Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 167 (2016) 206 – 215

Procedia Engineering

www.elsevier.com/locate/procedia

International Symposium on Dynamic Response and Failure of Composite Materials, DRaF2016

ANALYSIS OF THERMAL DAMAGE IN FRP DRILLING

L. Sorrentino, S. Turchetta, L. Colella, C. Bellini*

Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via G. di Biasio, 43, Cassino (FR), 03043, Italy.

Abstract

Among machining operations applied to polymeric composite materials, drilling is the more important one due to the need to implement mechanical couplings, which in most cases are not yet possible using structural adhesives. Such process is very critical because not only it causes the interruption of the fibers continuity, but also it can generate localized thermal shock in the resin, due to the presence of extremely hard and abrasive fibers and to the low thermal conductivity of the resin itself, that limits the heat dissipation. These phenomena are more severe in dry machining process, that are used in aeronautic industry. The poor FRP machinability is manifested in the induced phenomena of delamination, fragmentation and matrix thermal damage that cause negative outcomes, such as the reduction of the material fatigue strength and the consequent decay of long-term performance. The evaluation of such critical issues is possible through indirect analysis, that is through the analysis of some control parameters, such as the process forces and temperatures that assume different values depending on the combination of cutting parameters. Therefore, to acquire useful information for machining optimization is possible through process monitoring: the input data can be analyzed, processed and made available to optimize the process parameters in order to reduce critical issues such as the delamination, the fragmentation and the thermal damage.

The present work deals with the problem of damage due to the high temperatures reached during the FRP dry drilling process. The temperature was measured by K type thermocouples positioned in the workpiece, near the hole surface, and it was evaluated as a function of the main process parameters in order to estimate the critical cutting conditions that lead to critical temperature overcoming.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Organizing Committee of DRaF2016

Keywords: *CFRP (Carbon Fiber Reinforced Polymer); dry drilling; in process monitoring; temperature trends; process parameters; multisensorial system*

* Corresponding author. Tel.: +39-0776-2993698; fax: +39-0776-2993886.
E-mail address: c.bellini@unicas.it

1877-7058 © 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the Organizing Committee of DRaF2016
doi:10.1016/j.proeng.2016.11.689

1. Introduction

The fiber reinforced composite laminates mainly used in industries are CFRP (Carbon Fiber Reinforced Polymer) and GFRP (Glass Fiber Reinforced Polymer). Due to their considerable advantages in terms of performance, such as high strength-weight and stiffness-weight ratios, they are used to replace the traditional metal materials in a large range of sectors (aerospace, aeronautics, military) [1÷3]. Even if the composite components are designed to limit the machining operations, these often play an important role because they allow mechanical joints that cannot be performed by bonding. In fact, for the realization of the more complex assemblies, in which contributing components are made of different materials, the mechanical joints are made by rivets and bolts, so the execution of the holes becomes inevitable. Holes should be limited as much as possible as they cause the interruption of the fibers continuity and, consequently, the decrease of the resistance of the parts. In the drilling operation, the poor machinability of composite materials induces some phenomena such as delamination, fragmentation, thermal damage, low surface quality. These induced events generate negative effects such as the drastic reduction in fatigue strength of the material and the consequent degradation of the long-term performance. In order to minimize the described phenomena, to control some key parameters, such as the thrust force and the temperature reached during the cutting process, is necessary [4÷10]. They assume different values and meanings in function of the different drilling technologies that are currently used in FRP drilling, such as Conventional Drilling (CD) (cutting speed <100m/min; <8000rpm) or High Speed Drilling (HSD) (cutting speed >200m/min), and in function of the combination of cutting parameters [8]. In the aeronautical field, the use of refrigerant fluid during the machining of composite components is not allowed. The refrigerant fluid is considered detrimental to the maintenance of the chemical-physical characteristics of the resins of the composite materials. Therefore, dry cutting is preferred for such applications [11÷13]. In these conditions, the control of the process temperature becomes crucial as it is related to thermal matrix damage induced by machining.

