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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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ABSTRACT

Mechanical machining of fiber reinforced plastics has been subject to research for many years. Especially drilling with its resulting workpiece damage such as spalling or delamination still is critical. Approaches to reduce damage usually aim at reducing axial thrust forces and thus reduce the damage-causing effects. In this article two milling strategies for hole making with standard tools are presented, which actively direct process forces toward the center of the workpiece when machining the outer layers: a three-axial combined process of circular and spiral milling as well as a five-axial process called wobble milling. Better machining results are expected, as the material may act as its own back-up, thus reducing especially surface damages. Basic considerations and calculations regarding the direction of the theoretical process forces in dependence on the tool movement are given. Machining experiments have been performed on short glass fiber reinforced polyester and the resulting workpiece damage has been evaluated to assess the potential of the new strategies. Additionally some computer tomography scans have been obtained to qualitatively assess the machined surfaces. The experimental results support the presented idea: machining damage can be significantly reduced by machining strategies which direct the process forces inwards as compared to the reference process of circular milling. The results also indicate that the damage decreases with an increasing ratio of process forces which are directed toward the center of the workpiece.

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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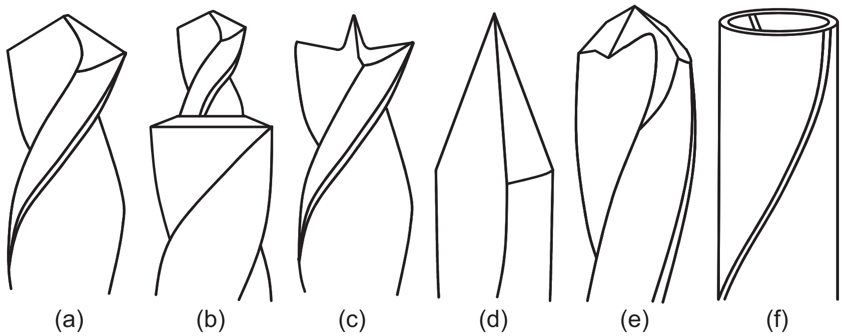

Fig. 1. Schematic of special drill bit geometries used for drilling of fiber reinforced composites: (a) standard twist drill; (b) step drill; (c) candle stick drill; (d) dagger drill; (f) multi-faceted drill; (e) core drill.

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