Assessment of surface integrity and dust while drilling of GLARE® FMLs

Imed Boughdiri1[1], Tarek Mabrouki[1], Redouane Zitoune[2], Khaled Giasin[3]

[1] Applied Mechanics and Engineering Laboratory (LR-11-ES19), University of Tunis El Manar, ENIT, BP 37, Le Belvédère, 1002 Tunis, Tunisia.

imed.boughdiri@enit.utm.tn, tarek.mabrouki@enit.utm.tn

[2] Clément Ader Institute, UMR CNRS 5312, University of Toulouse, Toulouse, France.

redouane.zitoune@iut-tlse3.fr

[3] School of Mechanical and Design Engineering University of Portsmouth. Portsmouth, UK.
khaled.giasin@port.ac.uk

Abstract. Fiber-metal laminates represent a promising type of hybrid material, resulting from the combination of a metal, usually an aluminum alloy, and a fiber-reinforced composite, such as a glass-fiber reinforced epoxy. Currently, GLARE (a fiberglass/aluminum composite) is used by many aerospace manufacturers for primary aircraft components. Few researchers have investigated this type of hybrid material in terms of cutting effort and hole quality, but none have studied the impact of machining on operator health. The present work aims to investigate the effects of input cutting parameters and the tool coating when drilling multi-material type GLARE® on finish roughness and generation of aerosol dust particles. The drilling tests were carried out using uncoated tools and coated ones with a thin film of diamond-like carbon (DLC) and Cristal. After drilling operations, obtained results reveal that DLC coated tools induced less roughness when compared to uncoated ones or Cristal coated drill. In addition, dust particle number generated while tests conducting, is affected by input cutting parameters. A lower speed of spindle promotes the diminution of the quantity of particles in the workplace compared to that recorded at higher speed of the spindle.

Keywords: Drilling, GLARE®, Coated tools, Hole quality, Dust.

1 Introduction

Novel issues arise during the drilling of hybrid and composite structures especially for Glass Aluminum Reinforced Epoxy (GLARE®), since a great number of holes are needed with high quality requirements. In addition, the low quality of drilled hole induces 60 % rejection of achieved pieces (Giasin et al. 2015). Therefore, optimization of cutting parameters when drilling FMLs with its different components will ensure good surface quality. Regardless, hole with geometric defects can induce severe strains on the fasteners, yielding important damage to structure (Ashrafi et al. 2013). In literature, few researchers have proposed understanding to explain these weaknesses and their investigations were mainly based on hole surface quality. (Giasin et al. 2019) have underlined that roughness parameters (Ra and Rz) were higher when drilling GLARE® laminates using tools coated with TiAlN than those coated with TiN and AlTiN/TiAlN. They have noted that those criteria are higher with spindle speed increase, although their variations. When drilling composite/metal material, (Zitoune et al. 2010) have found that the higher is the feed rate, the higher is the Ra, whereas the speed spindle has a less impact on surface finish roughness.

when drilling GLARE® 3 4/3-0.4 using cemented carbide tools, (Park et al. 2017) have reported that a combination of low spindle speed rotation (600 rpm) and high feed rate (0.2 mm/rev) induces the highest surface roughness. Many works have been conducted on cryogenic cooling (Giasin et al. 2021) and minimum quantity lubrication (MQL) (Giasin et al. 2018) when drilling GLARE® type multi-materials. Indeed, authors mentioned that the use of minimum quantity lubrication and liquid nitrogen cryogenic coolant can reduce the surface roughness of drilled holes.

Nevertheless, only few research works are dealing with the investigation of the health hazards induced by dust particle generation during cutting operations (Haddad et al. 2014). During trimming achievements, Nguyen-Dinh et al. (Nguyen-Dinh et al. 2020) emphasized that harmful dust amount evolves in the same direction as that of the feed rate and inversely decreases with spindle speed. . Other authors (Djebara et al. 2013) indicated that the higher the spindle speed and feed rate, the lower the emission of dust during machining. (Haddad et al. 2014) found that fine airborne dust particles released when cutting carbon fiber reinforced plastic materials at conventional speeds. Moreover, these authors have remarked that high trimming speeds affect operator health, significantly. The size of these harmful particles depends on the geometries of milling tools.

