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Original Research

COMPARISON OF ASSEMBLY HOLES QUALITY AFTER DRILLING AND HELICAL MILLING OF THE AL/CFRP STACKS

PORÓWNANIE JAKOŚCI OTWORÓW MONTAŻOWYCH PO WIERCENIU I FREZOWANIU SPIRALNYM KONSTRUKCJI PRZEKŁADKOWEJ TYPU AL/CFRP

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Abstract

Hybrid sandwich structures composed of aluminium alloys and CFRP (Carbon Fibre Reinforced Polymer) are now frequently used in the aerospace industry. One of the factors inhibiting their application is the difficult processing resulting from the anisotropic nature of this type of construction. These materials are often joined by screws or rivets requiring mounting holes. One of the main problems is ensuring the quality of the holes after machining. The aim of this study is to assess the hole quality (dimensional and shape accuracy) and the occurrence of delamination after machining of a Al 2024/CFRP sandwich structure. In this experiment drilling and helical milling results were compared. A traditional HSS twist drill and a PCD milling cuter with a straight cut were used. The machining was carried out with a variable cutting speed. The tests were performed for two strategy of the machining – Al/CFRP (Al 2024 T3 – Carbon Fibre Reinforced Polymer) and CFRP/Al (Carbon Fibre Reinforced Polymer – Al 2024 T3).

Keywords: Al/CFRP stacks, drilling, helical milling, hole quality

Streszczenie

Hybrydowe konstrukcje przekładkowe składające się ze stopów aluminium i kompozytów epoksydowo-węglowych (CFRP) są obecnie często stosowane w przemyśle lotniczym. Jednym z czynników hamujących ich zastosowanie jest trudna obróbka wynikająca z dużej anizotropowości tego typu materiałów. Konstrukcje te są często łączone za pomocą połączeń śrubowych lub nitowych wymagających otworów montażowych. Jednym z głównych problemów jest zapewnienie jakości otworów po obróbce. Celem artykułu jest ocena jakości otworów (dokładności wymiarowo-kształtowej) oraz występowania delaminacji po obróbce konstrukcji przekładkowej Al 2024/CFRP. W eksperymencie porównano wyniki wiercenia i frezowania spiralnego. Zastosowano tradycyjne wiertło kręte wykonane ze stali szybkotnącej oraz frez węglikowy o prostych zębach pokrytych powłoką diamentową (PKD). Obróbka została przeprowadzona ze zmienną prędkością skrawania. Testy przeprowadzono dla dwóch strategii obróbki – Al/CFRP (stop aluminium/kompozyt epoksydowo-węglowy) i CFRP/Al (kompozyt epoksydowo-węglowy/stop aluminium).

Słowa kluczowe: konstrukcja przekładkowa Al/CFRP, wiercenie, frezowania spiralne, jakość otworów

1. Introduction

The constant search for lighter constructions and faster means of transport led to dynamic technological developments. The search began for engineering materials that could meet the demands placed on them. Efforts have been made to develop a construction with adequate strength properties, while at the same time allowing the weight of the construction to be reduced. One such material is a sandwich structure.

One of the increasingly used constructions is a combination of metal alloys and fibre composites, especially CFRPs (Carbon Fibre Reinforced Polymers). Unlike metallic materials, CFRP is a heterogeneous material consisting of two phases: matrix and reinforcement. These phases have different structures and arrangements (Leprete et al., 2018). Such a structure leads to the occurrence of many post--process defects (e.g. delamination, debonding) and a different directionality of the material and surface roughness than after metal machining (Doluk & Rudawska, 2022; Karataş & Gökkaya, 2018) The combination of aluminium alloys and CFRPs enables the creation of a construction with less weight, high strength and corrosion resistance compared to an equivalent solid construction made of metal. These and other advantages of hybrid sandwich structures have contributed to their frequent use in the aerospace industry (Hegde et al., 2019). Machining of Al/CFRP structures presents even more difficulties than machining CFRP. The tool simultaneously machines materials with significantly different properties and different machinability. This results in rapid wear of the cutting tool and problems in achieving the desired machined surface quality (Poutord et al., 2013; Doluk et al., 2022). One way of joining sandwich structures is through the use of mechanical connections. In most cases, these require assembly holes, which are usually made in a drilling process. Nowadays, in order to increase the efficiency of the assembly and machining process, the aim is to make these holes in a single process operation desirable to obtain holes with the highest possible dimensional and shape accuracy. Surface quality is one of the determinants of accuracy and verification of manufacturing performance. Machining performance is closely related to the proper planning and management of the production system, including the appropriate selection of machining conditions (Kuczmaszewski et al., 2019; Matuszak et al., 2022; Gola, 2018). The determination of cutting conditions for highly anisotropic materials, which include Al/CFRP stacks, is extremely important from the point of view of reducing assembly errors, production time, as well as joint aesthetics.

