Tool wear monitoring and hole surface quality during CFRP drilling

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Abstract

The present investigation focuses on the evaluation of tool wear and surface integrity in the context of CFRP cutting. Series of drilling experiments were performed on CFRP plates using cemented carbide solid drills with the aim to investigate correlations between tool damage, cutting forces, temperature and hole surface quality. In particular, a new methodology has been developed to measure the drilling temperature and to assess the quality of the hole surfaces where occurred uncut fibers. As the surface roughness criterion is not relevant for such work materials, a discussion on the definition of the surface topography is proposed for CFRP work material.

Keywords: Drilling; Composite; Wear; Forces; Temperature;

1. Introduction

Drilling is one of the most important operations in the aerospace structures manufacturing because tens of thousands of holes are made. But, due to its abrasive behavior, the composite material is causing fast tool wear resulting in damages of the hole surface, thus initiation cracks appear leading to higher costs of maintenance. For this main reason, this paper deals with those tool wear aspects during CFRP machining.

2. State of the art

There are standards defining the conventional tool wear criteria but they do not define the edge sharpness evolution, therefore various measurement methods and different criteria are found in the literature. Faraz et al. [1] have introduced a new criterion named the cutting edge rounding (CER) especially used because the wear is a smoothly distribution along the entire cutting edge of carbide tools in drilling CFRP. Park et al. [2] and Denkena et al. [3] have also used a similar method by introducing a coefficient K defined by a $S\gamma$ /$S\alpha$ ratio as shown on Fig. 1.

According to Rawat and Attia [4], other wear patterns like chipping occur on the flank and rake faces because a sharp edge is not enough resistant to bear the high mechanical stresses induced by the carbon fibers,

Park et al. [2] have also shown that the carbon fibers may weaken the grain binder composed of cobalt and then, accelerate the risk of chipping and fracture of the cutting edges.

Cutting temperatures and forces increase with wear evolution whereas a degradation of the surface topography is found, thus authors [5-7] monitor indirectly the wear.

Tribological investigations conducted by Mondelin et al. [8] have confirmed that abrasion is the main wear mechanism during CFRP drilling.

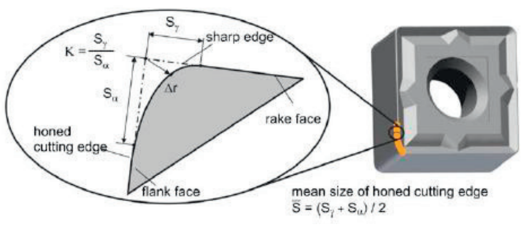

Fig. 1: Characterization of the cutting edge, after Denkena et al. [2]

3. Experimental set-up and method

The purpose of this study is the quantification of a wear criterion linked with the evolution of drilling forces, cutting temperatures and surface hole topography. The trials were performed on a CNC vertical HSM center using a K20 carbide drill (ref.: SD205A-12.0-56-12R1-T) with a 140° tool tip angle and a Ø12 mm diameter. The tests were performed on unidirectional CFRP T800M21 plates with constant cutting parameters currently used in industrial production defined in Table 1.

Table 1: Material characteristics and cutting parameters.

Unidirectional CFRP T800M21	Cutting parameters
• Plate thickness: 30 mm • Hole type : Through hole • Fiber content: 60% • Matrix material: Epoxy resin • Fiber size: Ø5 µm • Ply thickness: 250 µm	• Conditions : Dry • Vc = 100 m/min • f = 0.05 mm/rev • Acquisition frequency: 40 kHz

Forces (Fx, Fy, Fz) and torque (Mz) were measured with a piezoelectric rotating multicomponent dynamometer while the drilling temperatures were stored in real time by thermocouples inserted within the workpiece. K^+ and K^- (Chromel/Alumel) wires are embedded in a resin to form a thermocouple sensor as shown Fig. 2. During drilling, each edge cuts those wires providing a sudden electrical connection to get the information. By using this method, the temperature is known all along the cutting edge from the tip to the corner. Three thermocouples have been inserted in the workpiece at various depth (x= 5, 15 and 25 mm).

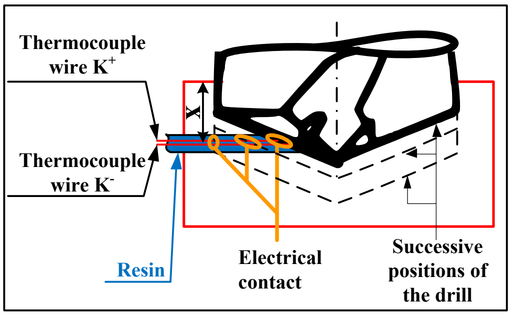

Fig. 2: Temperature measurement methodology.