The subjects of this study are based on the traditional mechanical machining, paying particular attention to the sensory monitoring of such processes and to the difficult machinability of materials such as polymer matrix composite laminates (FRP). In particular, the analysis was focused on the heat generation that inevitably appears on the surfaces of the machined piece due the tool-workpiece contact during processing. If this heat is not prevented or properly discarded, the limit temperature of the resin may be reached on the workpiece and thermal degradation processes may start. For a typical epoxy-based matrix, the critical degradation temperature ranges from 120 °C to 270 °C. The monitoring of the process temperature passes through both the analysis of heat transfer models, to know the temperature distribution on the workpiece, and the knowledge of the sensors types and monitoring systems placed on the tool edge and in the workpiece. The prediction of the temperature distribution in the workpiece can give useful information to optimize the cutting process, especially for CFRP [14÷20]. A bibliographic study revealed that for this purpose the most commonly used sensor was K type thermocouple (sensibility 41 μV/°C; ∅ = 0.1÷0.3 mm); their reliability was proved by comparing the measurements with values from other instruments, such as pyrometers and infrared cameras [14]. In [21] it was observed that the increase of temperature on the tool cutting edges during the CFRP drilling was lower than metallic materials drilling. This phenomenon can be attributed to the smaller amount of heat that is generated during the plastic deformation because CFRP laminates are brittle and chip is pulverized in the process.

The purpose of this work was the monitoring of the temperature measured in proximity of the machined surface during the dry drilling operation of polymer matrix composite laminates. In particular, it analyzed the temperature trend as a function of the main process parameters in both the traditional drilling and the high speed drilling, for two types of composite materials, with the objective of limiting the thermal damage due to the high temperatures reached near the hole surface.

2. Experimental activities

The experimental system used for the execution of the drilling tests was constituted by a CNC machining center, reported in figure 1a, and by a multi-sensory system, as described in [22]. The CNC was a three axes work center with a spindle power of 13.5 kW and a maximum speed of 15000 rpm. The multi-sensory system that allowed the in-process temperature monitoring during the drilling operation consisted of the following components:

- K type thermocouple (TERSID mod. HF/D-30-KK);
- Terminal block (National Instruments mod. CB-68LP);
- Acquisition board (National lnstruments PCl-6034E 200 kS/s, 16-Bit);
- LabVIEW® user interface.

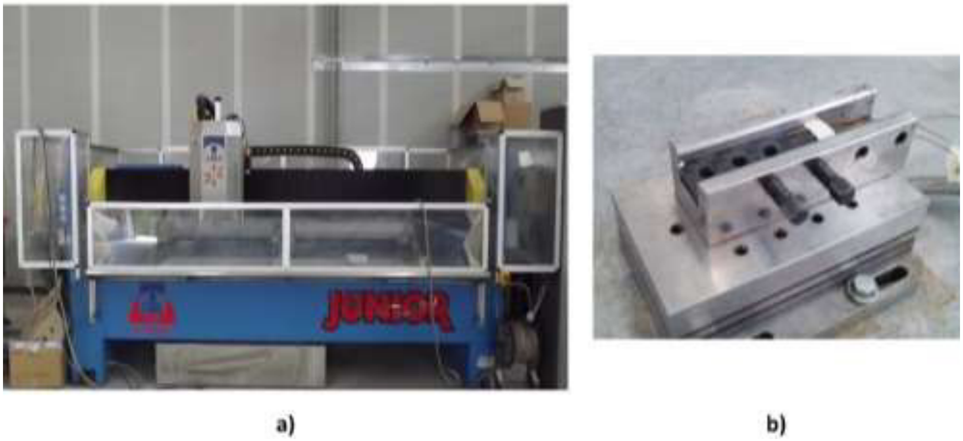

Fig. 1. (a) CNC machining center; (b) clamping system.

During machining each sensor emitted a voltage signal that was sent directly to the acquisition board through the terminal block CB-68LP. The acquisition board PCI-6034E was installed on the PC motherboard and it was connected to the terminal block CB-68LP through a multipin flat cable. The temperature sensors (generally the type K thermocouples generate tensions of tens of mV) were connected on this terminal block. The multi-sensory Data Acquisition System (DAQ), schematized in Figure 2, was interfaced with the Personal Computer equipped with a LabVIEW® application, suitably designed for signals acquisition and data storing. The used thermocouples presented a polyamide insulation for low and medium temperature (from -240°C to +260°C). They were characterized by a typical sensitivity of 41 μV/°C and a cable diameter of 0.25 mm.