In this framework, we intend to assess the effect of feed rate, spindle speed and coating tools on surface roughness evolution and dust generation while drilling composite GLARE® 2B 11/10-0.4 using an uncoated and coated tungsten carbide (K20) tool. The investigation will guide researchers to use optimized drilling conditions that induced the better surface finish and minimize harmful particles releasing.

2 Experimental setups

The drilling tests were performed by using a HSM machine tool which is referenced DMU 85 mono BLOCK CNC center with a maximum spindle rotation speed of 18000 rpm. The experimental procedure, as schematically illustrated in Fig. 1(b), consisted in using a force-torque dynamometer (piezoelectric Kistler 9272 dynamometer, model 5019) in which the GLARE sample is mounted, and a GRIMM aerosol spectrometer is exploited to detect ejected particles. In order to facilitate the mounting of the GLARE specimens on the dynamometer, the GLARE specimen was cut into test samples by water jet technology using the MACHINE FLOW MACH4-C abrasive water jet machine. Prior to the drilling trials, the drill must be firmly fastened to the tool holder by means of a thermal shrinkage process using an Easyshrink® 15 shrinkage bench. All trials performed in this investigation were performed in dry condition and were repeated three times to confirm the repeatability. Each ten holes set were drilled with new tool to avoid any effect on tool wear and aluminum alloy built up at drill edges.

. Drilling trials of GLARE® 2B 11/10-0.4 samples were established using coated and uncoated cemented carbide twist drills (grade K20) with a fixed diameter of 6 mm. The tool coatings are Diamond-Like Carbon (DLC) and Cristal. In this work, tools are coded by T1, T2 and T3 as shown in Fig. 1. The measuring of surface roughness was done by a Mitutoyo SJ-500/P surface instrument (Fig. 2(b)). The quantity of particles released in the air during experimental tests of GLARE® drilling was calculated with GRIMM aerosol spectrometer (Fig. 2(a)).

Mechanical property	**Symbol**	**UD S2/FM94 epoxy prepeg**	**Al2024-T3**
Young modulus (GPa)	E_{11}	54-55	72.2
	E_{22}, E_{33}	9.4-9.5	-
Ultimate tensile strength (MPa)	σ_{ult}	2640	455
Ultimate strain (%)	ε_{ult}	4.7	19
Shear modulus (GPa)	G_{12}	5.55	27.6
	G_{23}	3	-
	G_{13}	5.55	-
Poisson's ration	υ_{12}	0.33	0.33
	υ_{23}	0.0575	-
	υ_{13}	0.33	-
Density(kg/m³)	ρ	1980	
Thickness	***(mm)***	0.266	0.4064

Table 1. Characteristics of the two materials (S2/FM94&Al2024-T3)

Different feed rates and spindle speeds were used for all experiments as shown in Table 2. There is no real specific cutting parameter range for drilling a multi-material composed of two or three different types of materials in a single machining operation as shown in Fig.3 (Jallageas et al. 2016). To overcome this problem, the experimental approach Tool-Material Couple (TMW) was adopted for establishing the set range of cutting parameters defining the proper operation of the tool in the considered material. Add to this, feed rate and spindle speed are extended to 0.25 mm/rev and 18000 rpm, respectively, to study other parameters such delamination.

Feed (mm/rev)	from 0.02 mm/tr to 0.25 mm/tr
Spindle speed(rpm)	from 2000 rpm to 18000 rpm

