Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia CIRP 8 (2013) 316 – 321
www.elsevier.com/locate/procedia

14th CIRP Conference on Modeling of Machining Operations (CIRP CMMO)

Local approach of wear in drilling Ti6Al4V/CFRP for stack modelling

Antoine Poutord[a*], Frederic Rossi[a], Gerard Poulachon[a], Rachid M'Saoubi[b], Guillaume Abrivard[c]

[a]*Arts et Metiers ParisTech, Cluny, 71250, France*
[b]*SECO Tools, SE- 73782, Fagersta, Sweden*
[c]*EADS, Nantes, France*
* Corresponding author. Tel.: +33 3 85 59 53 88 ; fax: +33 3 85 59 53 70. *E-mail address*: antoine.poutord@ensam.eu.

Abstract

The drilling of stacks made of carbon fibre composite material (CFRP) and metal (aluminium or titanium alloy) is an operation more and more common in aerospace industry. However, this critical machining operation is not yet fully controlled. The knowledge of the cutting forces and the wear phenomenon is an important issue to assure a good quality of the hole.
The studies on the stack drilling usually do not break down the operations on both materials (CFRP and metallic alloy), which does not allow a full understanding of the impact of each part of the stack on the behaviour of tool, especially regarding its wear. Nevertheless, a study of the drilling of a single material does not lead us to the understanding of the stack drilling, because of the influence of a piece toward another.
This study, firstly, discusses the drilling of each material of the stack, titanium alloy Ti6Al4V and CFRP, individually. The impact of the local wear is assessed by investigating the variation of the cutting forces along the cutting edge (the computation is made by the decomposition of the thrust force and the torque during the progressive engagement of the drill point).
Furthermore, this study explains the drilling of an alternation of titanium alloy and CFRP in order to model its effect on a stack, while allowing the analysis of the wear for each material.

Selection and peer-review under responsibility of The International Scientific Committee of the “14th CIRP Conference on Modeling of Machining Operations” in the person of the Conference Chair Prof. Luca Settineri

Keywords: Drilling; CFRP; Ti6Al4V; Wear

1. Introduction

In aerospace applications, the hybrid structures made of carbon fibre reinforced plastic (CFRP) and metal, often Ti6Al4V or aluminium alloys, used in stacks are more and more used. These stacks becomes widely used because of their high performances in withstand high stress and reducing weight [1-3]. In the hybrid structures made of two or more materials, each one works independently or together, but the stack always provides structural advantages compared to one material that it replaces. This is the reason why the new structures of aeroplanes are made of more than 50% of CFRP in mass, widely used in stack [4].

This study deals with the drilling of stack of Ti6Al4V/CFRP. Brinksmeimer [5] showed that generated heat during Ti6Al4V drilling may damage CFRP. While most of the studies consider only the stack [6-8], in this study, the objective is to highlight the proper wear of each material, when drilled independently. This separation allows new measurements and interpretation of the results.

CFRP drilling

König [9, 10] studied the relationship between hole quality parameters and thrust force and proposed the concept of “critical thrust force” linked with a delamination initiating at the exit-ply. This notion has been completed by many other studies ever since, such as Tsao [11] who showed the importance of the chisel thrust force on the exit delamination. Many other researches have been performed in this way [12-13]. CFRP is a highly abrasive material [14], due to the

2212-8271 © 2013 The Authors. Published by Elsevier B.V. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of The International Scientific Committee of the “14th CIRP Conference on Modeling of Machining Operations” in the person of the Conference Chair Prof. Luca Settineri
doi:10.1016/j.procir.2013.06.109

hardness of the carbon fibre. The orientation between the fibre and the cutting edge also influences the cutting forces, the surface integrity and the local tool wear [15]. Furthermore, the carbon fibre seems to be able to attack the cobalt binder of WC-Co drill, which is the softer part of the tool, accelerating crack propagation and tool wear [16].

Ti6Al4V drilling

The tool wear mechanisms in Ti6Al4V drilling are totally different from those in CFRP. The low thermal conductivity and the high chemical affinity lead to catastrophic tool failure [17]. Chemical affinity may operate with the adhesion that occurs during the cutting of Ti6Al4V [18]. Tool wear is highly influenced by drilling parameters and drill geometry, increasing cutting speed or feed rate highly changes the tool lifetime [19].