Many of the problems encountered in the machining of hybrid sandwich structures are due to improperly selected machining conditions (Caggiano, 2018; Fleischer et al., 2018). In (Angelone et al., 2019) the influence of spindle speed (n = 300 – 6000 rpm) and feed rate (f = 0.05 – 0.15 mm/rev) on the damages of a hole diameter after drilling with two-flute twist drills (WC) was studied. The temperature in the cutting zone was also recorded. The results showed that using a feed rate of f = 0.15 mm/rev and spindle speed of n = 4500 rpm produced the highest hole quality. The use of lower values led to less dimensional parameters (roundness, delamination, smoothness). Zitoune et al., 2010, studied the influence of drill diameter and cutting conditions on hole quality, thus force, torque and circularity after machining. They presented the appearance of chips depending on the cutting parameters adopted. They noted that better results were obtained for lower drill diameters (< 6 mm). They showed that drill diameter and feed rate have the highest influence on the chip formation mechanism. In (Zitoune et al., 2016) the effect of cutting parameters during drilling with a traditional twist drill and a double cone drill was evaluated. Cutting forces, hole accuracy and CFRP/Al interface were recorded. It was noted that the double cone drill produced lower thus force values than the traditional twist drill. In (Shyha et al., 2011) an experiment was performed to determine the effect of cutting tool type (uncoated and coated drill) on burr height, delamination, hole edge and roughness after drilling in the Ti/CFRP/Al stacks. The entry and exit zones of cutting tool were investigated after flood cutting fluid and mist-spray. It was shown that the cutting environment had a highest effect on hole quality than the type of tool used. Bunting & Bunting, 2020, presented the influence of drill type (PCD drill vs. WC drill) and cutting parameters on hole drilling performance in the CFRP/Ti stacks. The cutting force values, dimensional and shape hole accuracy and burr height obtained with the drills analysed were compared. It was found that the use of a PCD drill increased the efficiency of the process due to the possibility of increasing the depth of cut. In addition, the holes made with the PCD drill had higher dimensional and shape accuracy. In (Torres et al., 2009) a prototype drill bit for drilling holes in carbon fibre/epoxy laminates was proposed. It was also shown that the use of a low cutting speed (v_c = 53 m/min) and a low feed rate (f = 0.025 mm/rev) could counteract excessive delamination of the tested material during machining. In the paper (Ciecieląg & Zaleski, 2022) the influence of material stiffness on cutting force and surface roughness after the milling of three types of materials: aluminium alloy, titanium alloy and CFRP was studied. It was shown that the investigated parameters of hole surface quality are influenced not only by the stiffness of the component, but also by their different properties (Young's modulus). In (Ciecieląg, 2023) the influence of cutting tool type on the cutting force and deformation of thin-walled components made of fibre composites (CFRP and GFRP) after the milling process was determined. It was shown that low feed rates should be used when machining thin-walled fibre composites, as this allows the lowest value of permanent deformation to be obtained.

Much research to date has focused on drilling holes in sandwich structures (Ciecieląg, 2023; Ahn et al., 2023; Wang et al., 2020; Kuoa & Sooa, 2014; An et al., 2020). However, most of these focus on drilling holes using specialised drills or those designed to machine one of the materials forming the sandwich structure (usually to a material with poorer machinability). There is a lack of studies focusing on the potential use and effectiveness of helix milling when machining holes in this type of material.

The aim of this study was to compare the holes quality (dimensional and shape accuracy) machined with a traditional uncoated twist drill and a straight-blade PCD cutter. An additional objective was to determine the influence of machining strategy (sample orientation during process) and cutting speed on the holes quality in the Al/CFRP stack.

2. Materials and methods

In this study a II-layered sandwich structure consisting of metal and composite was used. The research object was formed from Al 2024-T3 (Al) (EN 515:2017) and CFRP (Carbon Fibre Reinforced Plastics). Both materials were chosen because of their frequent use in aircraft constructions (Hegde et al., 2019; Labidi, 2020).The main properties of the alloy are presented in Table 1.