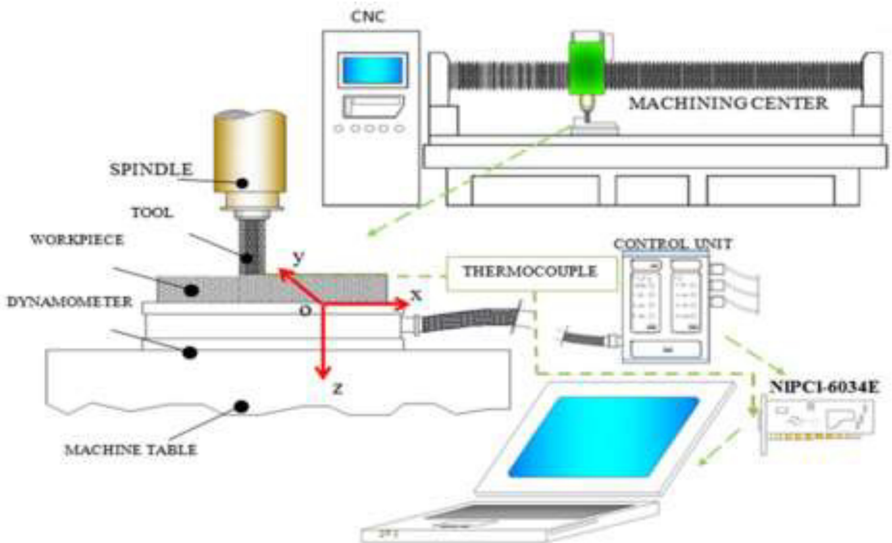

Fig. 2. Multisensorial System logic diagram.

Two types of specimens were tested: carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). They were manufactured following the standard vacuum bagging procedure and their dimensions were 100x24x8 mm.

GURIT SE70/RC303T/1270/38% prepreg type was used for CFRP. It was constituted by a carbon fiber twill fabric of 303 g/m^2, impregnated with SE70 epoxy resin, in percentage of about 38%. GFRP specimens were made of unidirectional glass fibers (0°÷90°) impregnated with CYCOM® 5216 modified epoxy resin, in a percentage of about 55%. The tool used in the tests was a twist drill in tungsten carbide and cobalt.

After thermal cure, the thermocouples were integrated inside the specimens through micro holes, arranged as in Figure 3. The micro holes were made using a helical drill bit with a diameter of 1 mm. The T1 thermocouple was placed at 1 mm from the hole, while the T2 thermocouple was placed at 3 mm.

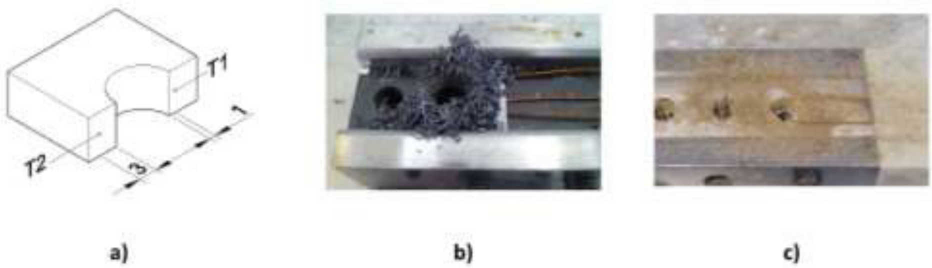

Fig. 3. (a) thermocouples arranged in the specimen; (b) CFRP specimen mounted in the test blocking system; (b) GFRP specimen mounted in the test blocking system.

The drilling tests were carried out according to the experimental plan shown in Table 1.

Table 1. Experimental plan.

Factors	# Levels	Levels
Cutting speed "Vc"[m/min]	3	47 – 251 – 376

Feed per revolution "f"[mm]	4	0.10 – 0.15 – 0.20 – 0.30
Materials	2	CFRP - GFRP
Replications	3	

3. Results

Signals from the thermocouples were acquired for each test condition. In Figure 4 there is the typical temperature versus time trend perceived by thermocouples for the CFRP drilling, relatively to the process condition of 251 m/min and feed rate of 0.10 mm/rev. As reported in the graph, the temperature increased almost linearly with the time during the machining, then it reached a maximum value and it started to decrease. In this case, the maximum temperature measured by the thermocouple placed at 1 mm from the hole surface was approximately 70 °C, while that one measured at 3 mm was about 55 °C.

