Drill hole machining of fibre reinforced thermosets using mounted points

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Abstract:
Carbon and glass fibre reinforced polymers are applied to an increasing degree in the major industries, like automotive and aircraft industry. These materials are usually machined using cutting tools. Twist drills for instance are used for inserting drill holes to join components. These tools are subjected to a high wear and rounding of the cutting edge due to the highly abrasive nature of the fibre content. In contrast, the use of diamond mounted points can be a promising option for inserting drill holes. The hollow structure of these tools significantly reduces the amount of material to be removed. Apart from that, diamond tools exhibit a high wear resistance to abrasive wear. The loss of a few individual diamond grains can be compensated by virtue of the high number of active cutting edges, especially by the self-sharpening effect of sintered mounted points. Within this paper, fundamentals of inserting drill holes in fibre reinforced plastics are presented on the basis of relevant process as well as result variables.

Keywords:
Fibre-reinforced plastics, Mounted points, Abrasive tools, Grinding, Drill hole machining

Introduction

Fibre reinforced polymers (FRP) are usually machined using cutting tools. Edge trimming is one of a few process steps where abrasive tools are applied [1]. The fibre orientation usually has a strong influence on the chip formation, the process variables and the values of the surface roughness when machining fibre reinforced polymers [2]. For grinding of thermoset matrix materials, an excess of the degradation temperature has strictly to be avoided [3]. In drilling CFRP, thermal effects are important with regards to diameter deviation [4]. The main quality criteria when drilling FRP are crack formation, damage of the peripheral zone and of the surface layers, the surface roughness and dimensional as well as roundness errors of the hole [5].

Grinding process and process parameters

The following findings are based on grinding experiments using mounted points and a five-percent oil-in-water emulsion at a pressure of $p_c = 20$ bar on a conventional machining centre. The 70 % by vol. carbon fibre-reinforced epoxy resin was machined using sintered as well as electroplated grinding heads. In contrast to the sintered grinding heads, the electroplated tool is characterised by a higher cutting edge depth and thus a lower bond wear.

Within the displayed total drilling length wear of the abrasive grains was not observed, **Fig. 1**. The abrasive parts of the coolant, especially broken off carbon fibres, lead to an increasing setting back of the bronze bond, circles in Fig. 1. Provided that a continuous axial bond wear takes place, with this type of tool a drilling length of more than hundred meters seems possible. The assumption of a low wear at a single diamond grain is backed by the linear run of the feed force and torque values, Fig. 1. A remarkable flattening of the diamond grains would lead to higher normal forces and an increasing number of active cutting edges and thus higher values of the measured process parameters. As expected, the process parameter values using mounted points are higher compared to that of processes using conventional drilling tools.

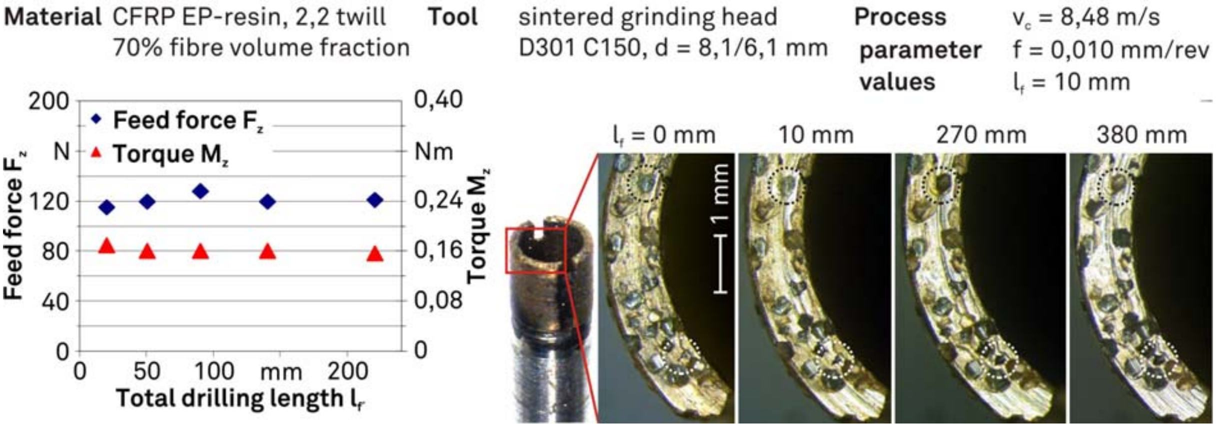


Figure 1: Influence of the total drilling length l_f on process variables and tool bond

