Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 99 (2021) 398–403

www.elsevier.com/locate/procedia

14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '20

Optimal cutting parameters and tool geometry in drilling of CFRP/CFRP stack laminates for aeronautical applications

Roberta Angelone[a,b,*], Alessandra Caggiano[a,c], Luigi Nele[b], Roberto Teti[a,b]

[a]*Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology (Fh J_LEAPT UniNaples), Naples, Italy*
[b]*Dept. of Chemical, Materials and Industrial Production Engineering, University of Naples Federico II, P.le Tecchio 80, 80125 Naples, Italy*
[b]*Dept. of Industrial Engineering, University of Naples Federico II, P.le Tecchio 80, 80125 Naples, Italy*

* Corresponding author. Tel.: +39 081 7682371; fax: +39 081 7682362. *E-mail address:* roberta.angelone@unina.it

Abstract

Drilling stands out as the most widespread machining process of carbon fibre reinforced plastic (CFRP) composite parts, primarily in the aerospace industry due to the extensive use of mechanical assembly using fasteners such as rivets or bolts. In this paper, drilling of CFRP/CFRP stacks for aeronautical applications is investigated using two different types of drilling tools, a traditional twist drill and an innovative step drill, under different spindle speed and feed rate conditions to evaluate the optimal drilling parameters and the most suitable drill bit geometry for one-shot stack drilling. Automatic image processing is applied to evaluate the hole quality parameters and the relationship between tool wear and hole quality is studied for both tool types.

Peer-review under responsibility of the scientific committee of the 14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 15-17 July 2020.

Keywords: CFRP/CFRP stacks; drilling; hole quality; tool wear

1. Introduction

Composite materials are progressively replacing traditional materials in many applications due to their exceptional properties. In particular, carbon fibre reinforced polymer (CFRP) composite materials exhibit an excellent combination of low weight, high mechanical strength and high rigidity, which is highly desirable for aerospace applications [1].

Indeed, the aerospace industry is particularly interested in employing lightweight materials to reach the target of lowering costs by enhancing efficiency and reducing emissions to improve the global environmental impact [2].

In aerospace component assembly, drilling is the main machining process employed to obtain the holes which normally act as housing for mechanical fasteners like bolts or rivets. Drilling of composite materials is very challenging for manufacturing engineers [3–5] due to material fragmentation and delamination that occur during the drilling operation which affect aesthetics and processed surface quality [6]. Conventional drilling processes using drill bits on CFRP laminates may damage the workpiece through chipping, cracking, delamination and high wear of the cutting tools [7–9]. Several critical defects like entry/exit delamination, internal delamination, geometric/dimensional errors, fibre pullout, and thermal damage have been reported [10,11].

In this research work, in order to find the optimal cutting parameters and tool geometry for the drilling of CFRP/CFRP stacks, an experimental testing campaign was carried out using diverse process parameter values (for cutting speed and feed rate) and two different drill bit geometries.

To lay the foundation for an on-line assessment of tool wear and hole quality via in-process image acquisition, tool wear level was estimated through image analysis and hole quality was evaluated by automated image processing.

2. Experimental setup

2.1. Workpiece details and process parameters

Experimental drilling tests were carried out on stacks made

Peer-review under responsibility of the scientific committee of the 14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 15-17 July 2020.
10.1016/j.procir.2021.03.056

of two CFRP laminates, each composted of 26 prepreg plies made of CYCOM 977-2 epoxy matrix and Toray T300 carbon fibres with stacking sequence $[\pm45_2/0/90_4/0/90/0_2]_s$.

The total thickness of each CFRP laminate was 5 mm and a very thin fiberglass/epoxy ply reinforced with 0°/90° fabric was placed on the front and back surfaces of the laminates for corrosion protection.

The CFRP laminates were fabricated by hand lay-up, vacuum bag moulding and autoclave curing. The surface texture of the laminates on the bag side was highly irregular compared to the mould side which is very smooth (Fig. 1).

The total thickness of the CFRP/CFRP stack is about 10 mm. In order to reproduce as close as possible the drilling conditions in the aerospace industry, the two laminates have been clamped and drilled together. The two CFRP laminates in the stack were placed with their bag side in contact to perform the experiments under the severest drilling conditions.