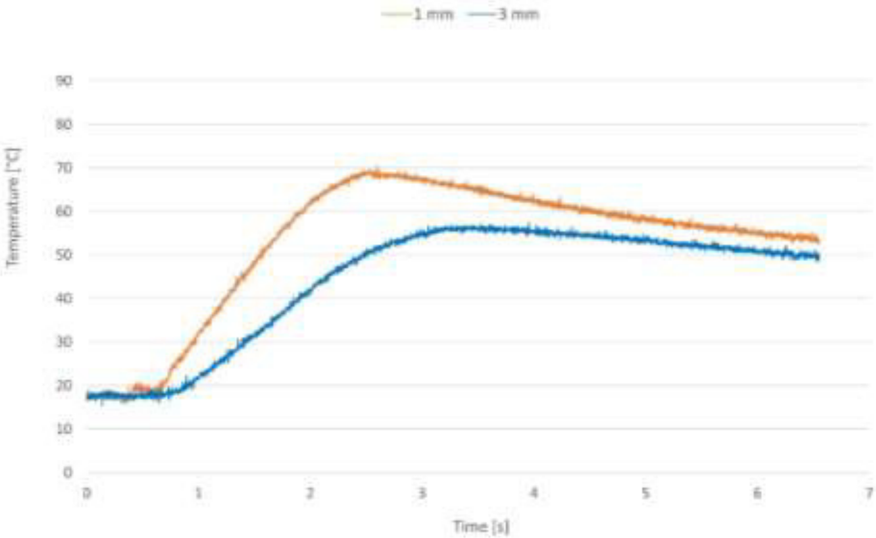

Fig. 4. Typical temperature versus time trend for CFRP drilling, with Vc=251 m/min and f=0.10mm/rev.

Figure 5 shows the temperature as a function of time measured by the two thermocouples during GFRP drilling. The drilling parameters were the same as the previous operation. As reported in the graph, the temperature trend was different from CFRP drilling. In fact, it rapidly increased in the first phase of machining and then it increased less quickly. Then the temperature reached a maximum value and finally it decreased at a slower rate. In this case, the maximum temperature measured by the thermocouple placed at 1 mm from the hole reached a maximum value of about 65 °C, while the maximum temperature measured by the thermocouple placed at 3 mm was about 30 °C.

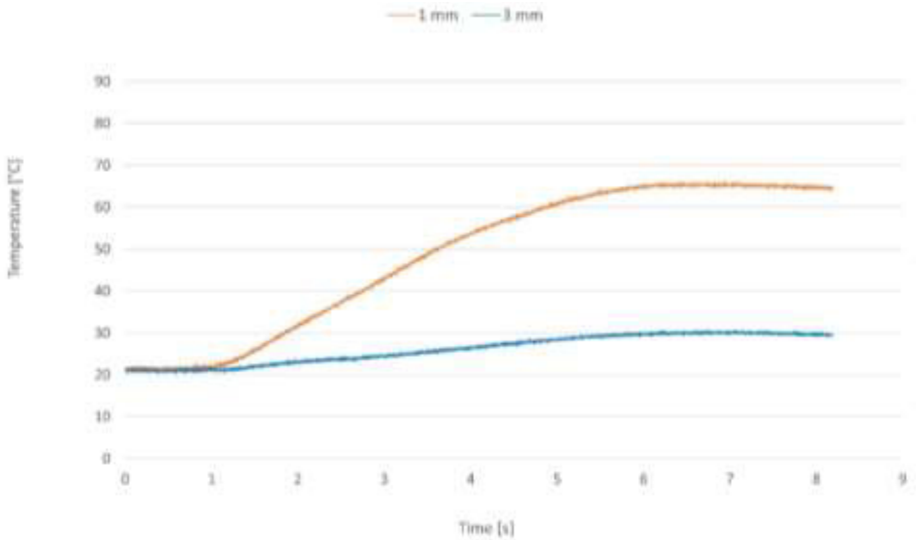

Fig. 5. Typical temperature versus time trend for GFRP drilling, with Vc=251 m/min and f=0.10mm/rev.

The figures 6-8 show the maximum temperature measured by both thermocouples (placed at 1 mm and 3 mm) as a function of feed rate, during CFRP drilling, for each different value of cutting speed. Figure 6 shows the temperature trend relatively to the cutting speed of 47 m/min. As reported in the graph, the temperature measured by the two thermocouples decreased with increasing feed rate. In particular, it passed from about 90 °C to about 60 °C for the closest thermocouple, while for the farthest it passed from about 57 °C to 50 °C.