Flank wear and chipping were observed on an optical microscope and the back edge evolution was characterized with a profilometer illustrated on Fig. 3(a). A special device was designed in order to always set the drill in the same localization for each edge measurement planes defined by the distance (R) as pointed out on Fig. 3(b).

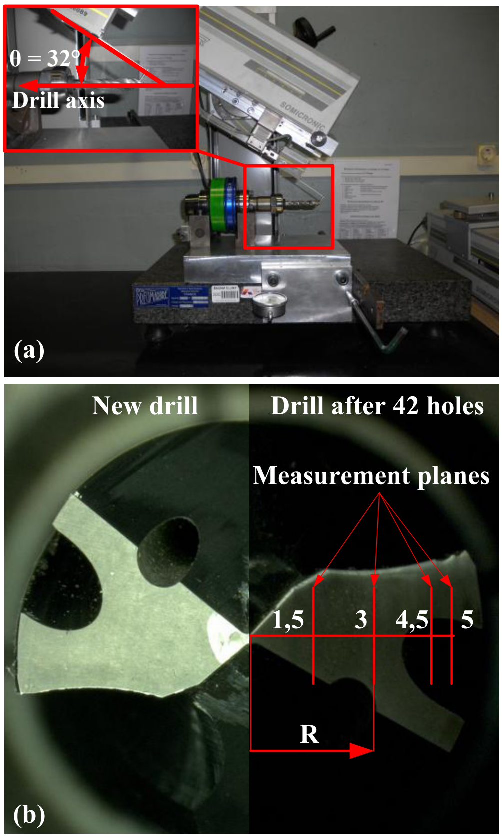

Fig. 3: (a)-Cutting edge measurement with a profilometer;
(b)-Localization of the measurement planes along the cutting edge.

4. Results and discussions

4.1. Drill wear

Abrasion is the main wear mechanism during drilling CFRP as shown on Fig. 4. The cutting speed gradient from the tip to the corner of the drill explains the smooth gradient wear along the cutting edge visible on Fig. 3(b) right side. Fig. 4(d) indicates that edge chipping appears after 810 mm drilled length, corresponding to 27 holes as observed by Rawat et al. [4].

The cutting modes defined by Wang et al. [9] are changing during each half drill turn due to the continuous variation of the χ_2 angle between the cutting and the fibers directions. As shown on Fig. 5, when χ_2 = -45° flank abrasion is the main wear mechanism because the carbon fibers undergo bending and followed of a breakage abruptly. Then, they come back to their original position by rubbing against the tool flank.

This mechanism leads also to margin abrasive wear as shown on Fig. 6 with a margin width twice as large after 42 holes pointed out by regular grooves space out with steps equal to the feed rate (50 µm).