Image analysis was conducted on 60 consecutive holes drilled with the same cutting parameters with 2 different tools:

- Traditional tool: a two-flute twist drill made of tungsten carbide, Ø 6.35 mm, featuring a 125° point angle (Fig. 2).
- Innovative tool: a two-flute step drill made of tungsten carbide, with the diameter growing from 4.95 mm to 6.35 mm in two steps with sharp elliptical margins (Fig. 3)

In order to identify the influence of the cutting parameters on the machinability of the CFRP stacks in terms of tool wear and quality of the holes, different cutting parameters were adopted for the experimental drilling tests. Three feed rate values and three spindle speeds were employed, as reported in Table 1. Each drill bit realized 60 holes in the CFRP/CFRP stack with the same process parameters. Every 10 drilled holes, the drilling operation was suspended to acquire images of the drill bit in order to evaluate the flank wear (VB).

For better comprehension, each process condition is assigned a letter "A - F" and prefixes "T" and "I" are used to identify the traditional twist drill and the innovative step drill.

Table 1. Experimental conditions in CFRP/CFRP stack drilling.

Experimental testing code	Spindle speed (rpm)	Feed rate (mm/rev)
A	2700	0.15
B	6000	0.11
C	6000	0.15
D	6000	0.20
E	9000	0.11
F	9000	0.15

2.2. Drilled hole quality parameters

2.2.1. Delamination analysis

Avoiding delamination becomes one of the main objectives in the drilling of CFRP materials since the applications of composite materials continue to grow in the aerospace and the automotive industries [12].

Two delamination mechanisms, i.e. peel-up and push-out delamination, may occur at the hole entry and exit when the axial forces exerted by the drill bit helix overcome the interlaminar strength of the workpiece.

To evaluate delamination significance, the most common parameter is the delamination factor, F_d, which considers the maximum extent of delamination in the radial direction. An alternative parameter that considers also the total damaged area is the adjusted delamination factor, F_{da} [13].

Image analysis was performed in Matlab to extract the two delamination characteristic parameters from the acquired images of the drilled holes following the procedure presented in [14]. The procedure consists of two main steps, focused on identifying the perimeter of the hole (and the parameters of the best fitting circumference) as well as the delaminated area.

The exit delamination (or push-down delamination at hole exit) is generally more severe than the entry delamination (or peel-up delamination at hole entry) [10]. Previous studies have confirmed the greater relevance of push-out delamination [15]; therefore, only the images acquired at the hole exit of the CFRP/CFRP stacks were further processed.

2.2.2. Dimensional and geometrical analysis

In addition to the above mentioned surface integrity parameters, also geometrical and dimensional hole characteristics were considered in the analysis. In particular, the hole diameter and the hole roundness.

It is expected that the hole diameter will decrease with increasing number of drilled holes but its value must remain within specified tolerance ranges which in the aeronautical sector are very tightly imposed.

Hole roundness is one of the main geometrical features to measure. According to the definition of ISO 1101:2012, roundness is calculated as the ratio between the diameters of the maximum inscribed circle and the minimum circumscribed circle [16].

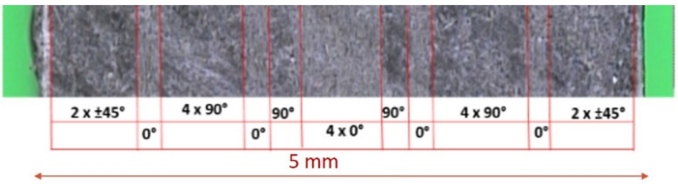

Fig. 1. Sequence of layers in one CFRP laminate.

Fig. 2. Traditional twist drill, side view.

Fig. 3. Innovative step drill, side view.

2.3. Tool wear evaluation

According to the literature, the most widely used parameter for tool wear monitoring during machining operations is the flank wear [3,17-21]. Although it is not possible to make an exact comparison between the two drill bit types employed in the experimental tests due to their different geometries, flank wear was measured for both of them and used to assess the behaviour of the two different drill bit types during the drilling process.

Tool wear measurements were performed during drilling tests after every 10 holes. A magnified picture of the cutting lip was acquired through an optical measuring machine (Tesa Visio V-200) to optically measure the flank wear VB. Fig. 4 shows the TC tool (traditional tool: T; process condition C: 6000 rpm - 0.15 mm rev) before starting the drilling procedure (left) and after the realisation of 60 holes (right).