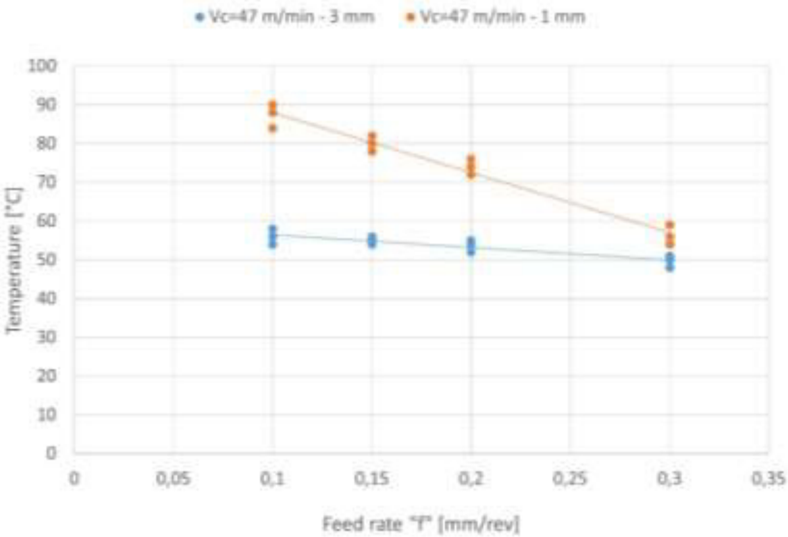

Fig. 6. Temperature trend as a function of feed rate for a cutting speed of 47 m/min during CFRP drilling.

Figure 7 shows the temperature trend as a function of feed rate for a cutting speed of 251 m/min. As reported in the graph, the temperature measured by the two thermocouples little varied with the feed rate. In particular, the maximum temperature measured by the thermocouple placed at 1 mm from the hole was approximately 70 °C, while that one measured by the thermocouple placed at 3 mm was about 60 °C. These values, compared with those ones recorded for a lower cutting speed of 47 m/min, show that the temperature, measured at 3 mm from the hole, assumed similar values independently of the cutting speed, while the temperature at 1 mm from the hole was lower for the higher values of cutting speed.

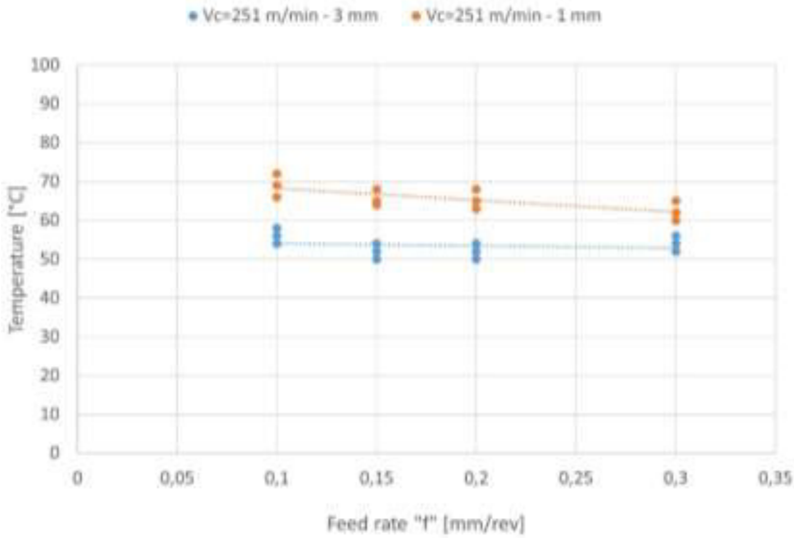

Fig. 7. Temperature trend as a function of feed rate for a cutting speed of 251 m/min during CFRP drilling.

As regards drilling with cutting speeds of 376 m/min, shown in Figure 8, a behavior similar to that recorded for the previous case was found, even if the temperatures were about 10 °C higher.