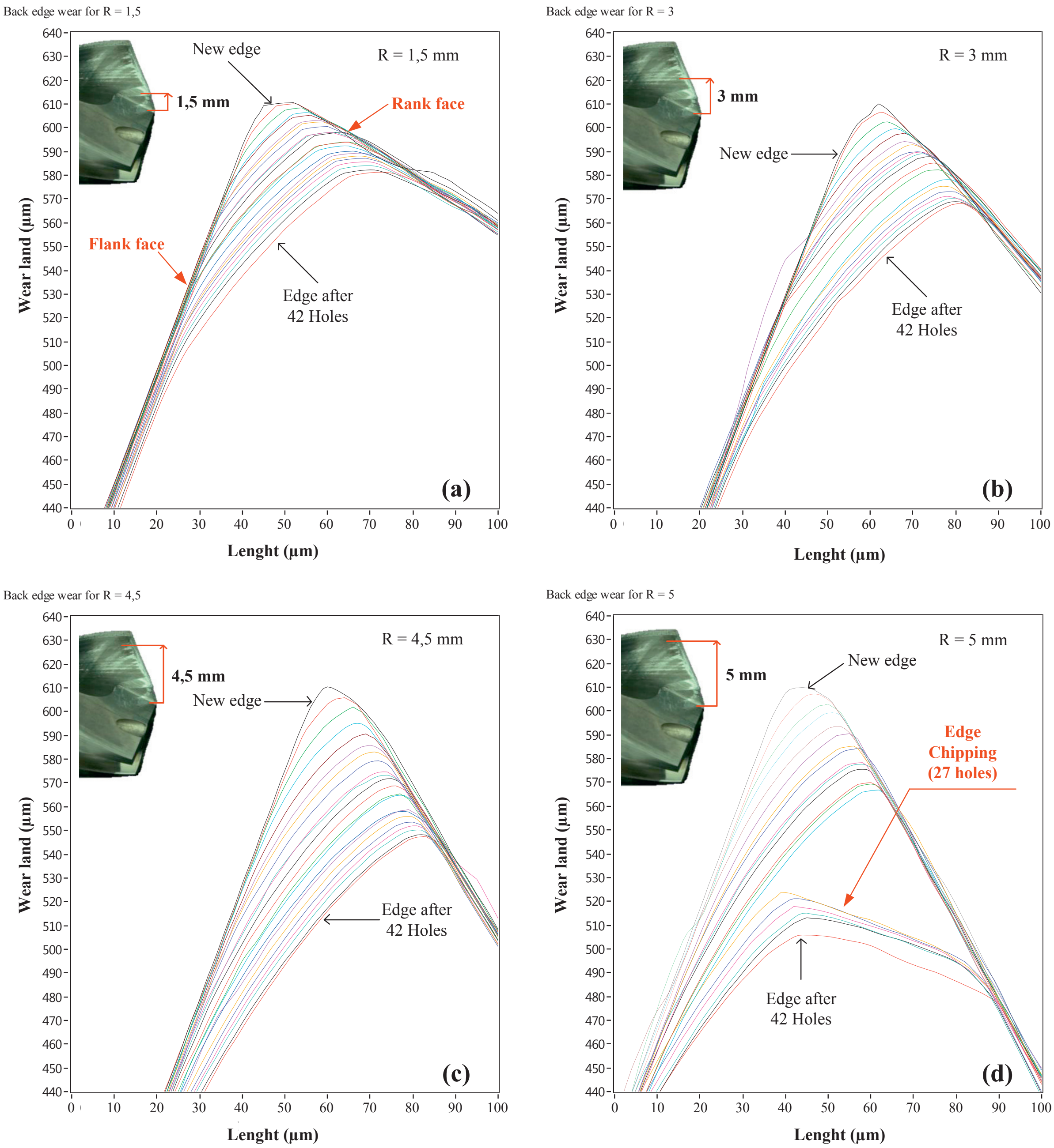

Fig. 4: Back edge criterion evolution versus number of holes.

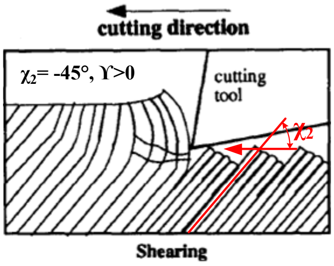

Fig. 5: Inappropriate cutting mechanisms in orthogonal machining of fibrous material when χ_2 is equal to -45° or 135° according to Wang et al. [9].

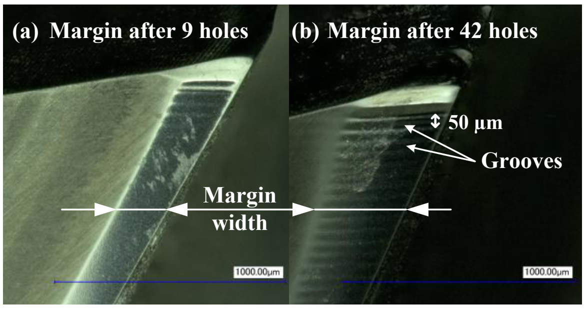

Fig. 6: Abrasive wear visible on the margin..

Wear is quantitatively measured every two holes in a vertical direction making a θ angle (32°) with the drill axis allowing to prevent the sensor ploughing with the tool faces as define on Fig. 7. The back edge criterion is plotted on Fig. 8 showing an evolution 50% faster near the tool corner rather than the tool tip.

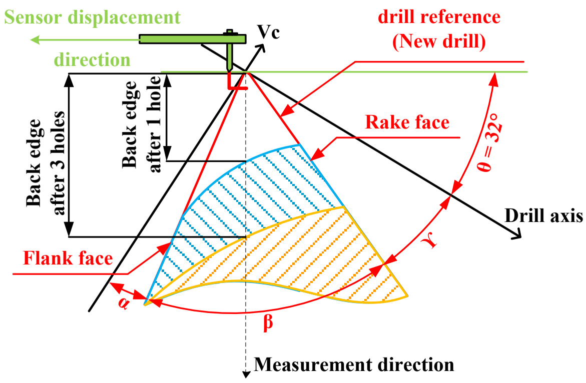

Fig. 7: Definition of the back edge criterion.