3. Results

To compare the quality of the CFRP/CFRP stack holes produced by traditional twist drills and innovative step drills, the following criteria were considered:

- Delamination factor (F_d), adjusted delamination factor (F_{da}): smallest value (as close to 1 as possible).
- Hole diameter: closeness to the nominal hole diameter (6.35 mm).
- Hole roundness: closeness to a perfect circumference (roundness = 1).

3.1. Tool wear

For each drilling condition, 6 VB values (3 for each) were measured and averaged to describe the tool wear development. The average VB values were plotted with different colors for each process condition in **Errore. L'origine riferimento non è stata trovata.**.

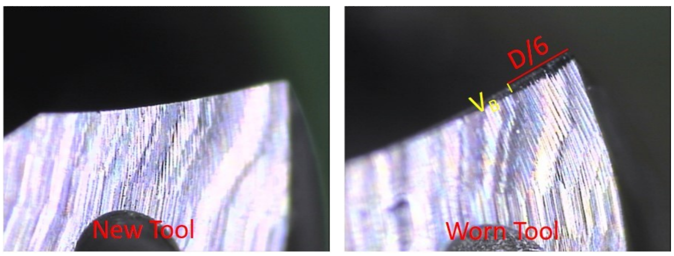

Fig. 4. Tool wear evaluation for TC tool: a traditional tool, T, operating with process conditions C (6000 rpm – 0.15 mm/rev).

Tool wear appears to progress more rapidly for the traditional twist drills than for the innovative step drills; this may depend on two issues:

- Innovative step drills also cut with margins and, therefore, a portion of the wear develops on them.
- VB is measured at D/6 which is 6.35/6 = 1.06 mm for traditional twist drills and 4.35/6 = 0.73 mm for step drills.

These issues make the data not directly comparable. Among the traditional twist drills, those showing lower wear growth are the TC, TD and TF tools. Among the innovative step drills, the IB, IE, IF tools displayed a better behaviour.

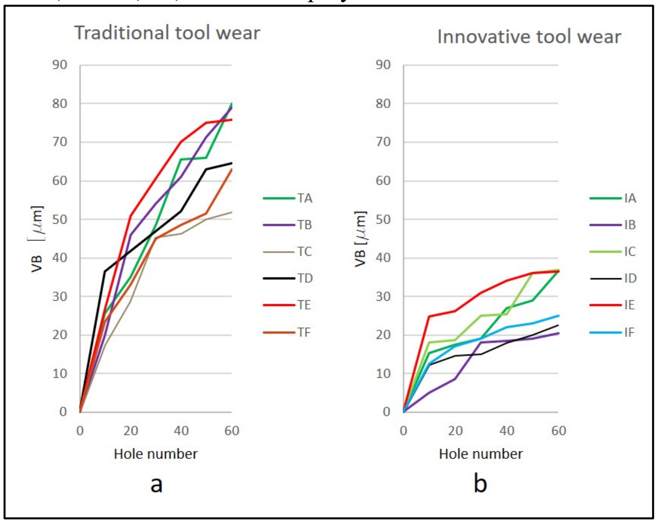

Fig. 5. Experimental tool wear curves for CFRP/CFRP stacks: (a) traditional twist drills T and (b) innovative step drills I with process parameters A to F.

3.2. Hole quality

The delamination characteristic parameters F_d and F_{da} were first measured at the hole entry on the top laminate of the CFRP/CFRP stack (Fig. 6); they are reported in Fig. 7 as a function of the hole number.

In this case, neither F_d nor F_{da} show any positive or negative trend with increasing number of holes; therefore, they seem less correlated to tool wear progression. The same behavior was found for all the tests performed; for this reason, the following sections will only refer to the hole exit delamination (push out delamination).

The traditional twist drills and the innovative step drills were compared in order to evaluate the best performing ones for each process condition.

The comparison between the results in terms of hole quality of traditional and innovative tools for process condition A is shown in Fig. 8-Fig. 11 by way of example.

The global results in terms of best tool for each process condition are reported in Table 2.

To identify the process conditions providing the best results, the top performing tools for each hole quality parameter were compared following the criteria discussed at the beginning of this section.

To improve the readability of the graphs reporting the evaluation of Fd, Fda and hole diameter (Fig. 14- Fig. 13), not all the process conditions were reported. The charts display the best performing tools together with the worst ones for the specific hole quality parameters.