Fig. 2 illustrates the influence of the cutting speed v_c and the feed f on the values of the feed force F_f and the torque M_Z. There is a comparatively low influence of the cutting speed on the process values, which is extensively described in the open literature for cutting processes as well [1, 5]. A thermal softening of the matrix material would affect the aforementioned values and can therefore be excluded within the chosen parameter range. For the feed force F_f and torque M_Z a declining run of the values can be noticed with increasing feed f. A reason for that are the changing engagement conditions at the single diamond grain. Furthermore, an increasing feed leads to a higher number of active cutting edges because of the lower kinematic cutting edge spacing. The results are higher values of the axial force and torque as the sum of the single grain's forces. This declining trend of the values is described in the open literature as well especially for glass- and fibre-reinforced composite materials with epoxy matrix, in most cases for cutting processes.

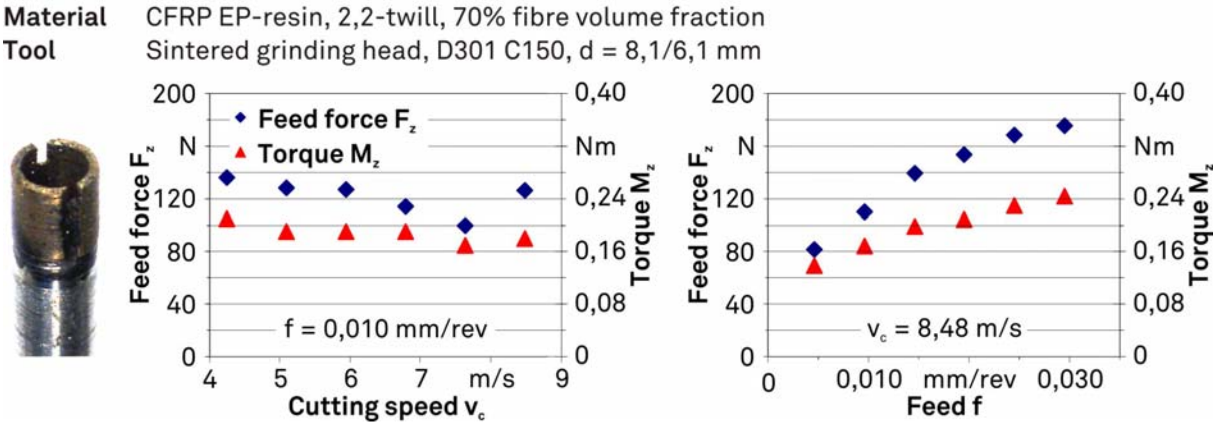
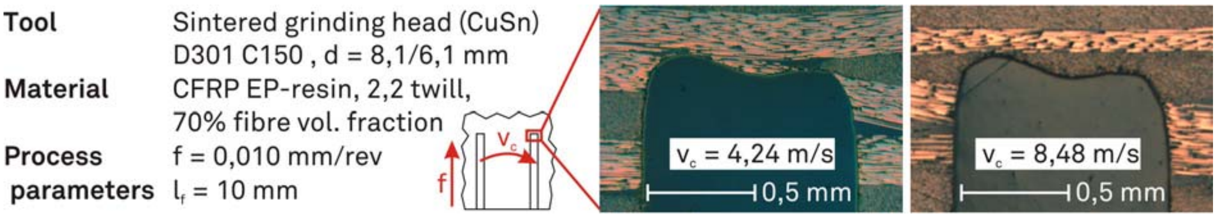


Figure 2: Influence of the process parameters on the process variables

A ring-shaped cavity leading in feed direction can be seen in the micrograph in **Fig. 3**, which is caused by the axial streaming and radial diverted mixture of coolant and abrasive chips. The top layer of the woven fabric will firstly be broken through by this cavity on the exit side of the drill hole. Potential delamination or fibre fractures will be cut by the following tool with a larger diameter, which decreases the material damage at the surface layer. At the same time, high tool loads and with it tool wear can be reduced. This effect seems particularly determined by the coolant pressure as well as the feed.