Table 2. Cutting parameters

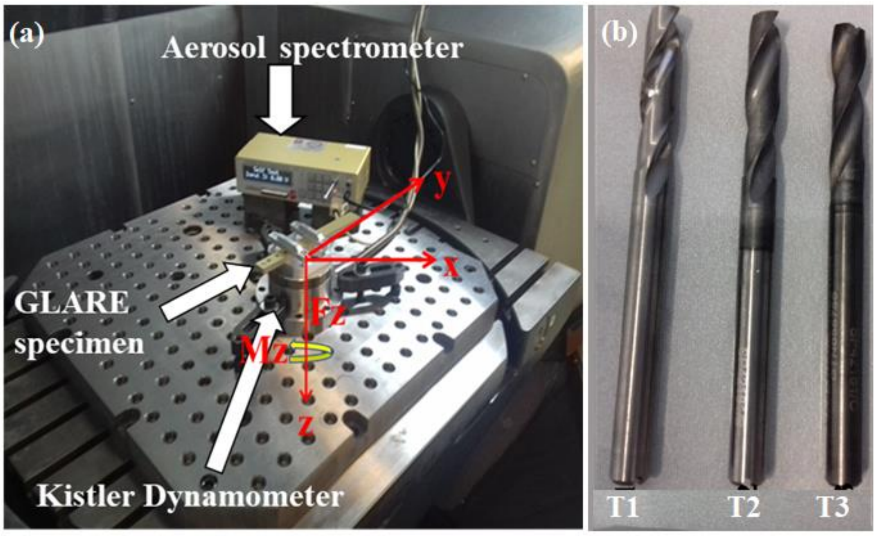

Fig. 1 (a) Drilling tools (b) experimental set up

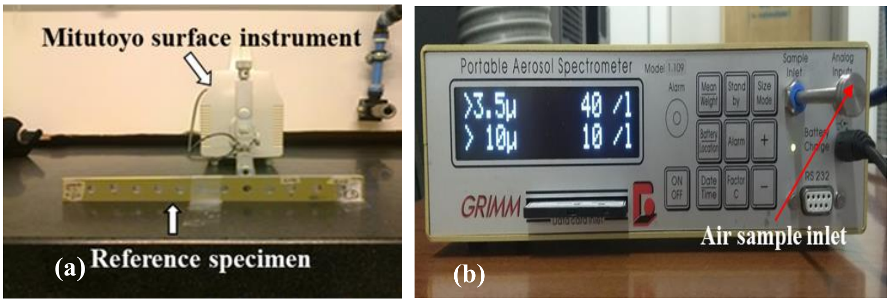

Fig. 2 (a) Mitutoyo surface roughness instrument (b) GRIMM aerosol spectrometer

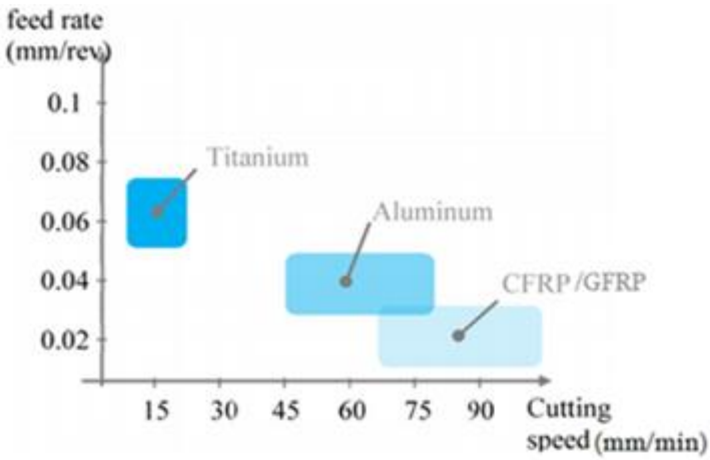

Fig. 3 Setting range of cutting parameters based on the material (Jallageas et al. 2016)

3 Obtained results and discussion

3.1 Surface finish in drilling of GLARE®

It is important to assess the geometric finish of drilled holes, that would result from the kinematic motions of the chisel, using standard measurement methods especially surface roughness. The values of roughness presented in this work correspond to the measure of generated surface when drilling both aluminum sheets and S-2 fiberglass layers.