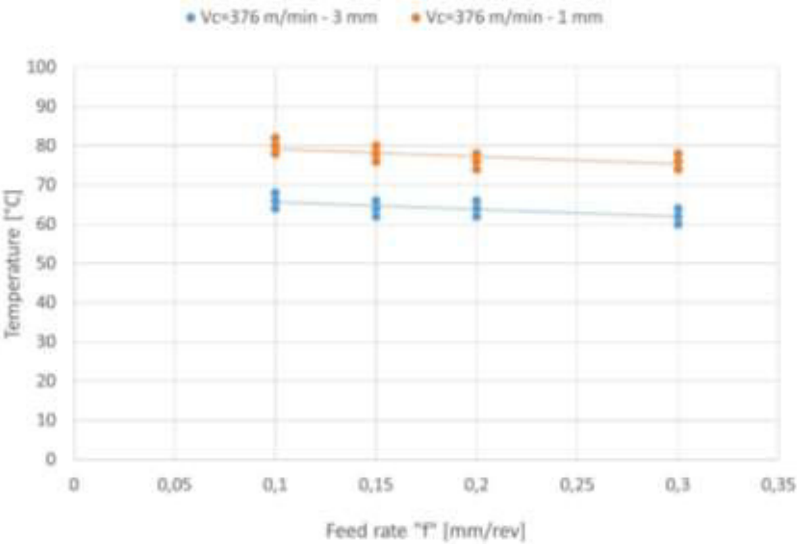

Fig. 8. Temperature trend as a function of feed rate for a cutting speed of 376 m/min during CFRP drilling.

The figures 9-11 report the temperature trend as a function of feed rate for GFRP drilling. Figure 9 shows the temperature trend registered by both thermocouples for a cutting speed of 47 m/min. In such a case, as pointed out by the graph, the temperature was independent from the feed rate. In particular, the temperature registered by the thermocouple placed at 1 mm from the hole was about 50 °C, while that one measured at 3 mm from the hole was about 30 °C.

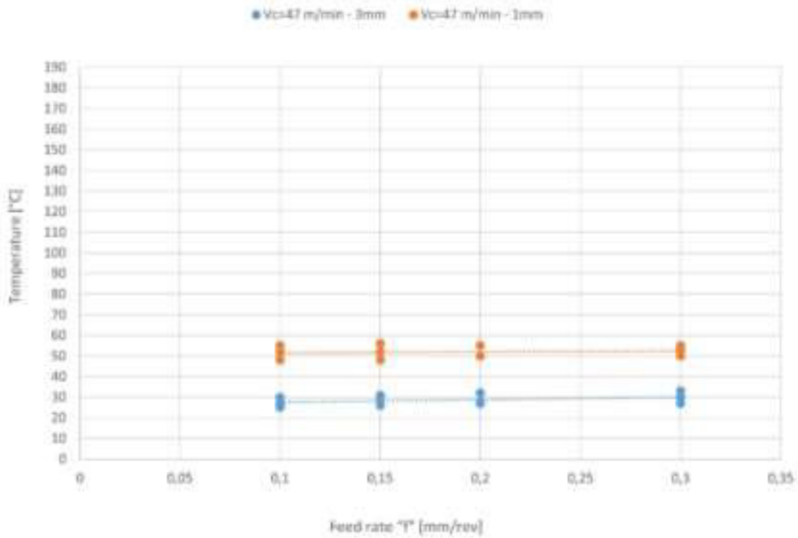

Fig. 9. Temperature trend as a function of feed rate for a cutting speed of 47 m/min during GFRP drilling.

Figures 10 and 11 refer to GFRP drilling with high cutting speed. In particular, cutting speed of 251 m/min and 376 m/min were analyzed. As reported in the two figures, the temperature linearly increased with increasing feed rate. For a cutting speed of 251 m/min, the maximum temperature registered by the thermocouples placed at 1 mm from the hole was about 100 °C, while the thermocouple placed at 3 mm found a maximum temperature of 40 °C. For a cutting speed of 376 m/min the maximum temperature registered by the thermocouple placed ad 1 mm from the hole was about 180 °C, while the temperature measured by the other thermocouple was about 50 °C. It must be noted that the former temperature was higher than the maximum tolerable one for this resin. In fact, the surface of the machined hole got darker, pointing out a resin degradation.