2. Experimental procedures

2.1. Workpiece materials

The carbon fibre composite (CFRP) laminates provided by an aerospace company, were made of unidirectional ply of carbon fibre in an epoxy matrix with a 0.25 mm thickness. The CFRP thickness plate was around 20.7 mm.

The titanium plate used is Ti6Al4V, with a 25.5 mm thickness and called titanium β.

2.2. Drilling experiments

A commercial drill (Seco – K20 type uncoated) recommended for titanium drilling was selected for this investigation. Main cutting tool parameters are listed in Table 1.

Table 1. Drill geometry

Wc drill (Grade K20)	
Drill diameter	12 mm
Flute length	55 mm
Point angle	140°
Helix angle	30°
Back taper	0.5 %

Machining experiments were performed on a 3-axis CNC vertical drilling machine (DMG 85VL) with a 25 kW spindle, maximal spindle speed of 18 000 rpm. The plate of CFRP was fixed in a vice and the Ti6Al4V one was clamped. The thrust force and torque were measured by a Kistler 9123 rotating dynamometer and monitored by an A/D board (NI 9188 and three NI 9215 cards, National Instrument, USA, with a data acquisition frequency of 50 kHz on each channel) and recorded on a personal computer using data acquisition software (Dasylab 11, NI, USA). The data was then operated with Matlab R2007b software.

In order to investigate how each material impacts the drill wear, three experimental campaigns have been carried out; the first is a succession of 18 holes in the CFRP plate with the first drill (noted C1). The second is the same in Ti6Al4V with a second drill (noted C2). The last experimental campaign is the drilling of one hole in Ti6Al4V followed by one in CFRP and then one in Ti6Al4V… in order to drill 18 holes in each material with one drill (noted C3).

Because of the differences between each material, the machining parameters changes for each one. A previous study of tool/material pair has been done to select suitable cutting parameters. The drilling cutting conditions are summarized in Table 2.

Table 2. Cutting conditions

Drill name	C1 or C3	C2 or C3
Material drilled	CFRP	Ti6Al4V
Cutting speed (Vc)	100 m/min	10 m/min
Spindle speed (N)	2652 rpm	265 rpm
Feed (f)	0.05 mm/rev	0.2 mm/rev
Cutting fluid	Dry	Dry

2.3. Wear analysis

The drill wear is measured by an optical microscope (with x20 – x200 lens) to control the drill wear patterns. A profile sensor is used to compare the cutting edge geometry between each drilling operation.

3. Results and discussion

3.1. Drilling forces

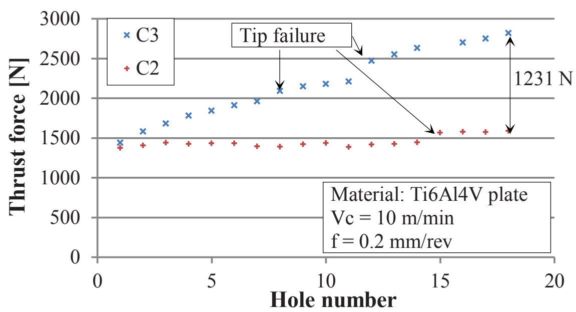

Fig. 1: Thrust force evolution for C2 and C3 drills in Ti6Al4V

Fig 1 shows the thrust force comparison between C2 and C3 drill versus the hole number in Ti6Al4V. As the number of holes increases, the thrust force rises significantly for C3 drill (+95% after 18 holes for the thrust force and +31% for the torque, as shown in Fig 4). While the increase in the thrust force for C2 drill is not so significant: +15% (or +215 N) for the thrust force and less than 5% for the torque as shown in Fig 4.

