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PROJECT REPORT

Experimental investigation of chip removal mechanisms in the drilling of carbon fibre reinforced polymer (CFRP) composites

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The results are presented and discussed in details in published papers [R1-R16]

1 Report on the critical review activities related to the project

A review of published experiences of crucial international researchers and research institutes on the chip removal of fibrous composites has been done within the framework of the present project. We have built a solid collaborative scientific relationship with the researchers of the Shanghai Jiao Tong University (China), the Technical University of Hamburg (Germany), and the University of Aveiro (Portugal). Five review papers [R1-R5] have been jointly published, mainly with the above-listed participants, led by the principal investigator of this project, Dr Norbert Geier.

Burr is one of the main macro-geometrical types of damage concerning machined features of carbon fibre-reinforced polymer (CFRP) composites. Even if it does usually not weaken the strength of composite materials, it is recommended to be removed. In both industry and academia, digital processing of optically captured images is the most common evaluation method for burr-characterisation. Nevertheless, there is no agreement on the measures and techniques of burr-evaluation in CFRPs. Recent key papers on burr formation, measurement and evaluation in CFRPs were reviewed by Poór et al. [R1] (Poór is the PhD student of Dr Norbert Geier) in an attempt to standardise and classify burr characterisation-related expertise. Burr formation mechanisms, burr measurement methods and burr parameters were critically reviewed, compared and discussed. The main advantages and disadvantages of burr measures were highlighted, and their possible future applications and prospects were also considered. Furthermore, burr measures reviewed were compared and discussed based on an experimental data set.

Considering that recent trends in miniaturisation and high-strength fibrous composites encourage the use of mechanical micro-drilling technology of fibre-reinforced polymer composites (FRPs), a review of micro-drilling is carried out by Balázs et al. [R2]. Although severe expertise has been gained through the past few decades on the machinability of FRPs, this information cannot be directly adapted to micro-drilling, mainly due to the size effect. Therefore, the challenges, recent experience, and future aspects of mechanical micro-drilling of glass and carbon fibre-reinforced polymer (GFRP, CFRP) composites were partly reviewed.

A short review of the difficulties, challenges and expectations of CFRP drilling has been conducted and published in [R3]. Furthermore, a review on drilling-induced delamination [R4] and on burrs [R5] has been conducted and published in a Hungarian journal.

2 Report on the development of experimental setup and methods

DoE: The mechanical machining experiments were designed by the design of experiments (DoE) methods (*i.e.* CCC, CCI, CCF, full factorial), required to achieve O1, O2, O3, and O4 goals. The factors, factor spaces, factor levels, optimisation parameters were set, and the experimental design matrices were created. The experimental instructions, risk analysis and emergency protocols were created.

Workpieces: The CFRP workpieces and their production was designed. They were then manufactured in the Composites Laboratory of the Department of Polymer Engineering, BME, by (i) silicon mould casting and (ii) compression moulding technology, and prepared for the machining experiments (they were cut by a diamond coated disk). A novel approach has been developed to minimise the machining-induced relatively large loads (acting on the spindle head of the machine tool), *i.e.* only one layer of carbon fibre reinforcement was embedded in 5-10 mm thick epoxy resin. The aging of epoxy workpieces was conducted in a natural environment (in a garden in Várgesztes, Hungary) for one year. A special fixture was designed and installed to position the workpieces to provide an identical aging environment. The epoxy workpieces were rotated in every one month. The key mechanical properties (from the point of view machining) of the original and aged epoxies have been measured and found that the deterioration of mechanical properties of the aged epoxy specimens is significant. A nominal tensile strength of 55.03±6.41 MPa and 14.15±3.66 MPa; and a specific impact strength (Charpy) of 6364±801 J/m^2 and 1843±350 J/m^2 was measured for the original and aged epoxies, respectively. These values were calculated through five measurements each. The Shore D hardness of the epoxies were also measured; however, no significant difference was found (84.38±1.58 vs. 84.76±1.93).

Fixtures: The R&D work and manufacturing of a special cutting tool holder that can orthogonally cut CFRPs in a 3D CNC machining tool environment indirectly, has been conducted. The special fixture for orthogonal cutting experiments (compatible with the KISTLER dynamometer) was designed, manufactured, and tested in a real manufacturing environment. These fixtures with the corresponding orthogonal cutting technology are under patenting (high-strength composites may induce relatively large cutting forces, putting on large loads on the bearings of the machine tool head).

CNC programs: The parametric CNC programs for machining experiments have been developed, programmed and tested. Safety instructions and issues has been included into the program to minimise the probability of increased machine tool damage.

The experimental setups are presented in detail in [R6-R16] publications, including applied materials and methods, experimental design tables and experimental environments.