Table 1. Properties of 2024-T3 aluminum alloy

Density	2.78 g/cm^3
Young's Modulus	73 GPa
Tensile Yield Strength	345 MPa
Fatigue Strength	138 MPa

The content of the main alloying elements in the alloy is: Al 93.5%, Cu 4.5%, Mg 1.5%, Mn 0.5%. The composite material was composed of 20 unidirectional prepregs CM-Preg TI02/1000 manufactured by Mitsubishi Chemical Group (Heinsberg, Germany). The plies sequence was [0/90]. The thickness of each layer was about 0.3 mm (epoxy tissue prepregs). The CFRP was made of CP006 epoxy matrix and high strength carbon fibres (about 60%). The laminate was fabricated by hand lay-up process and autoclave curing (for 60 minutes at 130˚C under pressure of 0.4 MPa). The main properties of the composite material are: density 1.75 g/cm^3, Young's Modulus E = 135 GPa, Tensile Yield Strength 1900 MPa.

The materials forming the sandwich structure were bonded using a two-part epoxy adhesive 3M DP460 (3M, Minnesota, USA) with a 2:1 mix ratio. The adhesive exhibits high peel and shear strength, which is why it has found applications in the aerospace industry. The adhesive composition was applied evenly to both surfaces to be joined using an applicator. The thickness of the adhesive was approximately 0.1 mm. Polymerisation process was carried out in vacuum bag at a pressure of 0.1 MPa for 24 hours. The samples were seasoned for 7 days under ambient conditions (at 23°C and approximately 35% humidity). Fig. 1 shows a schematic of the sample after the bonding process.

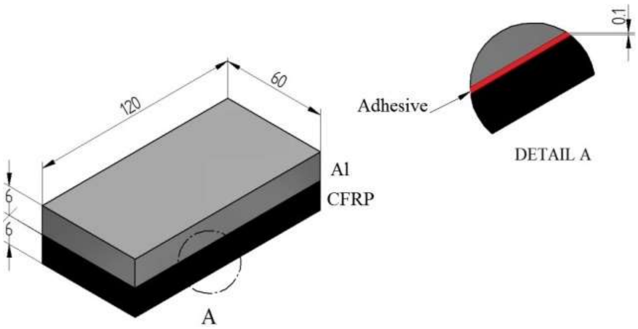

Fig. 1. Geometry and dimensions of the sample

The drilling and helical milling processes were performed on a CNC FV-580A vertical machining centre (AVIA, Warsaw, Poland). A schematic representation of the drilling and milling processes, including the location of the holes on the sample, is shown in Fig. 2. The drilling and milling tests were conducted on 6 consecutive holes with different cutting speed (3 holes after drilling and 3 holes after milling – Fig. 2b). The drilling and milling processes were carried out three times for each machining variant. Experiment was performed without coolant.

Two tools were used in the experiment. The first tool is a traditional twist drill made of HSS steel with a point angle 135° (Hoffman Group, Munich, Germany). The second one is a two-blade diamond (PCD) milling cutter with a straight cut (Hoffman Group, Munich, Germany). The shape and detailed dimensions of the tools are presented in Fig. 3.

The experiment also investigated the effect of cutting speed on the holes quality after machining. Three cutting speeds were selected for each of the two tools. As the tools used differed in geometry and material, different cutting speeds were selected for each tool. Table 1 summarises the values of the v_c parameter, depending on the machining process.