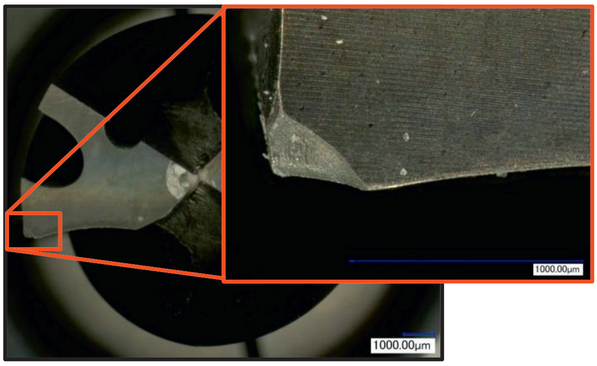

Fig 2.: Drill tip C2 failure after the 15th hole

Fig 2 shows the kind of tip failure that always occurs during the drilling of Ti6Al4V. Here on the 15th hole, due to high mechanical load in Ti6Al4V compared to CFRP as shown in Fig 11 and Fig 14. Similar events are visible on Fig 1 and induce steps on thrust force.

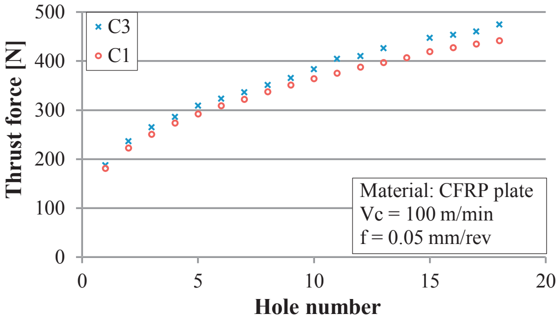

Fig. 3: Thrust force evolution for C1 and C3 drills in CFRP

On the stack drilling, most of the wear is due to the CFRP material, as underlined in Fig 1 and Fig 3.

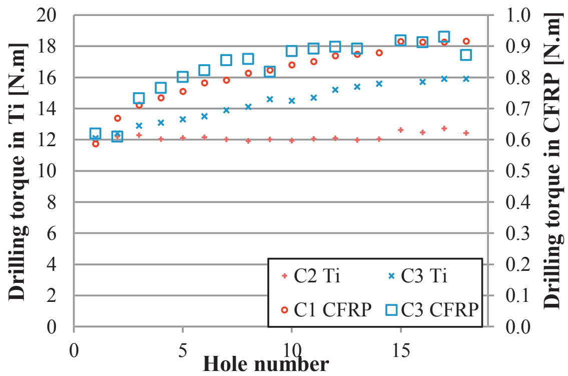

Fig. 4: Evolution of the total torque

These results suggest that the impact of the Ti6Al4V machining is not really significant for the drilling forces, for the first 18 holes. The comparison of the differences between drilling CFRP and drilling CFRP and Ti6Al4V plates alternately confirm that point, as showed in Fig 3.

3.2. Drill wear

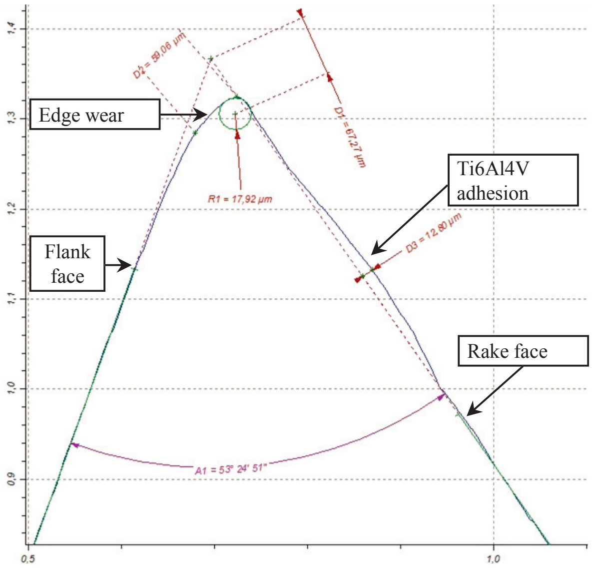

Fig. 5: Edge profile of the drill C3 after drilling the 12th hole in CFRP (after 12 holes in Ti6Al4V and 12 in CFRP)

Fig 5 presents the edge profile of C3 drill after drilling 12 holes in Ti6Al4V and CFRP, the last hole was in composite material. It is interesting to note that the Ti6Al4V adhesive layer does not disappear fully during CFRP drilling.