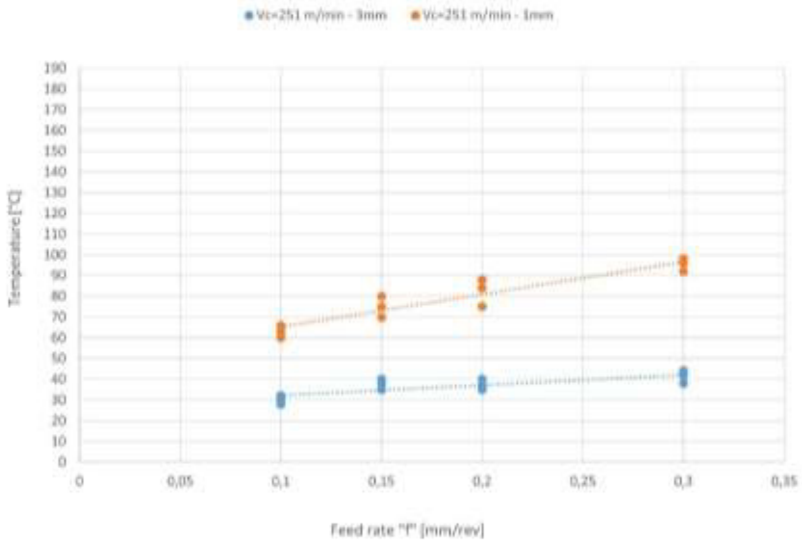

Fig. 10. Temperature trend as a function of feed rate for a cutting speed of 251 m/min during GFRP drilling.

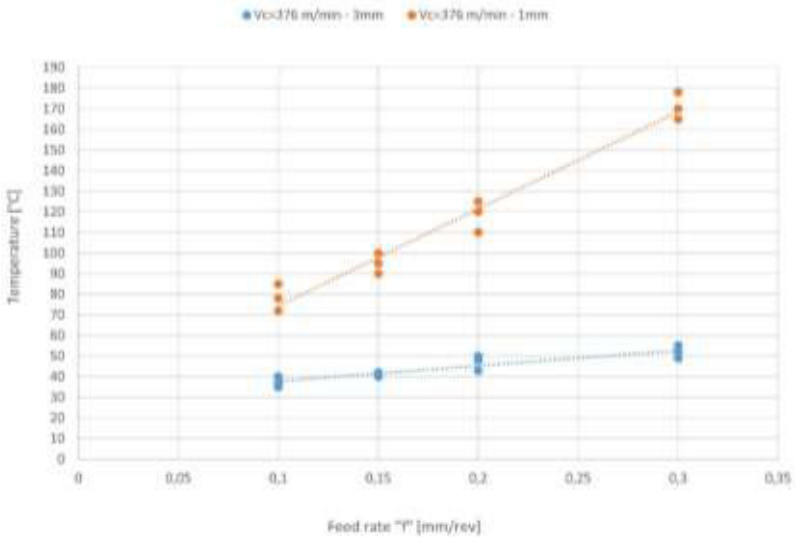

Fig. 11. Temperature trend as a function of feed rate for a cutting speed of 376 m/min during GFRP drilling.

As regards the temperature reached near the hole, comparing the results of both materials, an opposite behavior was noted. The CFRP, when machined at low cutting speed, reaches higher temperatures with low feed rate values, while for the GFRP the temperature was independent of feed rate. Moreover, for higher cutting speeds, the temperatures registered for CFRP were inclined to be lower. On the contrary, the behavior of GFRP was the opposite because higher temperatures were reached with high cutting speeds and with high feed rates. This behavior can be explained in the light of the higher thermal conductivity of CFRP compared to GFRP.

As it can be seen from the results, the maximum temperature recorded at 1 mm from the surface of the hole during CFRP drilling with low cutting speeds, that is in the traditional drilling, was about 90 °C. This value, that was already less than the critical temperature of the considered resin, further decreased at higher cutting speed, reducing the risk of thermal damage. On the contrary, too high temperature, that were critical for the resin, were reached for GFRP machining with high cutting speed, consequently the thermal damage was detected on the hole surface. For the considered GFRP, dry drilling at high cutting speed is possible up to 250 m/min. Above this value, the too high achieved temperatures generated an inevitable thermal damage in the material.

4. Conclusions

In the present work, dry drilling operation on both CFRP and GFRP was studied. In particular, the temperature trends reached in two different points (1mm and 3 mm from the hole surface) were measured by thermocouples and analyzed. It was found that the maximum temperature reached near the hole surface decreased with the increase of feed speed for CFRP, while it increased with feed speed for GFRP. Moreover, in CFRP drilling a reduction of temperature was found with the increase of cutting speed, while in GFRP drilling an intensification over the critical temperature threshold was found, consequently inducing a thermal damage in the material due to drilling operation.

References

[1] L. Sorrentino, M. Marchetti, C. Bellini, A. Delfini, M. Albano, Design and manufacturing of an isogrid structure in composite material: Numerical and experimental results, Compos. Struct. 143 (2016) 189–201.