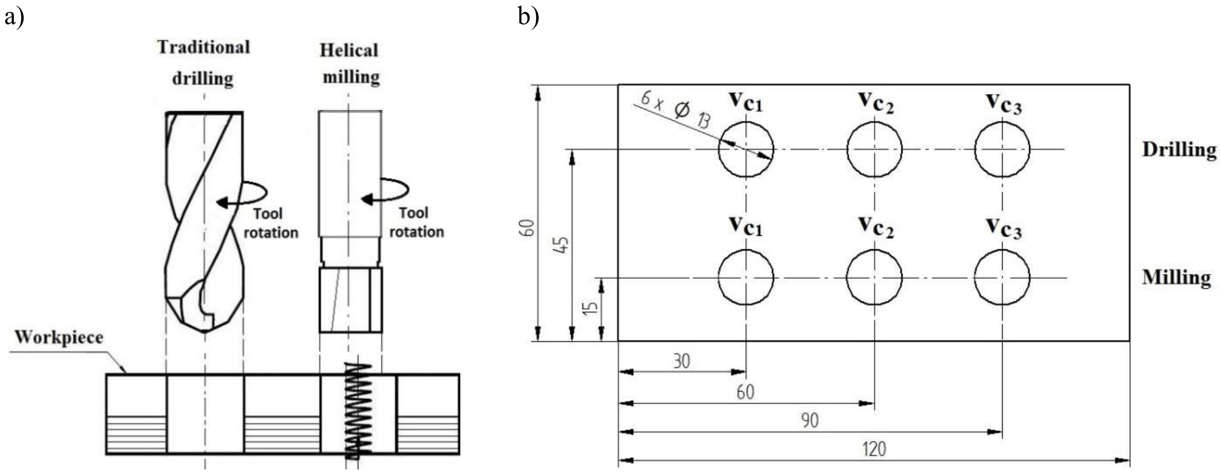

Fig. 2. Experimental setup: a) scheme of traditional drilling and helical milling, b) location of the holes on the sample

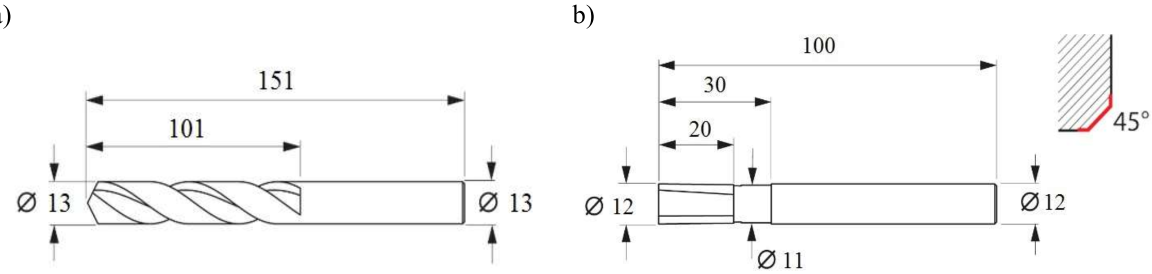

Fig. 3. The tools used in the experiment: a) HSS twist drill, b) PCD milling cutter (Hoffman Group Catalogue)

For the drilling process, a cutting speed in the range of v_c = 80 – 320 m/min was initially assumed (Table 2 pre-testing). However, due to the unacceptable quality of the holes (flow of the metal material in the drill entry zone – Fig. 4), the values of the v_c parameter were reduced after the process was carried out assuming these values (Table 2 – main test).

Table 2. Values of the v_c parameter depending on the type of the process

No.	Drilling		Milling
	Pre-testing	Main test	
1	v_c = 80 m/min	v_c = 15 m/min	v_c = 350 m/min
2	v_c = 160 m/min	v_c = 30 m/min	v_c = 425 m/min
3	v_c = 320 m/min	v_c = 60 m/min	v_c = 500 m/min

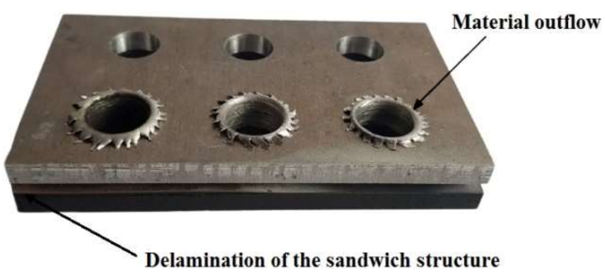

Fig. 4. Sample after drilling in the Al/CFRP strategy (pre-testing)

The cutting speed values used were selected based on the recommendations of the manufacturer of the tools used. The milling and drilling processes were carried out using a constant feed rate of f_z = 0.09 mm/blade and an axial depth of cut for milling a_p = 12.9 mm and for drilling a_p = 6.5 mm.

The third factor whose influence on the holes quality was investigated was the sample orientation during the cutting process. Two possibilities were considered:

- Al/CFRP strategy – the Al sheet on the top of the stack of the sandwich structure.
- CFRP/Al strategy – the CFRP sheet on the top of the stack of the sandwich structure.

The dimensional accuracy of the holes was defined by the arithmetic mean of the hole diameter D obtained after machining and the roundness factor F_R. This factor was expressed as:

$$F_R = \left|1 - \frac{D}{D_N}\right| \tag{1}$$

where:

F_R – roundness factor,
D – arithmetic mean of the hole diameter [mm],
D_N – nominal hole diameter [mm].