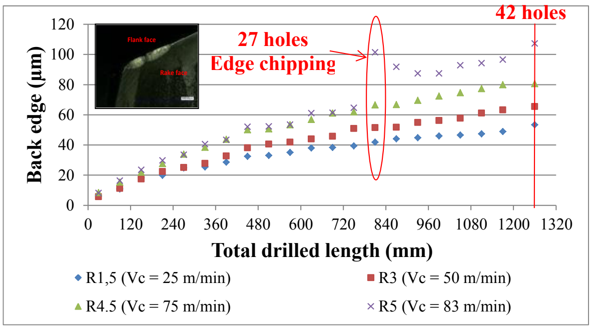

Fig. 8: Back edge criterion versus drilled length.

Wear could be indirectly measured by monitoring cutting forces and/or temperatures.

Fig. 9 displays that the temperature on the tool corner reached a steady value very quickly, closed to 450°C, whatever the hole depth. In contrast, after 5 mm drilled depth, the tool tip temperature is only 10°C higher than room temperature and reaches slowly to 100°C at the end of the operation (25 mm depth). This tip heating is due to the heat diffusion which is mainly generated by the tool corner.

The localized chipping occurring near the corners after 27 holes causes a rapid increase in temperature because more energy is needed to cut the fibers as highlighted on Fig. 8.

Tool wear affects also the forces with a doubling of the torque value due to the edge rounding while thrust force has grown threefold because of the ploughing effect of the flank face with the machined surface as plotted on Fig. 10.

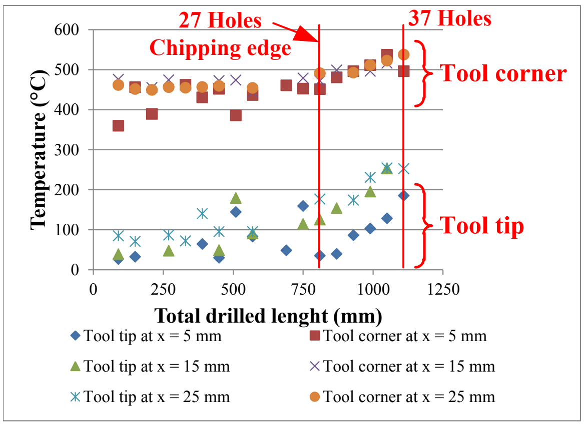

Fig. 9: Cutting temperatures evolution versus drilled length.

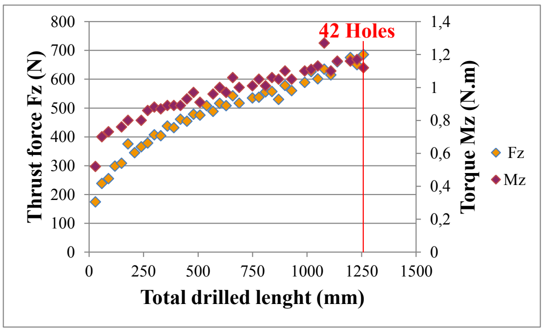

Fig. 10: Cutting forces evolution.

4.2. Surface topography of the hole

Back edge and margin wear imply a degradation of the hole surface integrity. The poor “surface roughness” of the hole is mainly due to the uncut fibers localized at $\chi_2 = -45°+k\pi$.
In this study, the surface topography is quantify with the percentage of uncut fibers surface compared to the total hole area ($\pi*12*h$). This ratio appears to be a criterion more relevant for such inhomogeneous materials than the surface roughness used in the literature. Fig. 11 highlights three zones showing the evolution of this ratio, measured with an optical microscope. During the honing stage, the edge is enough sharp to cut properly the fibers to get a uniform surface topography. Afterwards, from the hole #5 to the hole #27, this ratio evolves continuously with the back edge wear defined on Fig. 7. Finally, the edge rounding cannot be superior to the uncut chip thickness, hence, the uncut fibers area stabilizes from hole #28. The maximal value of the ratio reaches an asymptote at 20%. Fig. 12 is a proof of this surface topography evolution, clearly observable for each of the three stages.