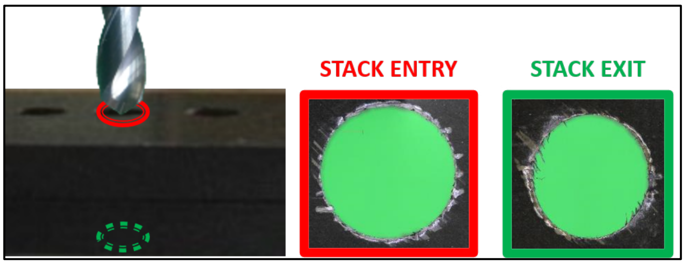

Fig. 6. Localization of hole images acquired on the CFRP/CFRP stack

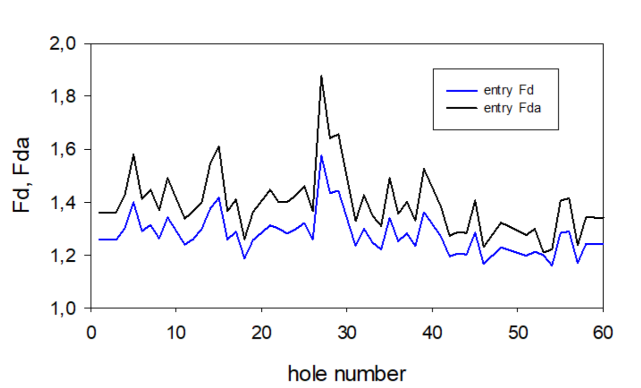

Fig. 7. Entry delamination vs hole number: traditional twist drill T, process condition C (6000 rpm – 0.15 mm/rev).

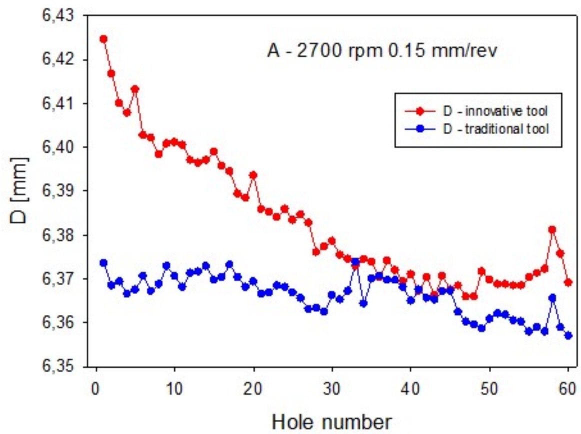

Fig. 8. Hole diameter for traditional twist drill and innovative step drill: process condition A (2700 rpm – 0.15 mm/rev).

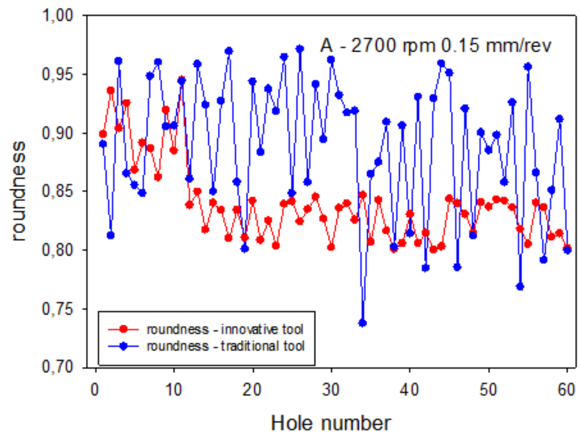

Fig. 9. Hole roundness for traditional twist drill and innovative step drill: process condition A (2700 rpm – 0.15 mm/rev).

As regards the Fd and Fda factors, similar considerations can be made. For both factors, the tools providing the best results (close to 1) are the traditional twist drills T working under process conditions C and D (TC, TD). The values are generally lower than 1.5 for Fd and 1.8 for Fda. The tool displaying the worst delamination results is the innovative step drill I working under process conditions B (IB): the average values are Fd = 1.7 and Fda = 2.2, exceeding the average values for the best tools by 0.4 for Fd and 0.8 for Fda.

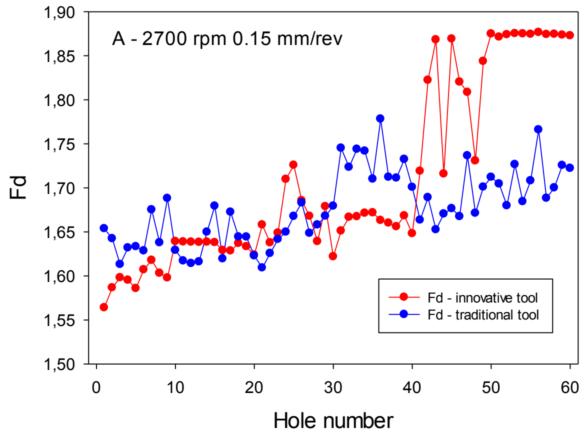

Fig. 10. Hole delamination factor, Fd, for traditional twist drill and innovative step drill: process condition A (2700 rpm – 0.15 mm/rev).

