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Specific machining forces and resultant force vectors for machining of reinforced plastics

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ABSTRACT

When machining fiber reinforced plastics, the machining forces may induce workpiece damage if they exceed the workpiece's anisotropic strength values. Knowledge of the resultant force vectors is therefore important to allow optimization of tool geometry and machining strategy. This article deals with experimentally obtained machining forces on short glass fiber reinforced polyester. Specific cutting, passive and axial forces have been determined for varied parameters of cutting velocity, cutting depth, cutting edge rounding and tool inclination. Generic multivariate regression models have been calculated, which, implemented in a kinematic simulation, allow calculation of machining forces (and direction) for arbitrary milling operations.

1. Introduction

Fiber reinforced plastics (FRP) are being increasingly used because of their superior specific properties, which makes them a good choice for lightweight construction. Even though the overall goal should be to manufacture FRP-parts without any mechanical machining, there is still a need for many subsequent machining operations. Examples are drill holes for screws or rivets, pocket milling operations or contour machining. However, due to the fact that composite materials are designed anisotropically, there are particular machining challenges. Machining forces are in many cases (e.g. drilling) acting in directions of lower material strength, thus causing permanent damages.

Resulting damages such as delamination, chipping or spalling are defined as permanent and thus critical [1]. Many researchers later correlated the extent of these damages to process parameters like feed and ultimately to the process forces [2,3]. Optimizations usually aim at reducing the forces by means of special tool geometries for drilling and milling [4,5] or adapted machining strategies such as circular milling [6]. Process strategies which are designed to direct resulting process forces toward the center of the workpiece when machining composites showed significant reduction in workpiece damages [7].

Besides special tool (macro-) geometries, the influence of the cutting edge's micro-geometry is an important influencing factor affecting process forces. When machining fiber reinforced plastics, significant changes of the cutting edge occur due to the fiber's highly abrasive nature during the cut. Rounding of the cutting edge is even proposed to be used as wear criterion for composite machining [8]. In consequence of geometry change, machining forces usually increase with increasing tool wear, which favors damages further. The special influence of cutting edge rounding (radius r_β) has lately been investigated by [9] for the machining of a titanium alloy. Cutting forces and feed forces both increased significantly within the investigated range of r_β.

Summarizing previous work, the most important influencing parameters on process forces are shown and compiled in Fig. 1. From this list the parameters of cutting velocity v_c, cutting edge radius r_β, cutting thickness h and tool spiral angle λ have been selected to be varied experimentally in order to evaluate their significance on process forces.

Of course absolute cutting force models are limited in their significance to the investigated and similar workpiece material. However, the direction of the resulting force (F_c/F_p) is an important parameter for the resulting workpiece loading. It also is expected to offer transferability to some extent, as it is highly dependent on the geometric cutting edge engagement conditions, which are investigated in this work.

2. Experimental setup and scope

An unconventional experimental setup has been chosen to obtain the data necessary to derive process force models. A machining center (Heller MC16) has been used as planer by using one of the linear axes to provide a linear cutting motion, thus providing constant cutting conditions for a set of process parameters. Plates of short glass fiber reinforced polyester obtained through a sheet molding compounding process (SMC) have been cut to specimen with a length of 100 mm (thickness 2.5 mm). The chopped glass fibers had a length of approximately 25 mm and a diameter of 15 μm. Fiber content was 22.3 vol%; fiber orientation was random. Since the SMC material does not have a particular fiber orientation which could have been varied experimentally, the material has been considered quasi-homogeneous.

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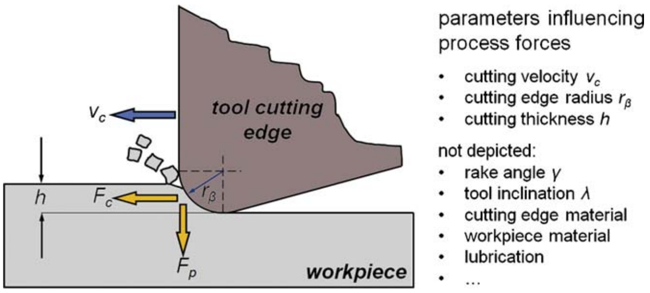

Fig. 1. Schematic presentation of the cutting edge during the cut.

Uncoated cemented carbide cutting inserts (WC/Co, WK08) have been mounted to a stationary spindle-held tool holder (rake angle $\gamma = 0^\circ$, clearance angle $\alpha = 7^\circ$). The setup allowed setting v_c, h and λ (by inclining the tool) directly by the machine center's controls. Additionally, r_β has been varied in five steps. The different radii have been prepared by rotatory drag finishing using an OTEC DF-3. A NanoFocus μSurf has been used to measure the radii following Wyen and Wengener's approach [9] at three different positions along the cutting edge. Cutting has been done without any coolant or lubricant. An overview of the experimentally varied parameters and their range is given in Table 1.

A complete combination of parameters has been used for $\lambda = 0^\circ$ in order to obtain a good data basis. For $\lambda = 20^\circ$ and 40° some less important combinations of parameters have been left out. However, the parameter combination of $r_\beta/h = 1$ has been additionally investigated for each cutting edge radius, as this particular cutting condition was expected to be specifically important.

