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Analysis of machining strategies for fiber reinforced plastics with regard to process force direction

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Abstract

Mechanical machining of composites, especially the machining of holes for bolts or rivets, poses challenges due to the anisotropic material structure. Machining forces may damage the workpiece permanently. Chipping or delamination are severe damages, primarily occurring at the workpiece's surface layers. Prior research has shown that machining induced damages can be significantly reduced by using machining strategies, which aim at directing the resultant process force vectors toward the center of the workpiece. This article presents detailed analyses of two such machining strategies with regard to the process force direction. A combined process of circular and spiral milling as well as five-axial wobble milling is analyzed. The influences of process and workpiece parameters (feed, tool inclination, tool spiral angle, cutting edge radius) on the resultant machining force vector are determined.

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Keywords: Machining, Composite, Cutting edge, Process forces

1. Introduction

The usage of fiber reinforced plastics (FRP) has been steadily increasing over the last decades. Such composite parts are usually manufactured near-net-shape, thus minimizing the need for subsequent machining operations. However, there is still the need of some machining, e.g. for the preparation of holes or defined surfaces for subsequent joining operations.

FRPs are heterogeneous and anisotropic by their very nature. They are designed in a way to carry loads through the workpiece optimally during their use. However, typical workpiece loads during their use can be very different to the loads resulting from mechanical machining. Specifically, drilling or hole making

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in general cause process force components which are acting perpendicular to the workpiece surface and which are directed outwards when the workpiece is penetrated. Such force components are usually acting on the rather weak matrix material when sheet composite parts are machined. The high-strength fibers are typically positioned approximately parallel to the composite parts surface and thus cannot absorb the critical forces. The composite's strength is much lower in this direction. Machining induced damages result if the loads exceed the material's strength.

2. Hole making in composite materials and machining induced damage

Any cutting of a composite's fibers reduces the part's overall strength and is thus to be minimized. Further damage like delamination or chipping is highly unfavorable. It has been shown, that machining induced damages may reduce mechanical material properties significantly [1-3]. Generally, obtaining good quality drill holes with no or little damage is regarded more critical at the tool exit side. Push-out delamination at the exit side resulting from excessive axial feed force has first been described by Hocheng and Dharan [4].

In order to minimize machining damages in hole making there are basically three different possibilities: 1) special drill bit geometries [5-8], 2) milling strategies such as circular milling [1, 9-12] and 3) the use of auxiliary devices such as back-up plates [13]. Special drill bit geometries and milling strategies generally aim at reducing process forces. Back-up plates virtually increase the material's strength at the outer plies. However, accessibility from the distant workpiece side has to be guaranteed.

The extent of drilling induced workpiece damage can usually be well evaluated at the top layers' surfaces. Delamination or local material failure can be assessed by optical microscopy or optical scanning methods with subsequent image processing [14-16]. The degree of the damage can then be calculated by using dimensionless ratios such as maximum damage length / drill hole diameter [13, 17] or damage area / drill hole cross section [16]. Davim et al. propose a combination of both of those ratios to allow for a calculation of an adjusted delamination factor [18] which is less sensitive to different types of material damages, e.g. single fiber pull out vs. complete circular layer delamination.

3. New machining strategies

A feasible approach to reduce machining induced damages when hole making lies in actively directing the resulting process force vectors toward the center of the workpiece when the material's outer layers are machined. The material acts as its own backup plate, thus significantly reducing the negative effect on surface integrity of the composites' machined areas as compared to reference processes. The results of experimental process evaluations and detailed process descriptions of two such machining strategies (combined process of circular and spiral milling, wobble milling) are presented in [19]. Since these two machining strategies are analyzed in detail (see section 5 and 6), a schematic representation (Fig. 1) and a brief description of the separate process steps is given.