3 Report on the fibre orientation analysis in CFRPs

The influence of fibre orientation has been investigated through orthogonal machining experiments, drilling and milling. Although the observation that the influence of the secondary fibre cutting angle (K_r) is not significant neither on the cutting force nor the chip removal, the primary fibre cutting angle (θ) has a significant influence on chip removal, burr formation and cutting force.

CFRP drilling and milling (as the mechanisms here can be associated with the mechanism to the orthogonal cutting's) experiments were conducted to analyse the influence of fibre orientation angle, feed and cutting speed on the cutting force, surface roughness and machining-induced burrs. The experiments were conducted on a Kondia B640 machining centre equipped by a Nilfisk industrial vacuum cleaner. The experimental results show that the fibre orientation has a significant effect on each response value. These effects have been modelled through response surface methodology (RSM). The models have a good agreement with the measurements. These results have been published in [R6, R9, R10, R14] publications.

Orthogonal cutting experiments were conducted in newly developed CFRP composite specimens. The novel CFRP structure's behaviour is the same as conventional UD-CFRP composites, but its orthogonal machining requires less force, thus it has a beneficial effect on the bearings of the machine tool spindle. This novel CFRP has only one layer of unidirectional reinforcement, therefore require less energy to be cut. The experiments were conducted on a Kondia B640 machining centre equipped by a Nilfisk industrial vacuum cleaner. The fibre cutting angle was varied between 0-180° using a variation interval of 45°. The cutting force was measured by a KISTLER 9257B dynamometer and processed by a Labview program. The cutting force was filtered by the moving average method to filter noise having high frequencies and low amplitudes. The interval of the moving average was iteratively determined. A second-degree polynomial model ($F_c(\theta) = 0.0064\,\theta^2 + 0.4128\,\theta + 46.463$) was fitted ($R^2$=0.9963) to the filtered force values which is adequately can predict cutting force for each fibre cutting angle. Therefore, by using the superposition principle, the cutting force of drilling can be predicted by the equation presented below.

$$F_c = \left(F_{c,o,C} - \left[(B_C - t)\frac{F_{c,o,E}}{B_E}\right]\right)\frac{d}{2tg(\frac{\sigma}{2})t} z \frac{f}{a}$$

Where the notations are as follows:

F_c	(N)	maximum of the main cutting force during drilling UD-CFRP
$F_{c,o,C}$	(N)	maximum of the main cutting force during orthogonal cutting of UD-CFRP
$F_{c,o,E}$	(N)	maximum of the main cutting force during orthogonal cutting of epoxy
B_E	(mm)	thickness of the epoxy workpiece
B_C	(mm)	thickness of the CFRP workpiece
t	(mm)	thickness of one layer of carbon fibre reinforcement
d	(mm)	diameter of the twist drill
σ	(rad)	point angle of the twist drill
z	(1)	number of the edges of the twist drill
f	(mm)	feed of the drilling
a	(mm)	depth of cut (uncut chip thickness) during orthogonal cutting CFRP

4 Report on the analysis of cutting tools in CFRPs

Machining experiments were conducted using coated and uncoated cutting tools with great variety of geometrical properties and the effect of tool geometry was evaluated. Drilling experiments were conducted by a fishtail drill and a brad & spur drill in CFRPs and found that the hole drilling-induced burr is significantly less if the fishtail drill was used [R9]. The possible reason is that these drills do not have chisel edge; therefore, the negative ploughing effect of the chisel edge is not acting on the composite layers. This is confirmed by another studies [R10, R14], where the same cutting tools were applied and recycled CFRPs were machined. In addition to the burr investigations, the cutting force indicated by these two cutting tools were analysed through RSM and ANOVA techniques. The results show that tool type has the most significant influence on the thrust force, followed by feed and recycled/virgin status. The fishtail twist drill required significantly less thrust force than the brad and spur drill. Furthermore, the thrust force is slightly higher (8%) in rCFRPs than in virgin CFRP composites. The two-way interaction between the tool and feed was found significant; therefore, we recommend optimising the drilling process in recycled CFRPs by the proper setting of feed using a solid carbide drill having “cut first and push second” effect without a chisel edge.

A conventional one-fluted and a honeycomb end mill was analysed in the drilling of GFRP composites [R11] and found that the sharper the cutting edge radius, the better the chip removal is, i.e. the crushing dominates the cutting mechanism instead of bending or delamination. If the crushing is dominating, the fibre reinforcements are not bent, *i.e.* they are mechanically supported against buckling. This will result in less machining-induced burrs and delamination.