Tool	Sintered grinding head (CuSn) D301 C150 , d = 8,1/6,1 mm
Material	CFRP EP-resin, 2,2 twill, 70% fibre vol. fraction
Process parameters	f = 0,010 mm/rev l_f = 10 mm

Figure 3: Micrograph of the drill hole's bottom

Workpiece quality

Thermal damage is one of the major problems when drilling CFRP. When using coolant, the compatibility of the chosen coolant and the matrix material has to be ensured. The investigated epoxy resin features a comparatively high resistance against water as well as oil and is therefore suitable for the application of coolant [6]. The pH-value of the used emulsion is pH = 9,0. Thermal and mechanical material damage is analysed with micrographs using a light-optical microscope, **Fig. 4**. The fibres lying perpendicular to the lateral area, upper part of picture 1, are cut without fibre pullout or bending strain induced fibre break. Parallel to the cutting direction, picture 2 in Fig. 4, pullouts of fibre bundles can partly be observed. In most cases this leads to dimensional errors of a few micrometres. On the basis of these micrographs, neither delaminations of the compound nor thermal damage can be noticed. The area of high epoxy content, picture 1 of Fig. 4, can be regarded as thermally critical because of a low heat conductivity of the epoxy resin. In literature, at this fibre orientation largest internal damage was measured [7]. Nevertheless, there is no visual difference to the matrix areas farther to the lateral surface. Thus it can be assumed that the process temperature did not exceed the degradation temperature and could sufficiently be reduced by the internal coolant supply. This can be attributed to the high fibre content and the carbon fibre's high heat conductance. The matrix material is a thermal barrier, so that heat conduction is assumed to primarily proceed in the fibre bundle direction. Furthermore, a significant amount of the thermal energy is conducted to the tool. The diamond grains are characterised by a high heat conductivity. Thus, the thermal energy can be conducted by the bronze bond to the grinding head. The coolant passes the grinding head on the inner and outer surface, resulting to a second way of heat dissipation apart from direct heat dissipation from the cutting zone. In contrast to grinding tools, the contact surface of cutting tools is much smaller, which might lead to higher local temperatures, attended by higher matrix damages. Apart from that, coolant is often avoided in cutting processes.