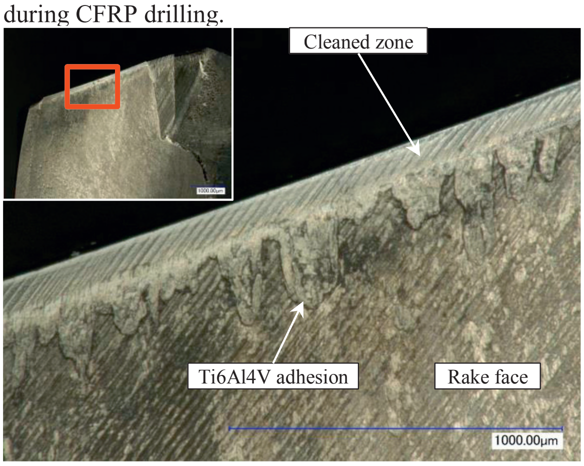

Fig. 6: Edge profile of the drill C3 after drilling the 12th hole in CFRP (after 12 holes in Ti6Al4V and 12 in CFRP)

Fig 6 shows the presence of Ti6Al4V adhesion on the rake face. This build-up layer (BUL) could protect the cutting edge during the drilling of CFRP, but the evolution of the thrust forces on Fig 3 allows to conclude that this layer of Ti6Al4V is quickly removed during the drilling due to the highly abrasive action of the carbon fibre.

3.3. Local forces on the drill

In order to complete the understanding of the wear, a study of the local forces along the main cutting edges and margin has been done. In order to know the effect of each portion of the edge, thrust force and torque have been decomposed during the introduction of the drill point into the material. Fig 7 shows the variation of thrust forces and torque during the drilling of Ti6Al4V plate. The study is focusing on the beginning of the curve (in the red box of Fig 7), that is shown in Fig 8. Between two verticals lines, the edge is engaged by 0.5 mm more on the X direction. By subtraction of each part, the distribution on various sub-division of the edge drill can be deduced.

A similar methodology has been used by Lazar [20] to consider the forces on the chisel and the cutting edge.

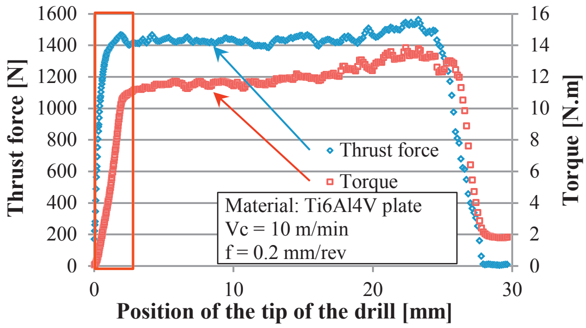

Fig. 7: Thrust force and torque during the drilling of the 1st hole in Ti6Al4V with drill C3

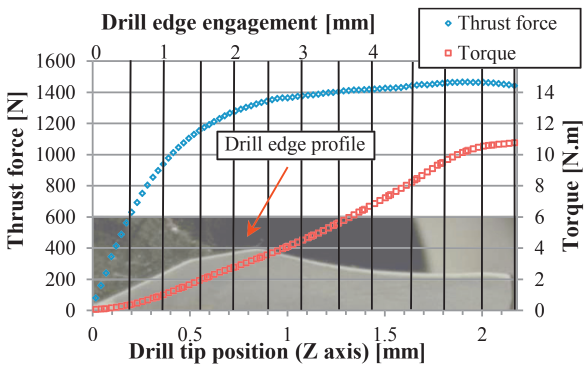

Fig. 8: Evolution of the thrust force and torque during the tip drill insertion

To find the distribution of the local cutting force along the main edge, the local torque is calculated like the thrust force in order to determine the local cutting forces. The cutting force is assumed to be constant on each edge segment. The application point of the equivalent local force is calculated for each segment. The choice for the 12th segment is the compromise between the noise and the number of sub-divisions.

This methodology is used in this part to have a better understanding of the local wear and distribution of the local forces.