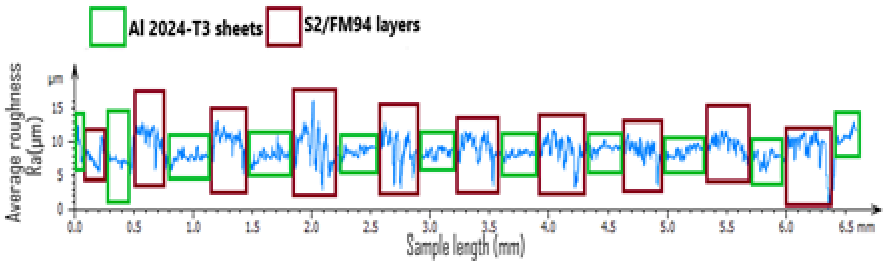

Fig. 4 Typical profile of average surface roughness for S2/FM94&Al2024-T3

Figure 4 shows that average Ra of S2/FM94 are higher than those corresponding to S2/FM94 profile. Overall, a variation between the surface finish measured in the composite layers and those measured in the aluminum sheets, within the same hole, was found. When the profilometer stylus moves across sheets of aluminum, less variations are drawn. Whereas, when it moves across layers of S2/FM94 geometrics, the stylus records more important irregularities a less regular texture. For example, fibers that are reoriented, due to the tool movement into the workpiece, often seem to lift up after the chisel has passed through. This creates irregular and rougher surface finish ((Boughdiri et al. 2021). In addition, in other study (Zitoune et al. 2005) authors reported that the surface finish of the final specimen (depending on fiber orientation) indicated a significant increase whenever fiber direction formed an angle greater than 45° with drilling direction. This is due to the shear mode of failure of the laminate with those angle orientations. Moreover, it can also be stated that composite material orientation affects the microstructure of the machined surface (Boughdiri et al. 2021). This can be explained by the heterogeneity of composite material constituents (glass fiber layers and aluminum sheets) and the influence of their orientation with respect to the cutting line direction.

Fig. 5 presents the variations of the average value of Ra and the Rt at range of feed rates between 0.02 mm/rev and 0.25 mm/rev) and when spindle speeds vary from [4000 to 12000] rpm. It can be noted that when feeds rise from [0.02 to 0.25 mm/rev] the values of both Ra and Rt are higher. This result corroborates with those in of (Giasin et al. 2015). In fact, the authors observed that surface roughness values increase as feed rate and spindle speed increase during drilling of GLARE® 2B with two configurations (11/10 or 8/7). The values of Ra do not exceed 3 µm in the majority of the drilled holes, for all tool types. For uncoated and coated tools, Rt is higher as the spindle speed changes from [4000 to 12000] rpm during drilling of GLARE® 2B 11/10 feed rate of 0.055 mm/rev. It has been noticed maximal and minimal values of Rt as a function of spindle speed for the cristal-coated tool and the Diamond-Like Carbon tool, respectively.

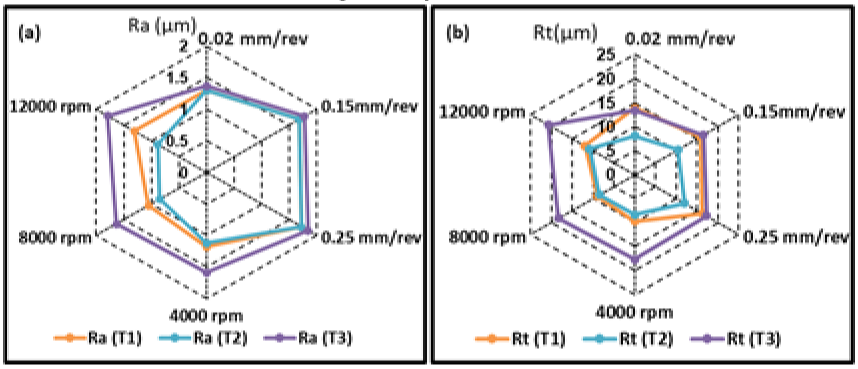

Fig. 5 Mean values of (a) Ra and (b) Rt for used tools under different cutting parameters.

As conclusion, it can be also highlighted that the DLC-coated tool gives a better surface roughness in the drilled hole compared to the cristal-coated tools and uncoated ones. Moreover, surface roughness limits are 1.05 and 20.71 µm and these measurements are all within the range of values found in the study of (Giasin et al. 2016). For GLARE® machining/drilling, there is no data available helping to give the required surface roughness for the aerospace industry. Manufacturers (Coromant 2010) reports that Ra of the hole do not exceed 3.2 µm for CFRP and 1.6 µm for metal alloys. Some manufacturers and cutting tool specialists have mentioned that manufacturing requirements for the most structure aerospace in term of surface roughness are less than 3.2 µm for made of carbon fiber and 1.6 µm for workpieces made of Aluminum alloys or Titanium ones.