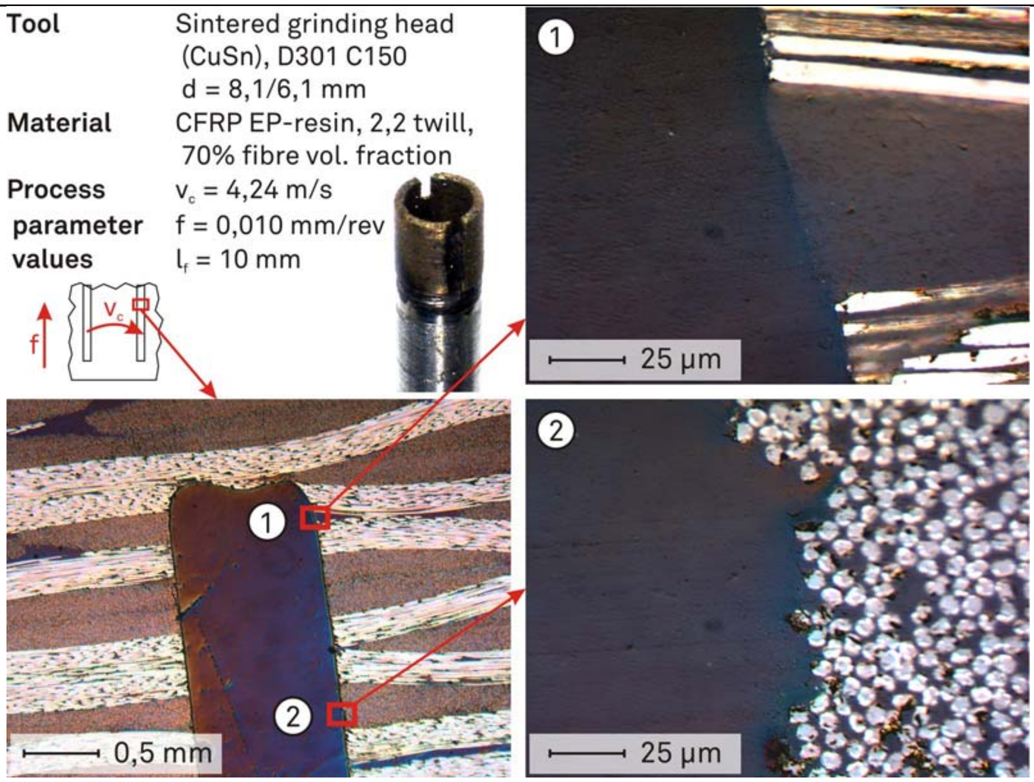


Figure 4: Micrographs of the peripheral zone at different fibre orientations

The surface quality was characterised on the basis of SEM micrographs, **Fig. 5**. Only marginal delaminations or fibre bundle pullouts were detected, so that cohesion of the compound is maintained on the tool entrance as well as on the tool exit. On the exit side of the drill hole fibre cracks can be observed, which are caused by the induced flexural strain of the tool's end face as the tool leaves the workpiece. The single fibres (small arrow in **Fig. 6**) or fibre bundles (larger arrows in Fig. 6) are detached from the matrix and in most cases broken at the next fibres crossing. Because of the cutting edge's highly negative rake angles, an exact cutting of the surface layer's fibres will be a challenging task. Here, a suitable process guidance could be a promising way to minimise the damage of the surface layer.