Ti6Al4V analysis

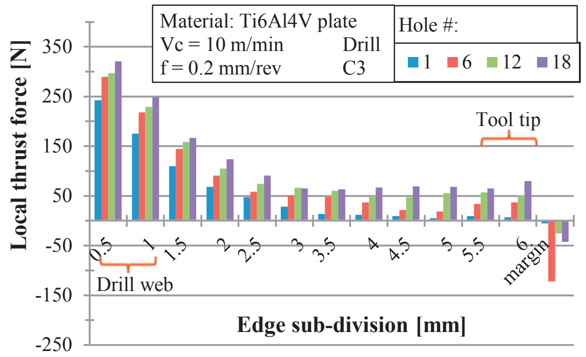

Fig. 9: Distribution of the thrust force along one cutting edge for the drill C3 in Ti6Al4V

Fig 9 represents the local thrust forces on one lip of the drill C3 in Ti6Al4V for the holes # 1, 6 12 and 18 (between each holes in Ti6Al4V, the tool drilling CFRP). The distribution of the forces along the cutting edge shows the importance of the drill web and the margin. The 2 mm web diameter centre of the drill is consuming more than 45% of the total thrust force. The second part of the drill that is particularly important is the margin, the thrust force on this part tends to turn up the plate. A new information is that the more the tool is worn, the higher the forces on the margin tend to turn up the plate. According to the drill wear, Fig 9 shows a continuous increase + 3-5 N/subdivision/hole.

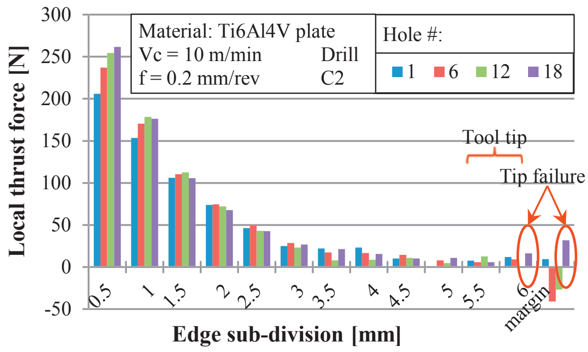

Fig. 10: Distribution of the thrust force along one cutting edge for the drill C2

Fig 10 allows us to compare the drilling of the alternating of materials with the drill C2 that cuts only Ti6Al4V plate. On that drill, most of the variation on the local thrust force is localised on the web. The forces on edge sub-divisions from 5 mm to 6 mm increase from the 14th hole, probably due to the tool tip failure (similar to Fig 2).

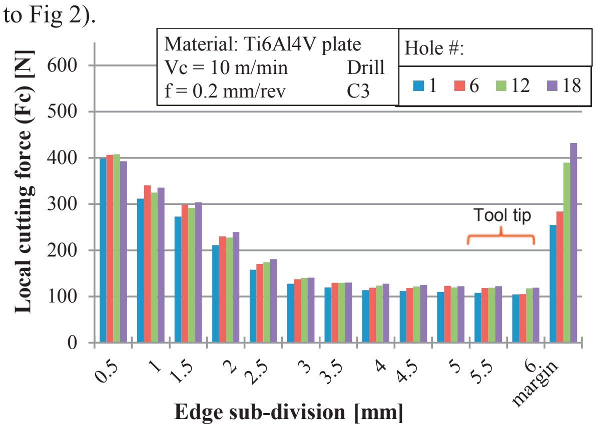

Fig. 11: Distribution of the cutting forces along one cutting edge for the drill C3 in Ti6Al4V

Fig 11 presents the evaluated cutting forces along the tool edge for the holes # 1, 6, 12 and 18. The very low variation on the web drill seems to show that there are no wear on these edge sub-divisions. But the local forces applied on the margin and on the tool tip increase a lot (more than 66% of the cutting force on the margin). The failure of the corner on the 8th and 12th hole probably leads to a larger rise up of the forces.

As the total forces on the drill C2 presented in Fig 4 do not seem to be changing, the local cutting forces indicated on Fig 12 confirm the minor wear during the Ti6Al4V drilling operation. The only cutting forces increases are on the web drill and on the margin, but much less than for the C3 drill.