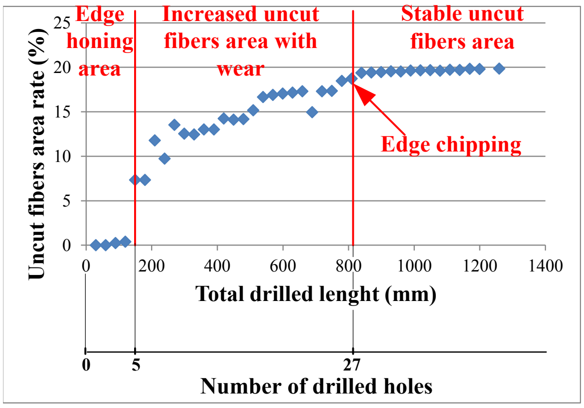

Fig. 11: Percentage of surface with uncut fibers.

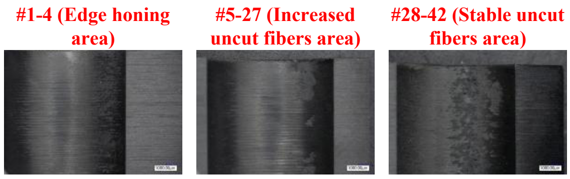

Fig. 12: Evolution of the surface topography of the hole.

A roundness measurement has been performed with a fully automated roundness/cylindricity device. The diamond probe has a conical tip form with a 5 µm radius and a 90° angle. Fig. 13 shows the uncut fibers areas localized between -10° to -45° and symmetrically at 135° to 170°. The explanation of these both zone positions are relevant with the cutting mechanisms discussed on Fig. 5. The angular range $\Delta\theta_{max}$ is equal to 35° correlating well the results found with the optical microscope. These values are consistent and confirmed the observations made by Bonnet et al.[10] and Piquet et al. [11] who showed that the fibers tearing are included in this angle range.

The uncut fibers heights shown on Fig. 14 vary between 60 and 100 µm while the variation does not exceed 10 µm on the rest of the profile.
Coming back to the definition of the CFRP surface topography, those observations highlight that the “surface roughness” measurement should be done circularly rather than in the axial direction of the hole in the case of unidirectional CFRP. For multidirectional CFRP, due to the fiber orientation according to the plies sequences, the measurement is more complex but can be deduced from the understanding derived of unidirectional CFRP study as shown on Fig. 15 and Fig. 16.

By using a mechanical probe, there is a risk to wear the indenter and to bend the position of the carbon fiber.

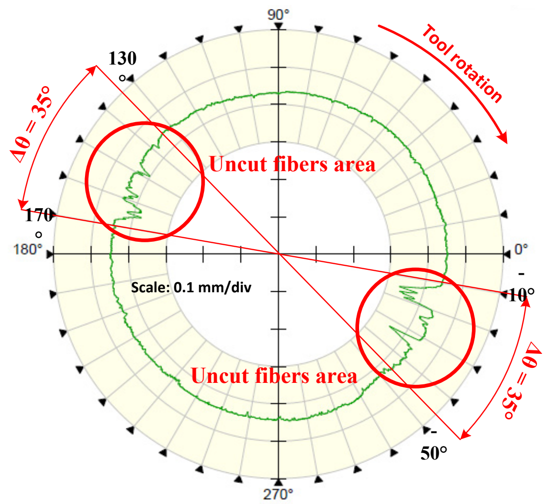

Fig. 13: Localization of the defect in a hole drilled in a unidirectional CFRP plate with fully automated roundness/cylindricity device.

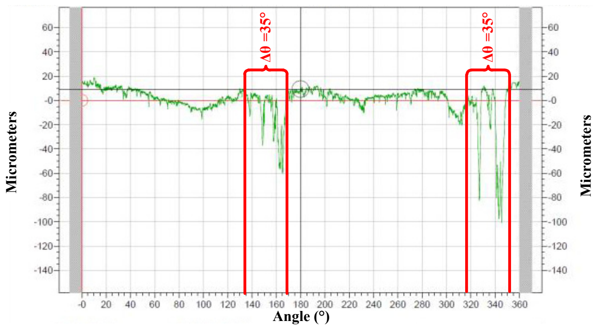

Fig. 14: Development of the hole.