[2] L. Esposito, L. Sorrentino, F. Penta, C. Bellini, Effect of curing overheating on interlaminar shear strength and its modelling in thick FRP laminates, Int. J. Adv. Manuf. Technol. (2016) 1–8, in press.

[3] L. Sorrentino, C. Bellini, D. Capriglione, L. Ferrigno, Local monitoring of polymerization trend by an interdigital dielectric sensor Int. J. Adv. Manuf. Technol. 79 (2015) 1007-1016.
[4] W. Hufenbach, L. A. Dobrzan´ ski, M. Gude, J. Konieczny, A. Czulak, Optimisation of rivet joints of CFRP composite material and aluminium alloy. J. Achieve Mater. Manuf. Eng. 20 (2007) 119–122.
[5] R. Teti, Machining of composite materials. CIRP Annals – Manuf. Technol. 51 (2002) 611–634.
[6] A.M. Abrao, P.E. Faria, J. C. Campos Rubio, P. Reis, J.P. Davim, Drilling of fiber reinforced plastics: a review, J. Mater. Process. Technol. 186 (2007) 1–7.
[7] R. Mishra, J. Malik, I. Singh, J.P. Davim, Neural network approach for estimate the residual tensile strength after drilling in uni-directional glass fiber reinforced plastic laminates, Mater. Des. 31 (2010) 2790–2795.
[8] D.F. Liu, Y. J. Tang, W. L. Cong, A review of mechanical drilling for composite laminates, Compos. Struct. 94 (2012) 1265–1279.
[9] S. Turchetta, Cutting force in stone machining by diamond disk, Advances in Materials Science and Engineering 2010, Article ID 631437, 6 pages, doi: 10.1155/2010/631437.
[10] L. Carrino, W. Polini, S. Turchetta, Wear progression of diamond mills, Diam. Relat. Mater. 12 (2003) 728-732.
[11] T. Yashiro, T. Ogawa, H. Sasah, Temperature measurement of cutting tool and machined surface layer in milling of CFRP, Int. J. Mach. Tools Manuf. 70 (2013) 63–69.
[12] T. L. Wong, S. M. Wu, G. M. Croy, An analysis of delamination in drilling composite materials, in: 14th National SAMPE technology conference, Atlanta, GA, USA, 1982. pp. 471–483.
[13] R. Stone, K. Krishnamurthy, A neural network thrust force controller to minimize delamination during drilling of graphite-epoxy laminates, Int. J. Mach. Tools Manuf. 36 (1996) 985–1003.
[14] J. Liu, G: Chen, C. Ji, X. Qin, H. Li, C. Ren, An investigation of workpiece temperature variation of helical milling for carbon fiber reinforced plastics, Int. J. Mach. Tools Manuf. 86 (2014) 89–103.
[15] S. Jahanmir, M. Ramulu, P. Koshy, Machinig of ceramics and composites, Marcel Dekker, Inc.1999, ISBN 082470178X.
[16] N. Koboević, M. Jurjević, Ž. Koboević, Influence of cutting parameters on thrust force, drilling torque and delamination during drilling of carbon fibre reinforced composites, Technical Gazette 19 (2012) 391-398.
[17] V. Krishnaraj, A. Prabukarthi, A. Ramanathan, N. Elanghovan, M.S. Kumar, R. Zitoune, J.P. Davim, Optimization of machining parameters at high speed drilling of carbon fiber reinforced plastic (CFRP) laminates, Compos. Part B- Eng. 43 (2012) 1791–1799.
[18] C.C. Tsao, H. Hocheng, Y.C. Chen, Delamination reduction in drilling composite materials by active backup force, CIRP Annals – Manuf. Technology 61 (2012) 91–94.
[19] K. Kerrigan, J. Thil, R. Hewison, G.E. O'Donnell, An integrated telemetric thermocouple sensor for process monitoring of CFRP milling operations, Procedia CIRP 1 (2012) 449 – 454.
[20] Y. Takeshi, O. Takayuki, S. Hiroyuki, Temperature measurement of cutting tool and machined surface layer in milling of CFRP, Int. J. of Mach. Tools Man. 70 (2013) 63–69.
[21] W.C. Chen, Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates, Int. J. of Mach. Tools & Man. 37 (1997) 1097–1108.
[22] L. Sorrentino, S. Turchetta, C. Bellini, L. Colella, In-process force and temperature monitoring while drilling composites, JEC Compos. Mag. 102 (2016) 46-48.