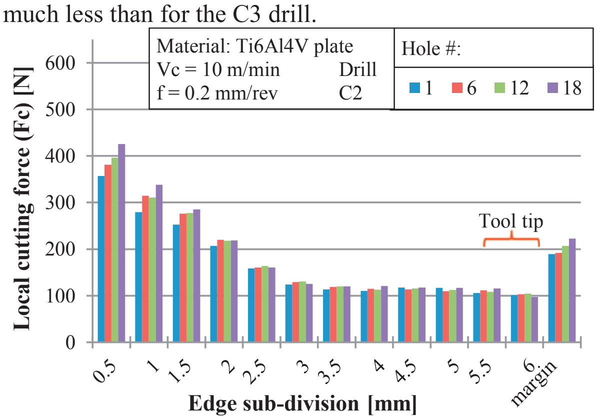

Fig. 12: Cutting force distribution along one cutting edge for C2 drill

CFRP analysis

The same analysis has been performed in the context of CFRP drilling. In Fig 13, the thrust force along the cutting edge displays more scatter when compared to Ti6Al4V, due to the material strong anisotropy. The ply orientations on the beginning of the material are not equalised, resulting a variation on the local feed forces. This methodology does not seem to be relevant for composite material if the first part of the CFRP is not quite isotropic.

The high level of the thrust force on the margin for the 1st hole is due to the important wear during the first hole drilling, resulting in an important torque evolution and a bad evaluation of the margin contribution.

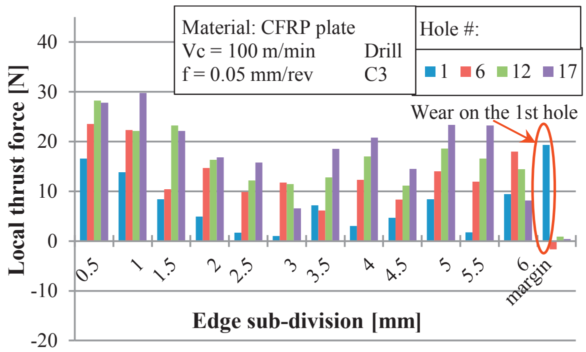

Fig. 13: Distribution of the thrust force along the cutting edge for the drill C3 in CFRP

Fig 14 shows the cutting forces along the cutting edge. This graph seems to be less impacted by the evolution of the ply because of the averaging on one rotation of the tool. While a half drill revolution, both cutting edges cut the fibres according to all the angle configurations (0-180°).

The cutting forces repartition highlights the significance of the chisel for the local pressure. Due to lever arm effect, margin represents 20 to 25% of the total torque even if the local pressure seems to be low.

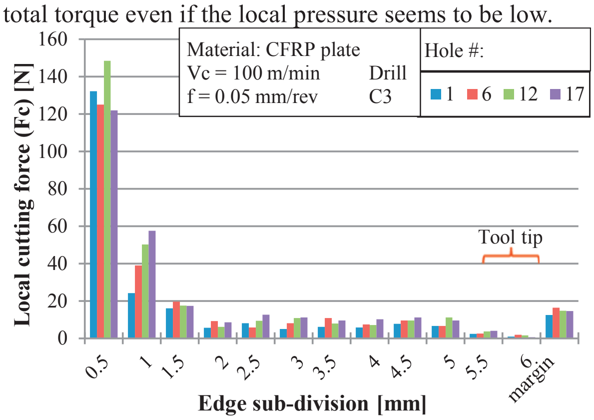

Fig. 14: Distribution of the cutting forces along one cutting edge for the drill C3 in CFRP

The study of the evolution of the local cutting forces on CFRP is less representative than in Ti6Al4V drilling with that methodology because of the ply and their non-homogeneous orientation. This analyse should be more representative in unidirectional composite.

4. Conclusion

It can be concluded from the present investigation that the major tool wear comes from the CFRP material. The wear generated by Ti6Al4V is mostly confined to cutting edge chipping on the drill corner.

The adhesion of material during drilling metallic material (build-up layer) is not strong enough to protect the edge during the CFRP machining. But it could also weaken the drill by a chemical wear process [17].

The study of the drill forces and the study of the torque highlight that CFRP is the main factor for the drill wear. Moreover, this wear impacts all the edges for the thrust force. The pressure increases uniformly with the number of holes drilled all along the edges (+ 3-5 N/subdivision/hole).

The distribution of the forces along the cutting edge denotes the importance of the chisel geometry for the total cutting forces.

The thrust forces along the margin increase with the wear, as the “critical thrust force” [9]. A critical force on the margin could be considered for modelling the entry delamination.

In a future research work, an investigation on the internal surface, linked with the tool wear and/or the forces evolutions will be performed.