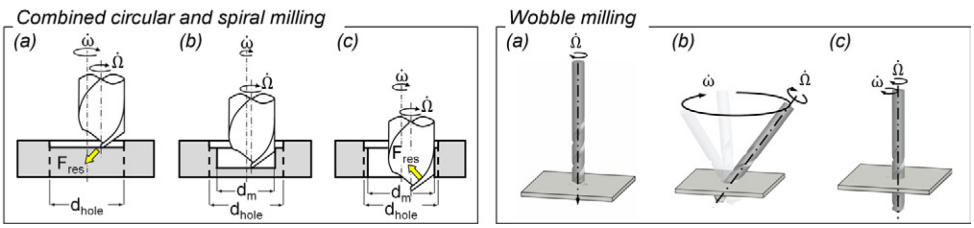

Fig. 1: Schematic representation of the new machining strategies of combined circular and spiral milling and wobble milling

The combined circular and spiral milling process consists of three steps: (a) circular milling of the hole at the top layer with low axial feeds, (b) piercing through the workpiece at a reduced diameter resulting in low tolerable exit side damages and (c) a spiral milling with subsequent circular milling which removes the previous damages completely. The resulting process forces are directed toward the center of the workpiece by the low axial feeds (step a) and the tool's helical pitch (step c).

Wobble milling is also a multi-stage process consisting of (a) pre-drilling with little tolerable damage inside the final drill hole's dimension, (b) the actual process step wobble milling and (c) circular milling without axial feed. The tool has no spiral angle. The resulting process forces are only dependent on the tool orientation during the cut. Wobble milling machines the workpiece's top and bottom layers identically, directing the resulting force vectors always toward the center of the workpiece.

4. Process force models and kinematic simulation

A kinematic simulation tool has been programmed in order to allow detailed process analyses as well as general analyses of the significance of separate process or tool parameters for complex milling operations. The tool follows a mechanistic modeling approach, calculating the resulting process forces at discrete timesteps for discrete sections along the cylindrical tool based on the instantaneous cutting edge engagement conditions. Specifically, the varying cutting thickness at the cutting edge is being used as the decisive process variable, allowing the calculation of the force components by any applicable force model. Multivariate regression models are determined on basis of experimental process force data obtained through a linear cutting process (orthogonal and oblique cutting) [20] for two different composite materials: a short-glass fiber reinforced polyester (SMC process) and a woven (0°/90°) epoxy matrix CFRP. Fiber content was 30 vol.-% for the SMC material and 50 vol.-% for the CFRP. A detailed description of the simulation tool's setup and its basic features is presented in [21].

5. Analysis of combined spiral and circular milling

Process analysis of the combined spiral and circular milling is focused on the last process step (Fig. 1), which machines the final hole edge at the tool exit side. Basic results of the kinematic simulation are presented in Fig. 2: (a) geometry of the undeformed chip, (b) cutting thickness at the cutting edge during one tool revolution and (c) the specific force components which are calculated from the cutting thickness. The plots are generated for a constant set of parameters (cutting edge radius r_β, tool feed $f_{t,r}$…).

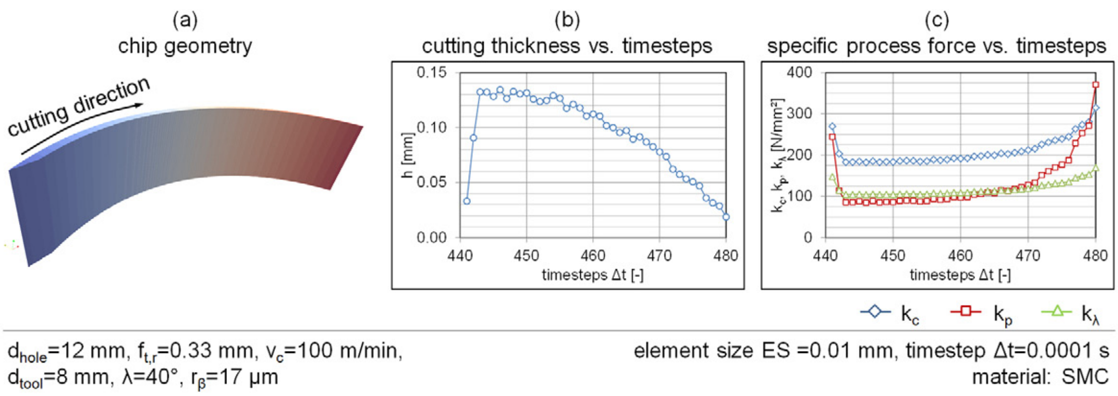

Fig. 2: Results of combined spiral and circular milling: (a) chip geometry, (b) cutting thickness and (c) specific process forces