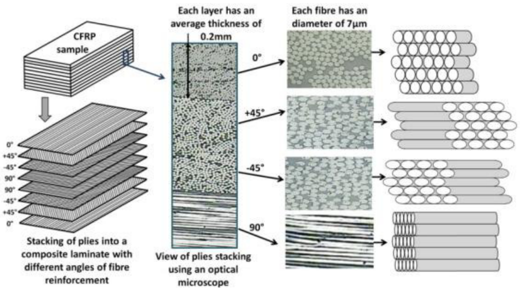

Fig. 15: Plies sequence of multidirectional CFRP, after Mondelin et al. [8].

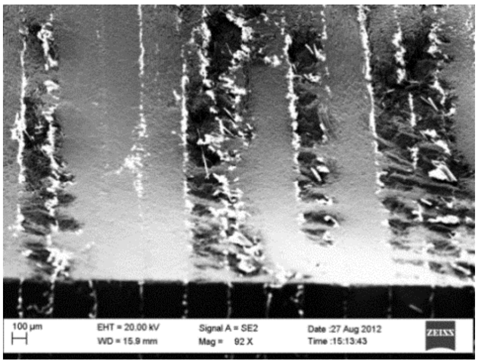

Fig. 16: Surface topography area of multidirectional CFRP T800M21.

5. Conclusion

An experimental campaign was carried out in order to study the carbide drill wear. The results of the investigation highlight the influence of tool wear on cutting forces and cutting temperatures. Abrasion is the main wear mechanism observed during CFRP drilling operation. This methodology has also shown that the temperature gradually increases with the abrasive wear of the cutting edges. Obviously the wear has a direct impact on the final surface topography of the hole. This temperature methodology allows, in the future, to model the temperature mapping on the cutting edge.

The measure of the uncut fiber area ratio can be a valuable criterion to define the surface roughness of the hole. More investigations need to be done in this way to improve this definition. To avoid the mechanical contact between the probe and the CFRP in the future, a device with a non-contact sensor is developed by using the confocal measurement principle. Thanks to this device, the prediction of the hole quality versus the orientation of the plies will be possible in the case of multidirectional CFRP.

The design of a new drill geometry with a cutting edge localized just behind both margins would allow to cut the uncut fibers while a combination of an inverse revolution with the going up of the tool.

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References

[1] Faraz, A., Biermann, D., Weinert, K., 2009. Cutting edge rounding: An innovative tool wear criterion in drilling CFRP composite laminates, International Journal of Machine Tools & Manufacture 249, p. 1185.

[2] Park, K., Beal, A., Kim, D., Kwon, P., Lantrip, J., 2011. Tool wear in drilling of composite/titanium stacks using carbide and polycrystalline diamond tools, Wear 271, p. 2826.

[3] Denkena, B., Lucas, A., Bassett, E., 2011. Effects of the cutting edge microgeometry on tool wear and its thermo-mechanical load, CIRP Annals - Manufacturing Technology 60, p. 73.

[4] Rawat, S., Attia, H., 2009. Wear mechanisms and tool life management of WC–Co drills during dry high speed drilling of woven carbon fibre composites, Wear 267, p. 1022.

[5] Ferreira, J.R., Coppini, N.L., Miranda, G.W.A., 1999. Machining optimisation in carbon fibre reinforced composite materials, Journal of Materials Processing Technology 92-93, p. 135.

[6] Brinksmeier, E., Fangmann, S., Rentsch, R., 2011. Drilling of composites and resulting surface integrity, CIRP Annals - Manufacturing Technology 60, p. 57.

[7] Murphy, C., Byrne, G., Gilchrist, M.D., 2002. The performance of coated tungsten carbide drills when machining carbon fibre reinforced epoxy composite materials, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 216, p. 143.

[8] Mondelin, A., Furet, B., Rech, J., 2010. Characterisation of friction properties between a laminated carbon fibres reinforced polymer and a monocrystalline diamond under dry or lubricated conditions, Tribology International 43, p. 1665.

[9] Wang, D., H., Ramulu, M., Arola, D., 1995. Orthogonal cutting mecanisms of graphite / epoxy composite. Part I: unidirectional laminate, International Journal of Machine Tools & Manufacture 35, p. 1623.

[10] Bonnet, C., Benmohammed, B., Poulachon, G., Rech, J., Girard, Y., 2011. CFRP drilling dodel: fiber orientation influence on mechanical load and delamination, Advanced Materials Research 223, p. 111.

[11] Piquet, R., Ferret, B., Lachaud, F., Swider, P., 2000. Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills, Composites Part A: Applied Science and Manufacturing 31, p. 1107.