References

[1] Ramulu, M., Branson, T., Kim, D., 2001, A study on the drilling of composite and titanium stacks, Composite Structures, Vol. 54, p. 67-77
[2] Zitoune, R., Krishnaraj, V, Sofiane Almabouacif, B., Collombet, F., Sima, M., Jolin, A., 2012, Influence of machining parameters and new nano-coated tool on drilling performance of CFRP/Aluminium sandwich, Composites: Part B, Vol. 43, p. 1480-1488
[3] Shyha, I.S., Soo, S.L., Aspinwall, D.K., Bradley, S., Perry, R., Harden, P., Dawson, S., 2011, Hole quality assessment following drilling of metallic-composite stacks, International Journal of Machine Tools & Manufacture, Vol. 51, p. 569-578
[4] Lantrip, J., 2008, New tools needed, Cutting Tool Engineering, Vol. 60 (8), 8 pages http://www.ctemag.com/pdf/2008/0808-Holemaking.pdf
[5] Brinksmeier, E. , Fangmann, S., Rentsch, R., 2011, Drilling of composites and resulting surface integrity, CIRP Annals – Manufacturing technology, Vol. 60, p; 57-60
[6] Park, K.-H., Beal, A., Kim, D., Kwon, P., Lantrip, J., 2011, Tool wear in drilling of composite/titanium stacks using carbide and polycrystalline diamond tools, Wear, Vol. 271, p. 2826-2835
[7] Kim, D, Ramulu, M., 2004, Drilling process optimization for graphite/bismaleimide-titanium alloy stacks, Composite Structure, Vol. 63, p. 101-114
[8] Kim, D, Ramulu, M., 2007, Study on the drilling of Titanium/Graphite Hybrid Composites, ASME Transactions Journal of Engineering Materials and Technology, Vol. 129, p. 390-396
[9] König, W., Wulf, Ch., Graß, P., Willerscheid, H., 1985, Machining of Fibre Reinforced Plastics, CIRP Annals - Manufacturing technology, Vol 34, Issue 2, p. 537-548
[10] König, W., Graß, P., 1989, Quality Definition and Assessment in Drilling of Fibre Reinforced Thermosets, CIRP Annals - Manufacturing technology, Vol 38, Issue 1, p. 119-124
[11] Tsao, C.C., Hocheng, H., 2003, The effect of chisel length and associated pilot hole on delamination when drilling composite materials, Machine Tools & Manufacture, Vol. 43, p. 1087-1092
[12] Zitoune, R., Collombet, F., 2007, Numerical prediction of the thrust force responsible of delamination during the drilling of the long-fibre composite structures, Composites: Part A, Vol. 38, p. 858-866
[13] Tsao, C.C., Hocheng, H., 2007, Effect of tool wear on delamination in drilling composite materials, International Journal of Mechanical Sciences, Vol. 49, p; 983-988
[14] Iliescu, D., Gehin, D., Gutierrez, M.E., Girot, F. 2010, Modeling and tool wear in drilling CFRP, International journal of Machine Tools & Manufacture, Vol. 50, p. 204-213
[15] Iliescu, D., 2008, Approches expérimentales et numériques de l'usinage à sec de composites carbone/epoxy, thesis, ENSAM Bordeau, France, 219 pages
[16] Rawat, S., Attia, H., 2009, Wear mechanisms and tool life management of WC-Co drills during dry high speed drilling of wofen carbon fibre composites, Wear, Vol 267, p. 1022-1030
[17] Ezugwu, E.O., Wang, Z.M., 1997, Titanium and their machinability – a review, Journal of Materials Processing Technology, Vol. 68, p. 262-274
[18] Ikuta, A., Shinozaki, K., Masuda, H., Yamane, Y., Kuroki, H., Fukaya, Y., 2002, Consideration of the adhesion mechanism of Ti alloys using a cemented carbide tool during the cutting process, Journal of Materials Processing Technology, Vol. 127, p. 251-255
[19] Yang, X., Richard Liu, C., 1999, Machining titanium and its alloys – Review article, Machining Science and Technology, Vol. 3(1), p. 107-139
[20] Lazar, M.-B., Xirouchakis, P., 2013, Mechanical load distribution along the main cutting edges in drilling, Journal of Materials Processing Technology, Vol. 213, p. 245-260