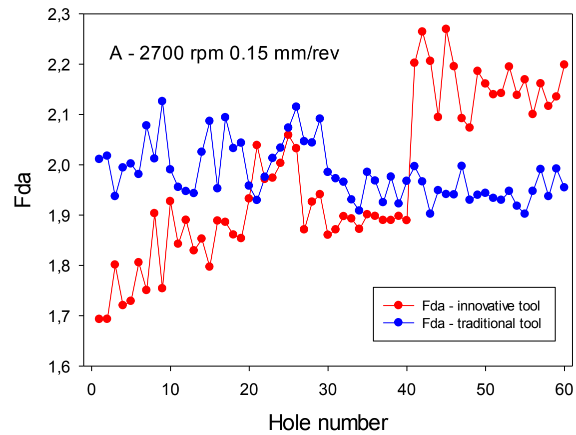

Fig. 11. Hole adjusted delamination factor, Fda, for traditional twist drill and innovative step drill: process condition A (2700 rpm – 0.15 mm/rev).

Table 2. Best performing tool for each process condition and quality parameter.

Process condition	Fd	Fda	Diameter	Roundness
A	T	T	T	T
B	I	I	T	T
C	T	T	T	T
D	T	T	T	T
E	T	T	T	T
F	I	I	I	T

The tools providing the best results in terms of hole diameter (as close as possible to nominal diameter 6.35 mm) are the traditional tools working under process conditions C and D (TC, TD). In the same chart, the innovative step drill I

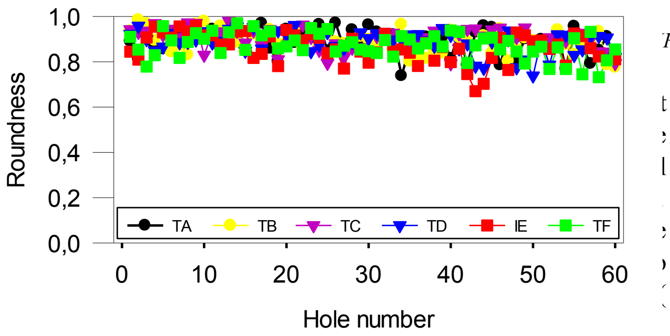

Fig. 15). Table 3 reports the obtained results: all roundness values are in the range 0.65-0.98 and the tools providing the most satisfactory results are the traditional tools T working under process conditions C and D (TC, TD).

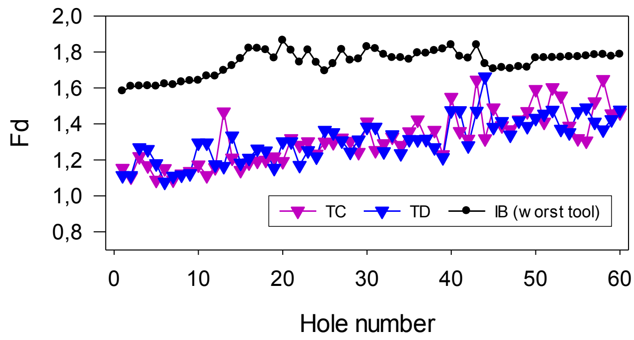

Fig. 12. Best and worst performing tools in terms of delamination factor, Fd.

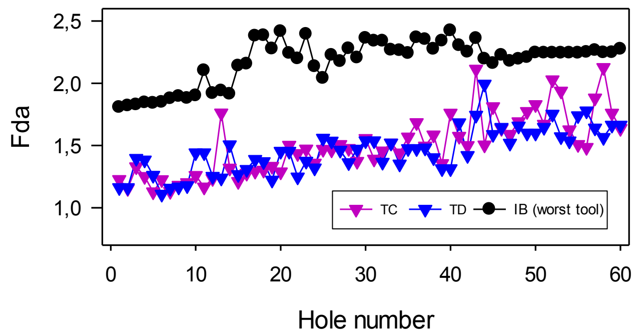

Fig. 13. Best and worst performing tools in terms of adjusted delamination factor, Fda.