3.2 Dust generation

During the machining of GLARE or others multi-materials, two types of chips are formed from the two material components: aluminum chips and laminate chips. The latter, which are composed of fibers and matrix material, break down into very fine particles during machining, due to the high brittleness of the different components. These particles, suspended in the air near the machining area, represent a real danger for the environment and the health of the operators, due to their carcinogenic properties and the non-respect of the industrial application standards. Indeed, if an operator inhales these particles, he risks encountering several respiratory problems, because these particles can become permanently lodged in the pulmonary alveoli. However, researchers have not studied this aspect and very few publications are available in the literature. This section focuses on the study of the effect of machining parameters on the number of harmful particles in such a production area contaminated with composite dust. This allows to establish the necessary procedures, depending on the parameters used, to avoid the harmful effects of these particles on the operator's health.

Fig. 6 illustrates particles number of calculated sizes in one liter of air for different drilling parameters. It is pointed out that the majority of particles captured in the air have sizes of 0.25 µm and 1 µm. In further investigations, most of released particles have sizes from [0.5 to 1.5] µm during drilling operation of hybrid material made of bio-composite (Li et al. 2014) and from [0.25 to 0.70] when trimming CFRP (Nguyen-Dinh et al. 2020). Another range less pronounced is between 1 µm and 2 µm, where the number of particles is fewer than in the first region. The other ranges present lower particle numbers.

For all tools, the particle number in the size range [0.25 to 1.00] represents approximately 96% of measured aerosol dust. When drilling with the three drills it can be noticed (Fig. 5(a) to (c)), that for different particles ranges of size the increase in particles number is recorded with the higher spindle speed and lower feed rate.

Fig. 7 shows total number of particles measured at different (a) feed rates per reverse and (b) spindle speeds. It appears that the value of highest particles number per liter of air is produced at a spindle speed of 18,000 rpm and a feed of 0.055 mm/rev. For most holes, a reduction in feed rate from 0.25 mm/rev to 0.02 mm/rev and a rise in spindle speed variation from [2000 to 18000] rpm resulted in an increase in the total number of particles released when drilling tests of GLARE® 2B using tools T1, T2 and T3. This is due to the fact that theoretical chip thickness and feed rate – in contrast to spindle speed- are directly proportional. This results automatically in a diminution in the number of airborne dust particles. The finer the chips have become, the more the dust is produced as a result of their defragmentation (because of its very low weight). Similarly, above certain sizes, these aerosols fall due to their weight (Haddad 2014).

The results achieved with all types of tools do not give a meaningful comparison between uncoated and coated tools concerning the number of the released particles. Hence, coated tools make several effects on number and size of particles generated in the workplace as compared to uncoated ones. These observations differ from those in (Haddad et al. 2014) during trimming tests carried out during the machining of CFRP samples. It looks that DLC coated tool T2 records a lower generation of particles than uncoated drill T1 and Cristal coated drill T3. In addition, the T1 tool also releases less dust than the T3 coated tool. The Cristal coating is characterized by a micro-crystalline morphology resulting in a rough reaction and increasing the release of dust particles.