A TiAlN coated carbide twist drill (TIVOLY 3XD-D10100B47) was applied for drilling tests in flat and curved CFRP composites [R8]. The drilling-induced burr was found to be significantly influenced by the radius of the CFRP specimen. Compared to previous results obtained by uncoated drilling tools, the burr formation and probability of burr formation was not found significantly different.

5 Report on the fibre length analysis in CFRPs

The effect of the length of reinforcing carbon fibres was determined through drilling experiments in CFRPs with different reinforcement structures (*i.e.* milled fibre, chopped rovings and nonwoven mat). A total of 180 drilling experiments were carried out using uncoated solid carbide cutting tools. Six different CFRP composites (recycled and virgin with different reinforcement structures) were tested at different feeds (0.15; 0.25; 0.35 mm/rot.). The burr characteristics (burr factor and contour burr factor) and microstructure were analysed by optical (Dino-Lite AM413TL) and scanning electron microscopy (JEOL JSM 6380LA). The analysis of variance (ANOVA) was used to determine whether a factor and/or interaction term has a significant influence on the response values or not.

The results prove that the smaller the length of fibres, the better the mechanical supporting circumstance of the fibre reinforcements (mainly due to the better impregnation quality); therefore, the smaller the possibility of machining-induced burr and delamination formation is. The ANOVA result prove that the cutting tool has the most significant influence (F-value=20.01; P-value=0.000) on the burr factor, followed by the material type (F-value=18.73; P-value=0.000). Significant fibre pull-outs, voids and non-homogeneous impregnation were observed through scanning electron microscopy in chopped carbon fibre–reinforced composites, which might have caused the significant burr. More fibre pull-outs were observed in virgin chopped CFRP than in recycled CFRP. Furthermore, pull-out was not significant in the case of the nonwoven mat CFRP, and the quality of adhesion was acceptable; only significant matrix smearing was observed with each fibre cutting angle. These results are discussed in detail in [R14] publication.

6 Report on the degradation degree analysis in the matrix of CFRPs

The machinability of freshly manufactured and aged pure thermosetting epoxy resins (*i.e.* matrix material of typical CFRP applications) were analysed, because the polymer is expected to be degraded during the project period not the carbon fibre reinforcement. As it was shown in **Section 2**, the naturally aged epoxy specimens degraded successfully in the selected environment and period. The machinability of these degraded epoxy specimens and "freshly" manufactured epoxy specimens were tested at various conditions on the Kondia B640 machine tool of the Department of Manufacturing Science and Engineering, BME. The uncut chip thickness (*i.e.* feed in the case of drilling) and the cutting speed was varied between 0.1-0.2 mm and 10 000-20 000 mm/min, respectively. The experiments were conducted in a dry condition, without the application of any coolants. The cutting force was measured by a KISTLER 9257B dynamometer, the surface roughness was tested by a Mitutoyo SJ400 surface tester and a Keyence VR-5000 3D profilometer. The analysis of variance (ANOVA) was used to determine whether a factor and/or interaction term has a significant influence on the response values or not.

The ANOVA results show that the degradation has the most significant influence (P-value= 5.85; P-value=0.028) on the specific cutting force (k_c - N/mm^2), followed by the cutting speed (P-value= 5.68; P-value=0.030). The specific cutting force was found significantly smaller in the case of the aged epoxy specimens, than that of newly manufactured ones. It was also found that the larger the cutting speed, the smaller the specific cutting force. In addition, none of the influences of the interaction terms was to be found significant.

The ANOVA results show that the uncut chip thickness has the only significant influence (P-value= 272.74; P-value=0.000) on the average surface roughness (*Ra*) and roughness depth (*Rz*) parameters. Although the influence of the degradation was found to be not significance at the significance level of 0.05, it is considered to be significant at the significant level of 0.1. The experimental results suggest that larger the *Ra* and *Rz*, if the epoxy is aged. Therefore, more investigations are needed in the future to explain the influence of polymer degradation on the surface quality of machined epoxy resins.

In summary, the machining experimental results prove that the degraded polymer requires less energy for chip removal; however, the surface quality seems to be worse.

7 Summary

The chip removal, cutting energetics, burr formation and microgeometry of machined surfaces in CFRP composites were investigated through various machining experiments (orthogonal cutting, drilling and milling) and cutting tools. Predictive models were developed by response surface methodology and polynomial regression to predict and optimise machining processes of CFRP composites. The experiences gained through this experimental work is published in 8 journal papers in Q1 ranked journals, 4 journal papers in a peer-reviewed Hungarian journal, and four conference papers in conference proceedings [R1-R16]. The main and sub-goals of the OTKA PD20 134430 project is reached and a significant progress has been achieved in the field of *composite machining science* [R1-R16].

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