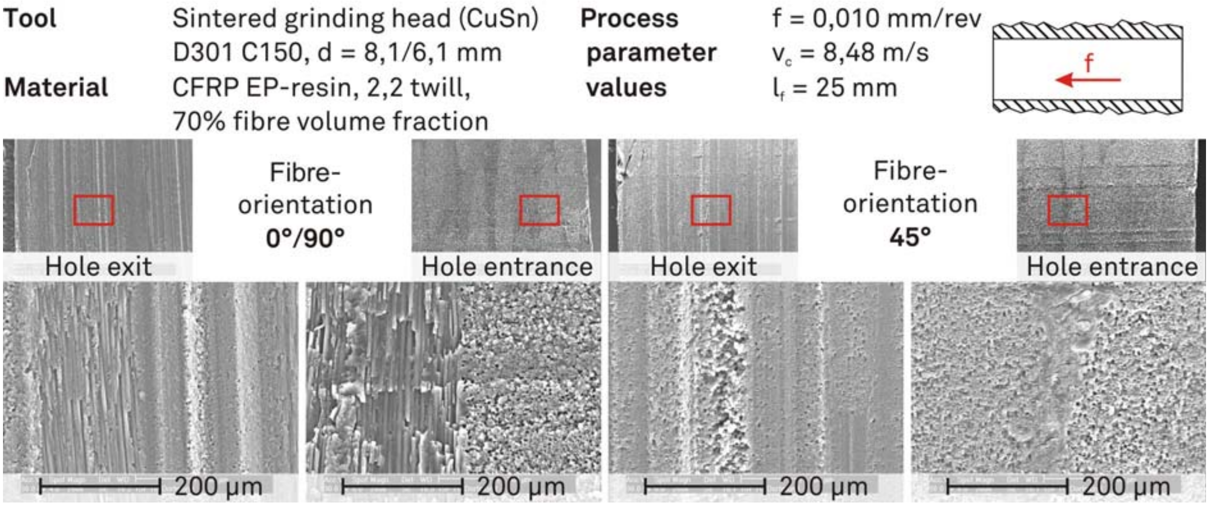


Figure 5: SEM micrographs of lateral surface at different fibre orientations

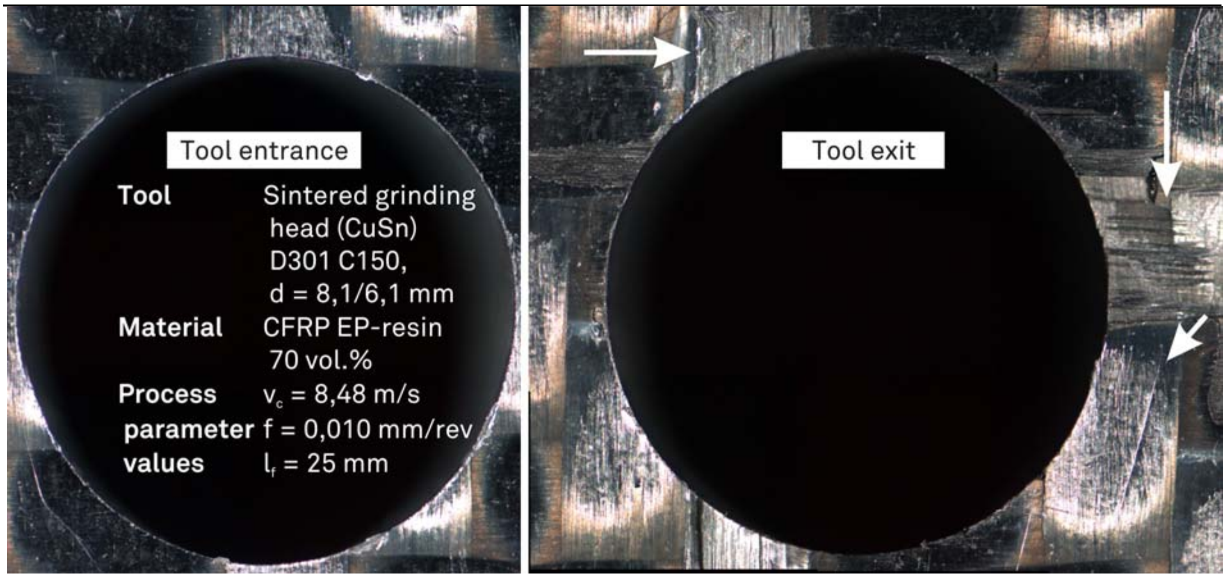


Figure 6: Delaminations of the surface layer

Figure 7 shows values of the arithmetical mean deviation of the roughness profile Ra and the average surface roughness Rz in reference to the drilling length l_f. A dependence of these values on the surface roughness can be noticed, which have been described in many cases in open literature. At a fibre orientation angle of 45° lower roughness values were measured, compared to a fibre orientation parallel or perpendicular to the 2-2 twill fabric orientation. Due to the measured data's standard deviation of less than Ra = 0,14 µm and Rz = 0,85 µm respectively a dependence of these values on the fibre orientation can be assumed. In some cases scanning electron micrographs show delaminations of the last fabric layers at a distance of about 0,2 mm from the hole exit, **Fig. 8**, picture 2. Traces of the brittle-hard chip formation can be noticed in picture 1, which results in a relatively homogeneous surface of the generated hole. Apart from chip formation, the mentioned highly abrasive mixture of coolant and abrasive chips affects the lateral surface, as can be seen in picture 3. When the tool breaks out through the surface layer at the exit side, the coolant is no longer directed along the outer surface of the grinding head and the hole's lateral surface. The effect can clearly be observed in Fig. 8, picture 3. Here, the area is shown in which the joint patch between the grinding head and the steel shaft is located during the tool's exit. In the micrograph's right part, axial running traces of the abrasive influence can be noticed, that is influenced by the coolant pressure and volume flow. The absent shaving effect results in higher values of the surface roughness near the exit side, Fig. 7.