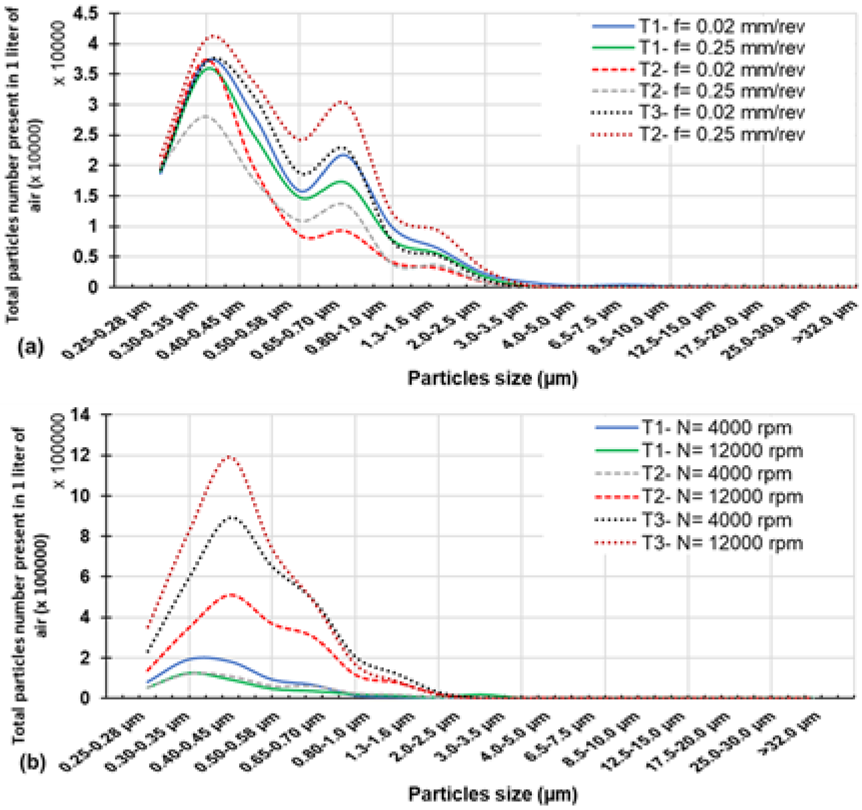

Fig. 6 Measurements of particles number with (a) fixed spindle speed and (b) fixed feed for different tool types

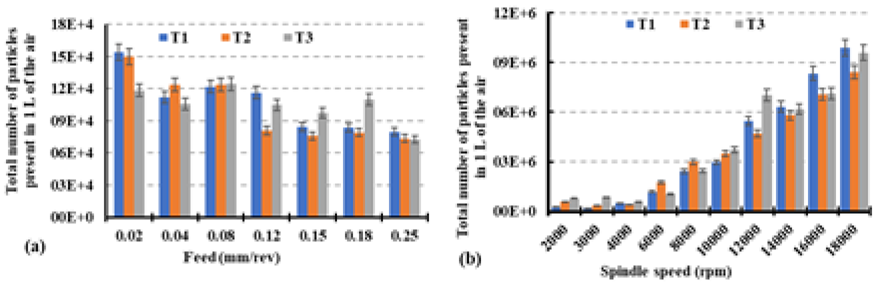

Fig. 7 Evolution of the number of particles measured at differents (a) feeds and(b) different spindle speeds (Boughdiri et al. 2021)

4 Conclusion

In this work, an experimental investigation in samples of multi-material type GLARE® 2B (with 11 sheets of aluminum and 10 layers of S2/FM94 composite) drilled with uncoated and coated tools, was realized at different cutting conditions. The effect of machining factors (feed rate per reverse and spindle speed) on the surface finish assessment and dust generation was analyzed. Results showed that surface roughness values are proportional to feed and speed of the spindle during drilling tests. The study of the surface roughness of the holes (Ra and Rt) in terms of feed rate and spindle speed shows that less surface defects are obtained when drilling GLARE® 2B 11/10 -0.4 samples with spindle speeds lower than 8000 rpm and feed rates of 0.055 mm/rev. Also, DLC coating ensures better hole surface roughness than Cristal coated tool and uncoated tool. In addition, material type and cutting parameters have the most important impact on the generation of airborne dust. Two parameters affecting the number of aerosol dust which are the cutting parameters and coating types. The increase in feed and decrease in spindle speed reduces the number of particles released in the workplace. In the meantime, the present work will be extended to qualify the interaction between drill and this type of GLARE® based on cutting force measurements. A drilling numerical model is also going to be built to make more physical comprehension of the pre-cited drill workpiece interaction.

Acknowledgements

This research project was a result of collaboration between Applied Mechanics and Engineering Laboratory (University of Tunis El Manar, ENIT, Tunis, Tunisia) and Clément Ader Institute (Paul Sabatier University of Toulouse 3). The first author would like to thank Clément Ader Institute members for their technical support. GLARE® samples are provided by the Fiber Metal Laminate Center in the Netherlands, and tools were supplied by Guhring® company. So, special thanks for Prof.Jos Sinke from FMLC and Mr. Ian Goffey from Guhring®company.