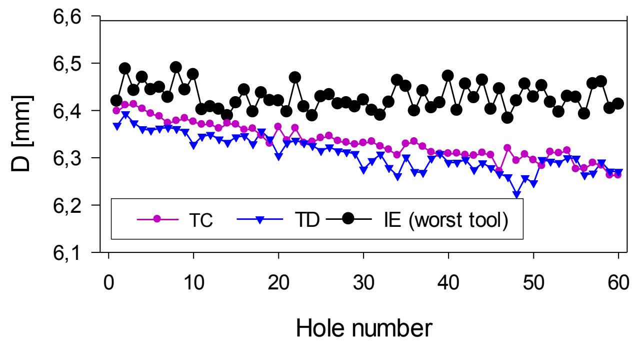

Fig. 14. Best and worst performing tools in terms of hole diameter, D.

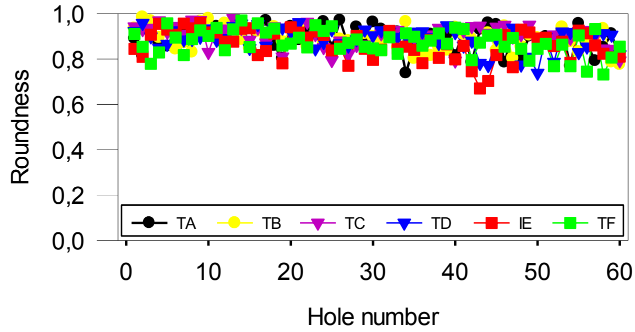

Fig. 15. Performance of all tools in terms of hole roundness.

Table 3. Tool performance in terms of hole roundness.

	Fd	Fda	Diameter	Roundness
Best performing tools	TC/TD	TC/TD	TC/TD	All tools in the acceptable range

4. Conclusions

The purpose of this work was to lay the foundation for the on-line assessment of hole quality and tool wear during drilling of CFRP/CFRP stacks through in-process image acquisition and processing. Drilling tests were carried out with a traditional twist drill and an innovative step drill under different process conditions.

The most significant parameters for assessing the hole quality in CFRP stack laminates were identified in terms of delamination (Fd, Fda) and geometrical characteristics (diameter, roundness).

An optical measuring machine was used to measure tool wear after a given number of drilled holes and to capture magnified hole images for the estimation of features describing the hole quality in terms of exit delamination.

An automatic procedure for image analysis was developed to estimate all the parameters related to the hole quality.

Drilling tests were carried out on CFRP/CFRP stacks with different feed rate and spindle speed values using traditional twist drills and innovative step drills to select the best process parameters and most suitable tool geometry for CFRP/CFRP stack drilling. The following results were obtained:

- Innovative step drills are less effective than traditional twist drills.
- The best process parameters are 6000 rpm - 0.2 mm/rev and 6000 rpm - 0.15 mm/rev.
- The study of tool wear confirms the obtained results.

In the framework of future manufacturing foresight and Industry 4.0 [22,23] the implementation of an on-line image acquisition system to capture drilled hole images is the future progress for the development of a machine learning procedure for automatic evaluation of hole quality.

Acknowledgements

The Fraunhofer Joint Laboratory of Excellence on Advanced Production Technology (Fh J_LEAPT UniNaples) at the Dept. of Chemical, Materials and Industrial Production

Engineering, University of Naples Federico II, is gratefully acknowledged for its support to this research activity.

References

[1] Campbell FC. Structural composite materials. 2010.

[2] M'Saoubi R, Axinte D, Soo SL, Nobel C, Attia H, Kappmeyer G, et al. High performance cutting of advanced aerospace alloys and composite materials. CIRP Annals - Manufacturing Technology 2015; 64: 557–580. doi:10.1016/j.cirp.2015.05.002.

[3] Zitoune R, Krishnaraj V, Collombet F. Study of drilling of composite material and aluminium stack. Compos Struct 2010; 92: 1246–1255. doi:10.1016/j.compstruct.2009.10.010.

[4] Fleischer J, Teti R, Lanza G, Mativenga P, Möhring HC, Caggiano A. Composite materials parts manufacturing. CIRP Annals 2018; 67: 603–626. doi:10.1016/j.cirp.2018.05.005.

[5] Caggiano A. Machining of fibre reinforced plastic composite materials. Materials (Basel) 2018. doi:10.3390/ma11030442.

