented in the CNC-programs. Wobble milling on the other hand needs a significantly higher effort to be implemented. Since it is a five-axial machining process the tool length and its z-position is of crucial importance, which is not

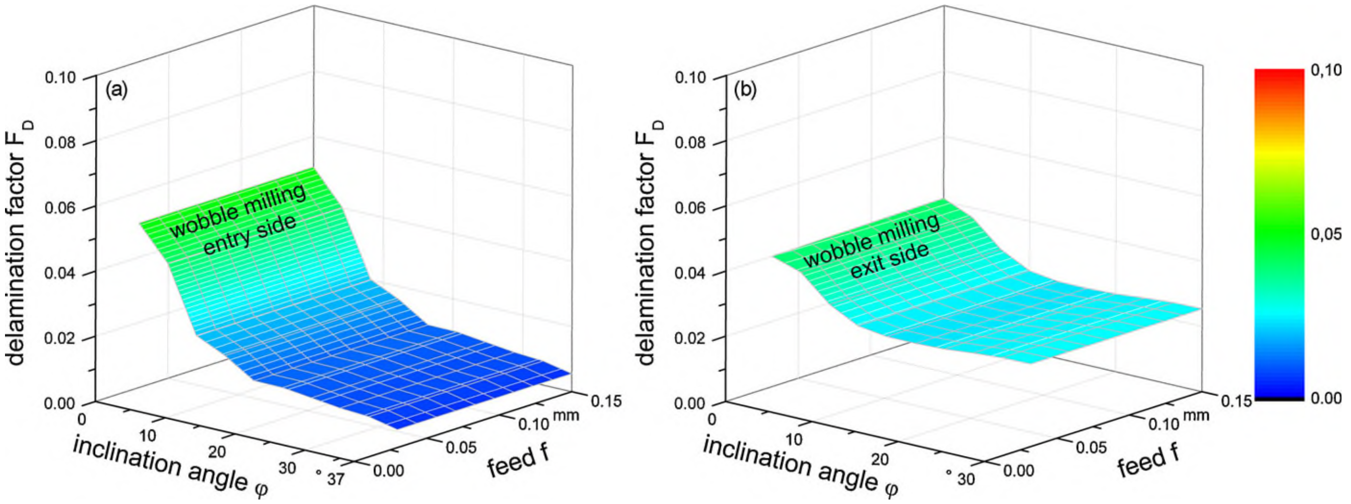

Fig. 14. Comparison of entry side damage (a) and exit side damage (b) (weighted mean) of wobble milling.

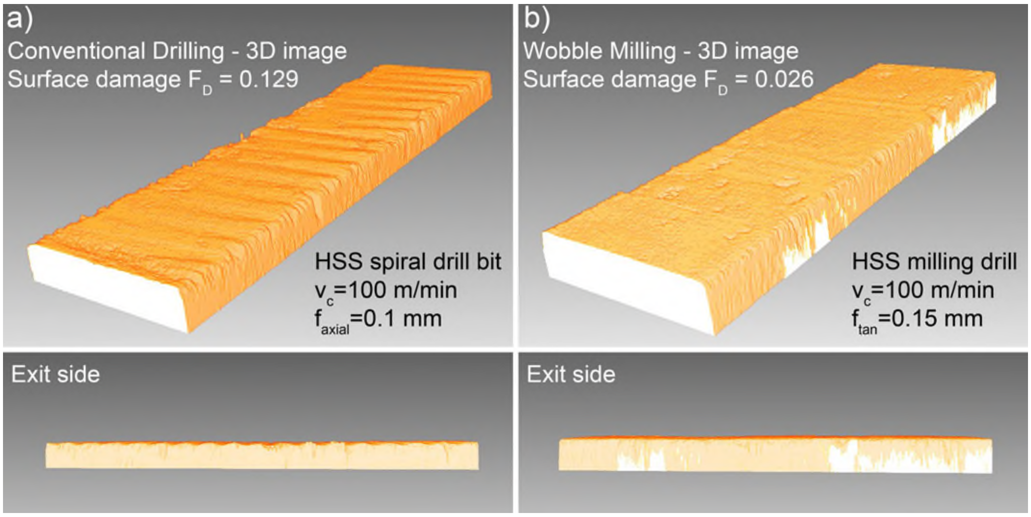

Fig. 15. CT-scans of the drill hole surfaces of a hole machined by conventional drilling (a) as well as wobble milling (b) (unrolling of the machined surfaces).

necessary to the same extend for circular milling or conventional drilling. Also, process times are higher as compared to circular milling when a machine tool is used. Summarizing it can be stated, that the combined process is well applicable as it is. Wobble milling requires some more work in order to be practicable for industrial use – especially with regard to machining time.

6. Conclusion

The presented idea suggests that machining damage in composite drilling might be reduced by directing process forces toward the center of the workpiece. Two machining strategies complying with that idea have been described and evaluated experimentally through machining short glass fiber reinforced polyester. Conventional circular milling was used as a reference process to compare the new strategies to. The following points can be concluded:

- Direct comparison of the combined process (circular and spiral milling) with conventional circular milling shows significantly less exit side damage.
- Implementation of the combined process is very straight forward and not much more complex than conventional circular milling.
- Five-axial wobble milling causes even less damage than the combined process.
- However, implementation of wobble milling is much more complex because it is a five-axial process. Currently it is a viable choice if process time is less important than the difference in surface damage that can be obtained compared to three-axial processes.
- Feed rate has the greatest influence on workpiece damage for the three-axial machining strategies. Higher feed rates generally correspond to greater damage.
- The machining results of wobble milling are mostly influenced by the tool's angle of inclination. Tilting the tool to the maximum possible angle φ_{max} reduces damage the most. Also, entry and exit side can be machined simultaneously only at φ_{max}.
- Qualitative analyzes of the walls of holes machined by the new process strategies show no negative effects. However, the three- and five-axial machining strategies achieve better qualities than conventional drilling.

Summarizing these points the presented strategies clearly show beneficial influence on machining (surface) damage by directing process forces toward the center of the workpiece. However, especially for wobble milling there are points that need to be investigated further:

- The major drawback of wobble milling becomes visible in the relatively low maximum feed rates. Process time is considerably higher compared to circular milling when a machining center is used. Since there is no negative influence of higher feed rates recognizable within the range investigated, it may be worth investigating machining with machine tools or devices which allow for higher feed rates.
- Correlating force vectors (absolute value and direction) with the tool's micro-geometry and the composites anisotropic mechanical strength is the logical next step to derive a model which allows precise prediction of critical machining conditions.
- The effect of the propagation of pre-generated damage through the machining has to be investigated further to allow the derivation of allowable limitations to this kind of damage.

Further research at the wbk Institute of Production Science will focus on these points.

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