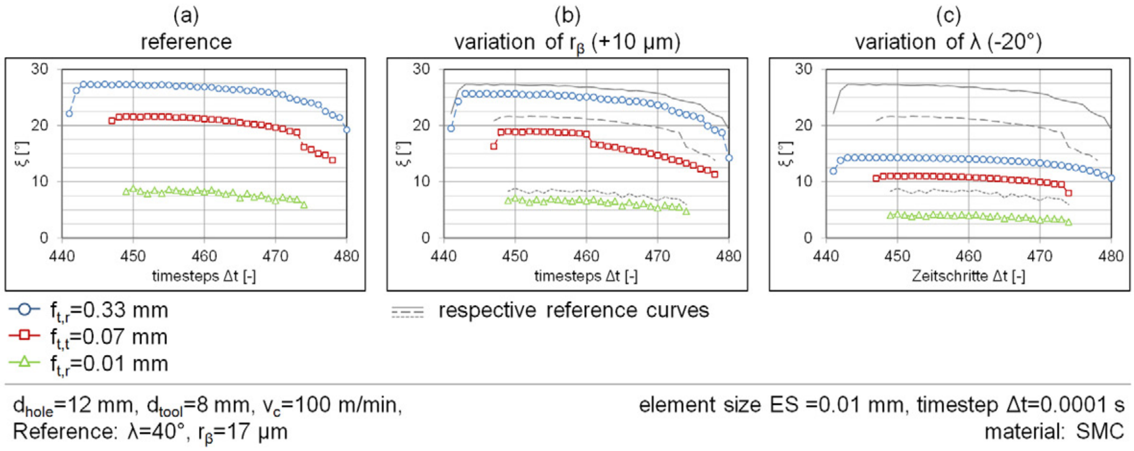

Fig. 3: Results of combined spiral and circular milling, feed variation: (a) reference, (b) additional variation of cutting edge radius r_β (c) additional variation of tool spiral angle λ

Since the direction of the resultant force vector and the degree at which is directed toward the center of the workpiece are especially significant, the effective force angle ξ is calculated from the spatial force components acting on the workpiece. ξ is defined as the angle between the resultant force vector and the workpiece surface; a positive value meaning, that the resultant force vector is directed toward the center of the workpiece at the tool exit side, which is the desirable situation.

The results of variations of the most significant parameters are presented in Fig. 3. The plots show some remarkable results concerning process force direction by use of a helical end mill. First, the feed variation (a) shows clearly, that the effect of the tool's helical pitch diminishes at lower feed rates. Also, an increase of cutting edge radius (increased tool wear) causes the effective force angle ξ to drop (b). Since the geometric cutting edge engagement can basically be described by the ratio of r_β/h, both trends can be explained in the same way. A reduction of the h or an increase of r_β leads to the cutting to take place at the rounded tip of the cutting edge to a greater extent. Thus, the (helical) secondary cutting edges have a decreasing influence on the direction of the overall cutting forces. Finally, a variation of the helical angle (Fig. 3c) leads to a significant change of ξ. Understandably, the less the circumferential cutting edges are pitched, the less they can contribute to an active axial force direction.

6. Analysis of wobble milling

During wobble milling, the process step of milling with an inclined tool while rotating it around a fixed point (wobble milling) has to be focused on during a process analysis. The final hole edge at the top layers is machined with the resultant process forces being directed toward the center of the workpiece. The results which are presented in the following are focused on the effective force angle ξ and the influence of process and tool parameters on it during this very process step. First, however, two aspects need to be mentioned previously, which are necessary to understand the plots given in Fig. 4. Fig. 4a shows the undeformed chip geometry for one tool revolution during wobble milling. The cut begins at the pre-drilled hole wall and continues toward the final hole's diameter. The final hole edge is machined at the end of each respective cut. Also, the chip geometry shows, that cutting thickness and cutting width are changing continuously during the cut. In order to evaluate process force directions during the cut and visualize the results, four discrete Points of Interest (POIs) are defined along the cutting edge (Fig. 4b). The resulting process force directions at each of these POIs are then displayed separately (Fig. 4c-f).