[6] Jain S, Yang DCH. Delamination-Free Drilling of Composite Laminates. J Eng Ind 1994; 116: 475–481.

[7] Karnik SR, Gaitonde VN, Rubio JC, Correia AE, Abrão AM, Davim JP. Delamination analysis in high speed drilling of carbon fiber reinforced plastics (CFRP) using artificial neural network model 2008; 29: 1768–1776. doi:10.1016/j.matdes.2008.03.014.

[8] Caggiano A, Nele L. Artificial Neural Networks for Tool Wear Prediction Based on Sensor Fusion Monitoring of CFRP/CFRP Stack Drilling. Int J Automation Technology 2018; 12: 275–281. doi: 10.20965/ijat.2018.p0275.

[9] Caggiano A, Rimpault X, Teti R, Balazinski M, Chatelain JF, Nele L. Machine learning approach based on fractal analysis for optimal tool life exploitation in CFRP composite drilling for aeronautical assembly. CIRP Annals 2018; 67: 483–486. doi:10.1016/j.cirp.2018.04.035.

[10] Dharan CKH, Won MS. Machining parameters for an intelligent machining system for composite laminates 2000; 40: 415–426.

[11] Angelone R, Caggiano A, Improta I, Nele L, Teti R. Temperature Measurements for the Tool Wear and Hole Quality Assessment during Drilling of CFRP/CFRP Stacks. Procedia CIRP 2018; 67: 416–421. doi:10.1016/j.procir.2017.12.235.

[12] Raja R, Jannet S. Experimental investigation of high speed drilling of glass fiber reinforced plastic (GFRP) composite laminates made up of different polymer matrices. Int J Mech Prod Eng Res Dev 2017; 7: 351–358. doi:10.24247/ijmperddec201739.

[13] Davim JP, Rubio JC, Abrao AM. A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates. Composite Science and Technology 2007. doi:10.1016 /j.compscitech.2006.10.009.

[14] Caggiano A, Angelone R, Teti R. Image Analysis for CFRP Drilled Hole Quality Assessment. Procedia CIRP 2017; 62: 440–445. doi:10.1016 /j.procir.2017.03.045.

[15] Caggiano A, Centobelli P, Nele L, Teti R. Multiple Sensor Monitoring in Drilling of CFRP/CFRP Stacks for Cognitive Tool Wear Prediction and Product Quality Assessment- Procedia CIRP 2017; 62: 3-8. doi:10.1016 /j.procir.2017.03.047

[16] ISO. Geometrical product specifications (GPS) — Geometrical tolerancing — Tolerances of form, orientation, location and run-out. Iso 11012012(E) 2012; 3: 110.

[17] Teti R. Tool wear monitoring through acoustic emission, CIRP Annals 1989, 38/1: 99-102. doi: 10.1016/S0007-8506(07)62660-2.

[18] D'Addona DM, Matarazzo D, Ullah AMMS, Teti R. Tool wear control through cognitive paradigms. Procedia CIRP 2015; 33: 221-226. doi: 10.1016/j.procir.2015.06.040.

[19] Karam S, Centobelli P, D'Addona DM, Teti R. Online Prediction of Cutting Tool Life in Turning via Cognitive Decision Making. Procedia CIRP 2016; 41: 927-932. doi: 10.1016/j.procir.2016.01.002

[20] Park K, Beal A, Kim DD, Kwon P, Lantrip J. Tool wear in drilling of composite / titanium stacks using carbide and polycrystalline diamond tools. Wear 2011; 271: 2826–2835. doi:10.1016/j.wear.2011.05.038.

[21] Zitoune R, El Mansori M, Krishnaraj V. Tribo-functional design of double cone drill implications in tool wear during drilling of copper mesh/CFRP/woven ply. Wear 2013; 302: 1560–1567. doi:10.1016 /j.wear.2013.01.046.

[22] Mekid S, Schlegel T, Aspragathos N, Teti R. Foresight Formulation in Innovative Production, Automation and Control Systems, The Journal of Foresight - The Journal of Futures Studies, Strategic Thinking and Policy 2008; 9/5, Emerald, ISSN 1463-6689: 35-47.

[23] Schuh G, Anderl R, Gausemeier J, ten Hompel M, Wahlster W. Industrie 4.0 Maturity Index–Managing the Digital Transformation of Companies. Acatech, Berlin, 2017.