References

Giasin K, Ayvar-Soberanis S, Hodzic A (2015) An experimental study on drilling of unidirectional GLARE fibre metal laminates. Compos Struct 133:794–808. doi: 10.1016/j.compstruct.2015.08.007.

Ashrafi S, Sharif S, Farid A, Yahya M (2013) Performance evaluation of carbide tools in drilling CFRP-Al stacks. J Compos Mater 48:2071–2084. doi: 10.1177/0021998313494429.

Giasin K, Gorey G, Byrne C et al (2019) Effect of machining parameters and cutting tool coating on hole quality in dry drilling of fibre metal laminates. Compos Struct 212:159–174. doi: 10.1016/j.compstruct.2019.01.023.

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

Giasin, K. (2018) The Effect of Drilling Parameters , Cooling Technology , and Fiber Orientation on Hole Perpendicularity Error in Fiber Metal Laminates, The International Journal of Advanced Manufacturing Technology 97: 4081–99

Giasin, Khaled, Alisha Dad, Emmanuel Brousseau, Danil Pimenov, Mozammel Mia, Sezer Morkavuk, and Ugur Koklu (2021) The Effects of through Tool Cryogenic Machining on the Hole Quality in GLARE® Fibre Metal Laminates, Journal of Manufacturing Processes 64 (April): 996–1012. doi: 10.1016/j.jmapro.2021.02.010

Park, Sang Yoon, Won Jong Choi, Chi Hoon Choi, and Heung Soap Choi (2017) Effect of Drilling Parameters on Hole Quality and Delamination of Hybrid GLARE Laminate. Composite Structures 185(1): 684–98. doi: 10.1016/j.compstruct.2017.11.073

Haddad M, Zitoune R, Eyma F, Castanie B (2014) Study of the surface defects and dust generated during trimming of CFRP: Influence of tool geometry, machining parameters and cutting speed range. Compos Part A Appl Sci Manuf 66:142–54. doi: 10.1016/j.compositesa.2014.07.005

Nguyen-Dinh N, Hejjaji A, Zitoune R, Bouvet C, Salem M (2020) New tool for reduction of harmful particulate dispersion and to improve machining quality when trimming carbon/epoxy composites. Compos Part A Appl Sci Manuf 131:105806. doi: 10.1016/j.compositesa.2020.105806

Djebara A, Jomaa W, Bahloul A et al. (2013) Dust emission during dry machining of Aeronautic Aluminum Alloys . Proc 1st Int Conf Aeronaut Sci 1–8

Jallageas, Jeremy, Matthieu Ayfre, Mehdi Cherif, Jean Yves K’nevez, and Olivier Cahuc. (2016) Self-Adjusting Cutting Parameter Technique for Drilling Multi-Stacked Material. SAE International Journal of Materials and Manufacturing 9 (1): 2018–22. doi: 10.4271/2015-01-2502

Imed Boughdiri, Khaled Giasin, Tarek Mabrouki, Redouane Zitoune (2021) Effect of cutting parameters on thrust force, torque, hole quality and dust generation during drilling of GLARE 2B laminates, Composstruct 261: 113562. doi: 10.1016/j.compstruct.2021.113562.

Zitoune R, Collombet F, Lachaud F et al. (2005) Experiment-calculation comparison of the cutting conditions representative of the long fiber composite drilling phase. Composites Science and Technology 65: 455-466. doi: 10.1016/j.compscitech.2004.09.028

Coromant, S (2010) Machining carbon fibre materials, in Sandvik coromant user’s guide - composite solutions

Li MJ, Soo SL, Aspinwall DK, Pearson D, Leahy W (2014) Influence of lay-up configuration and feed rate on surface integrity when drilling carbon fibre reinforced plastic (CFRP) composites. Procedia CIRP 13:399–404. Doi:10.1016/j.procir.2014.04.068

Giasin Khaled, Ayvar-Soberanis Sabino (2017) An Investigation of burrs, chip formation, hole size, circularity and delamination during drilling operation of GLARE using ANOVA. Compos Struct 159:745–60. doi: 10.1016/j.compstruct.2016.10.015