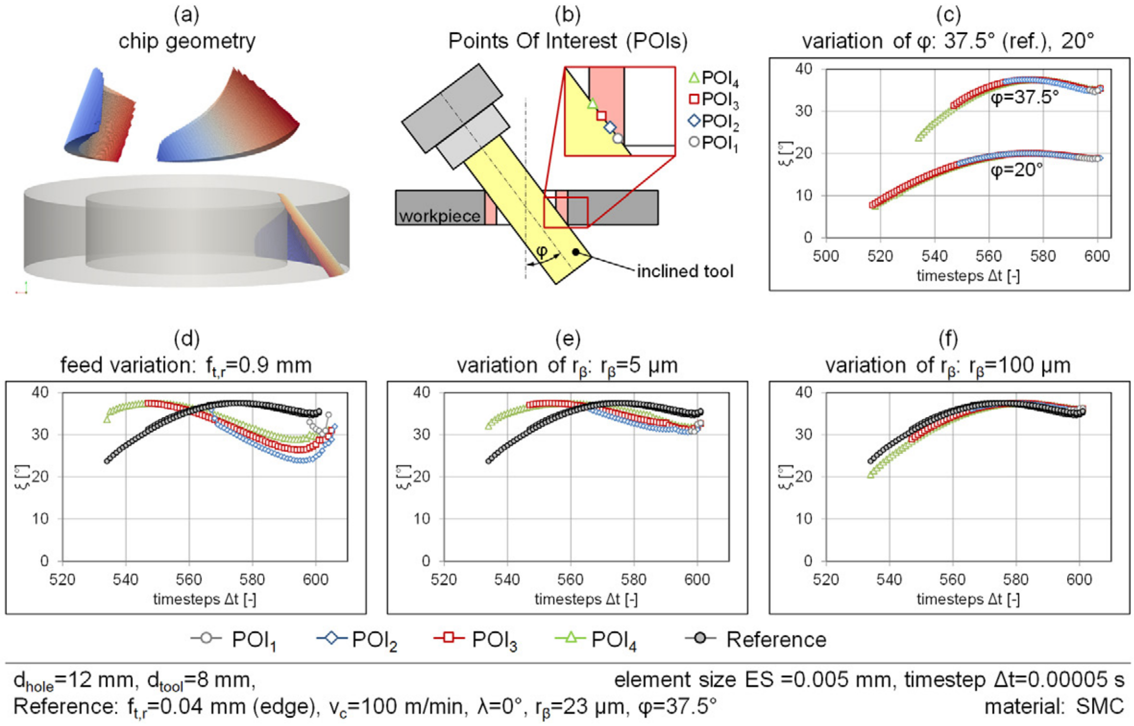

Fig. 4: Results of wobble milling, influence on effective force angle ξ: (a) chip geometry, (b) discrete Points of Interest (POIs) along the cutting edge, (c) variation of tool inclination φ, (d) variation of tool feed $f_{t,r}$, (e) and (f) variation of cutting edge radius r_β

The first of the varied parameters is also the most significant one (Fig. 4c). The tool inclination angle φ determines the theoretical maximum of the angle ξ. Thus, decreasing φ proportionally decreases the degree at which the resulting process forces are directed toward the center of the workpiece. In Fig. 4c it can also be seen, that the angle ξ does not significantly decrease at low cutting thicknesses toward the end of the cut. Due to the tool's orientation and the increasing significance of the passive force at low cutting thicknesses, the curve of ξ vs. time even increases slightly at the end of the cut. A moderate increase of feed rate does not influence process force direction significantly. Fig. 4d thus shows the force direction for a highly exaggerated feed rate. The general trends remain the same. Also, a decrease of cutting edge radius (Fig. 4e) as well as a highly exaggerated increase (Fig. 4f) does only shift and change the ξ-curve slightly. It is remarkable, that wobble milling is not sensitive to tool wear with regard to force direction.

7. Concluding Remarks

Summarizing the presented results, the following points can be concluded:

1. Process force direction (effective force angle ξ) is effectively directed toward the center of the workpiece for both new strategies throughout the complete decisive process steps.
2. Decreasing feed rates per tooth as well as increasing cutting edge radii (tool wear) diminish the effect of a helical cutting edge with regard to directing the resultant process axially.
3. During wobble milling, only the tool inclination angle φ has a significant influence on the angle ξ.
4. Wobble milling is not sensitive to tool wear with regard to process force direction, as an increasing cutting edge radius r_β (tool wear) does not influence the resulting process force direction negatively.

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