For each investigated parameter combination forces have been measured in the three spatial axes by using a Kistler 9255B three component dynamometer. As constant cutting conditions have been used, the forces could be immediately related to cutting, passive and transverse force ($\lambda > 0^\circ$). Average values and standard deviations of the forces have been calculated and used for the subsequent derivation of multivariate regression models. The forces have then further been calculated to specific forces (N/mm^2) by dividing them by cutting thickness and specimen thickness. The experimental setup and the measured forces at the cutting edge are shown in Fig. 2.

3. Regression models

The experimentally obtained force measurement data showed a trend, which is commonly known for many years in metal cutting and led to the formulation of the Victor–Kienzle-formula [10]: disproportionate increase of specific cutting forces (k_c) at low cutting thickness. The important role of the cutting edge radius has been added later to the formula by [11] for micro-machining. Both of the models are based on power function approaches, which show the relation of the respective parameters as straight lines in double logarithmic plots. Fig. 3 shows plots of the specific cutting forces k_c vs. cutting thicknesses h for the investigated range of cutting edge radii. Power function regressions for one varying parameter (h) are plotted into the diagram. Their parameters and coefficients of determination are given as well. Besides the good fit

Table 1
Range of the experimentally varied parameters.

Parameter	Units	Range
Cutting velocity v_c	m/min	5, 10, 20, 30, 40
Cutting thickness h	mm	0.005, 0.01, 0.05, 0.1, 0.2, 0.3 (add.: 0.015, 0.035, 0.055, 0.075, 0.095)
Cutting edge radius r_β	μm	15, 35, 55, 75, 95
Tool inclination λ	°	0, 20, 40

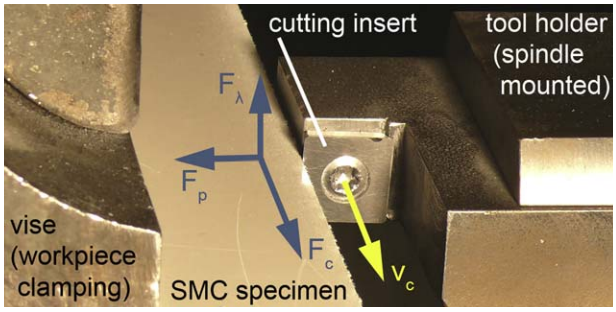

Fig. 2. Experimental setup: clamped SMC specimen, cutting insert during the cut, direction of the measured process forces.

the data show a strong interdependence of k_c to the cutting edge radius r_β.

As univariate models are not well suited to describe the interdependencies between multiple parameters, the approach of multiplying power functions of the separate process variables has been chosen. For the example of k_c this may be written as:

$$k_c = v_c^{m_{vc}} \cdot h^{m_h} \cdot r_\beta^{m_{r\beta}} \cdot \lambda^{m_\lambda} \cdot C \qquad (1)$$

This approach can then be simplified to a linear problem by logarithmizing both sides of the equation, which enables multi-variate linear regression to determine the model constants. Combining this equation with the experimentally obtained data a linear system of equations can be derived, which is then used to determine the model constants by the method of least squares. Comparing the process models with the experimental data, a non-linear deviation is evident (see Fig. 4a). This deviation exists for all the calculated models of k_c, k_p and k_c/k_p. Within the investigated range the compliance of regression and experimental data is only as good as ±50%. This relatively large error has to be addressed further and compensated as good as possible.

Taking into account the assumption that the cutting conditions at the cutting edge are very different for small cutting thicknesses ($h < r_\beta$) as opposed to larger cutting thicknesses ($h > r_\beta$), it is proposed to divide the model for the respective two cases. Following this proposal two separate multivariate regressions are performed using only the particular set of experimental data ($h < r_\beta$ and $h > r_\beta$). Data obtained at the ratio of $h = r_\beta$ are being used for both models, thus reducing the inevitable discontinuities at the intersection. The combination shows a much better fit to the experimental data (±20%) and is thus preferable (Fig. 4b). The same is true for the models of specific passive force k_p and force direction, represented by the ratio of k_c/k_p. A list of the model parameters and respective coefficient of determination R^2 for the separate regression models is given in Table 2, completing the general formula:

$$y(v_c, h, r_\beta, \lambda) = v_c^{m_{vc}} \cdot h^{m_h} \cdot r_\beta^{m_{r\beta}} \cdot \lambda^{m_\lambda} \cdot C$$
$$y = \{k_c, k_p, k_c/k_p\} \qquad (2)$$

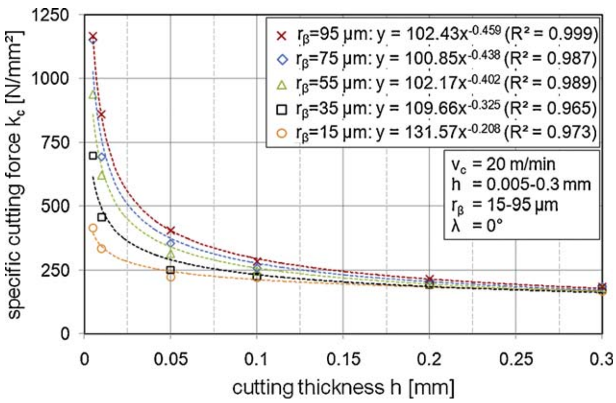

Fig. 3. Specific cutting forces (k_c) vs. cutting thickness (h): experimental data and power function regressions.