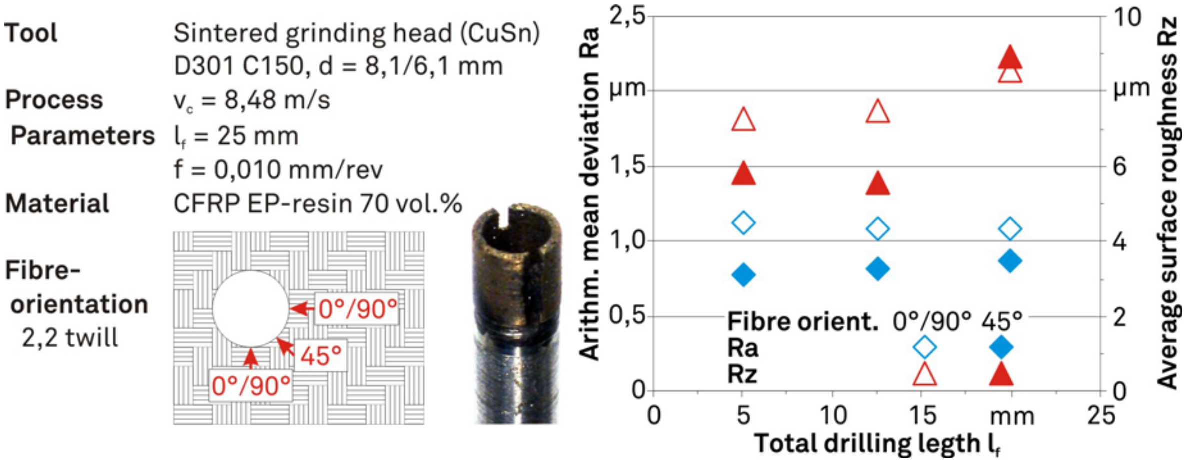
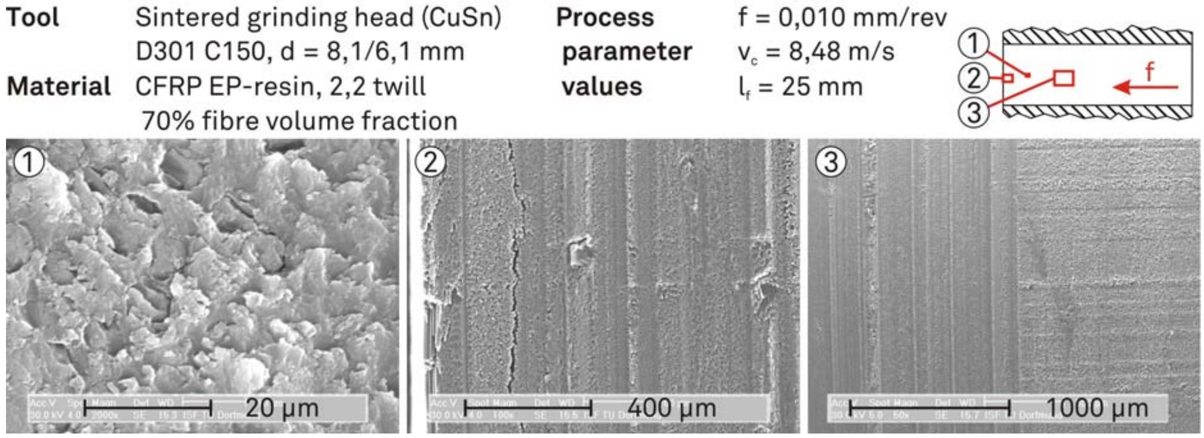


Figure 7: Surface roughness for arithmetical mean deviation Ra and average surface roughness Rz



Tool Sintered grinding head (CuSn) D301 C150, d = 8,1/6,1 mm
Material CFRP EP-resin, 2,2 twill 70% fibre volume fraction
Process parameter values f = 0,010 mm/rev, v_c = 8,48 m/s, l_f = 25 mm

Figure 8: SEM micrographs of the lateral surface

The limits for inserting drill holes in fibre reinforced polymers are primarily determined by the matrix material. Experiments with 30 % by vol. glass fibre-reinforced semi-crystalline thermoplastic (PA66) the tool's chip space of the gets clogged within the first millimetre of drilling length, resulting in high axial forces higher than $F_Z = 250$ N. In general, the existence of glide planes in thermoplastic materials impede the chip formation in grinding processes. Material separation by grinding is particularly convenient for thermoset materials, like the investigated epoxy resin. Inserting drill holes in FRP with thermoplastic matrix materials with a significantly higher fibre content seems to be feasible, because of an earlier chip break.

Conclusion

The given results of drill hole machining demonstrate the general qualification of the grinding process for inserting drill holes in carbon fibre reinforced thermoset plastic. The high abrasive resistance of the diamond grains make large total drilling length achievable. As a result, there is only a minor influence of the cutting speed and a major influence of the feed on the measured process forces. Regarding the workpiece quality, no thermal influence on the matrix material was detected. The mixture of coolant and abrasive chips affects the machining process as well as the generated surface. The fibre orientation is reflected in the surface roughness values of the lateral surface. Avoiding delaminations poses a challenge especially at the exit side. For a comprehensive understanding of the process, an optimal tool design and optimal process guidance as well as the identification of the material-related limits, further research is necessary.

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