Both parameters were compared with the adopted target values. The value of the hole diameter D was compared to the nominal hole diameter D_N (D_N = 13 mm), while the F_R factor was compared to 0. In both cases, values closer to the adopted ones indicated better dimensional hole accuracy. The hole diameters were measured using a Zeiss Accura II CMM (Oberkochen, Baden-Württemberg, Germany). Each of the obtained hole diameter values was the arithmetic mean of the three hole measurements.

During machining structures with very different properties, it may not be sufficient to compare the cutting effects solely by means of dimensional accuracy. It is also necessary to determine the condition of the hole edges. The shape accuracy of the holes was assessed visually with a Keyence VHX-500 digital microscope (Japan, Osaka) using a magnification of 500 times.

3. Results and discussion

Figs. 5 – 8 show the effect of the cutting speed and machining strategy on the hole quality in the tool entry and exit zone after the helical milling.

In the case of the milling process with the Al/CFRP strategy, all the actual hole diameters obtained were lower than the nominal diameter (D_N = 13 mm). The closest actual diameter value (D = 12.922 mm, F_R = 0.006) to the nominal diameter was obtained in the tool entry zone using the parameter v_c = 500 m/min. The hole with the lowest dimensional accuracy (D = 12.587 mm, F_R = 0.035) for this milling strategy was also obtained in the tool entry zone, but at the cutting speed of v_c = 350 m/min (Fig. 5 and Fig. 6).

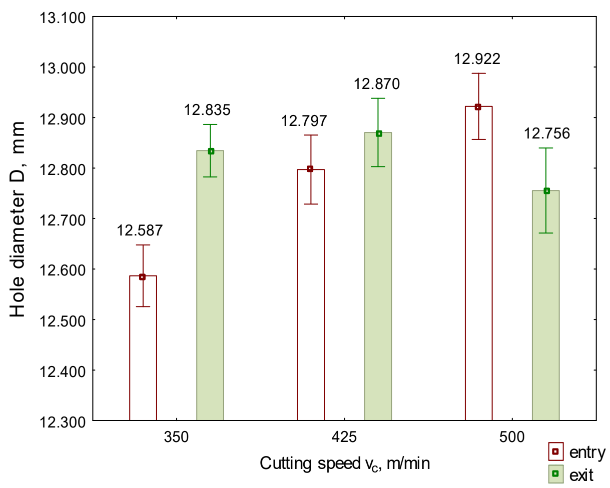

Fig. 5. Hole diameters for the Al/CFRP strategy after milling

It was observed that after the milling process using the Al/CFRP strategy, an increase in the v_c parameter resulted in an increase in the dimensional accuracy of the holes in the tool entry zone (lower F_R values). In the milling cuter exit zone, a similar trend was observed for the first v_c parameters, but for the highest cutting speed (v_c = 500 m/min), a hole with a diameter least close to the nominal diameter was obtained in the tool exit zone. For the analysed milling strategy, holes with higher dimensional accuracy were obtained in the tool exit zone (composite material) in most of the cases considered. This was probably due to the stiffening effect of the metal layer above the composite material.

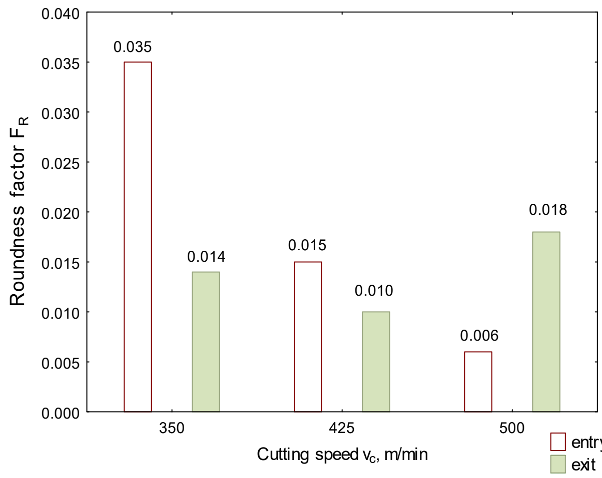

Fig. 6. Roundness factor F_R for the Al/CFRP strategy after milling

Milling with the CFRP/Al strategy produced the highest dimensional accuracy (D = 12.844 mm, F_R = 0.012) in the tool exit zone after using v_c = 500 m/min. Similarly to the Al/CFRP strategy, the lowest dimensional accuracy (D = 13.853 mm, F_R = 0.066) was obtained in the tool entry zone for a cutting speed of v_c = 350 m/min (Fig. 7 and Fig. 8). Increasing the cutting speed resulted in a decrease in the hole quality in the tool entry and exit zones.

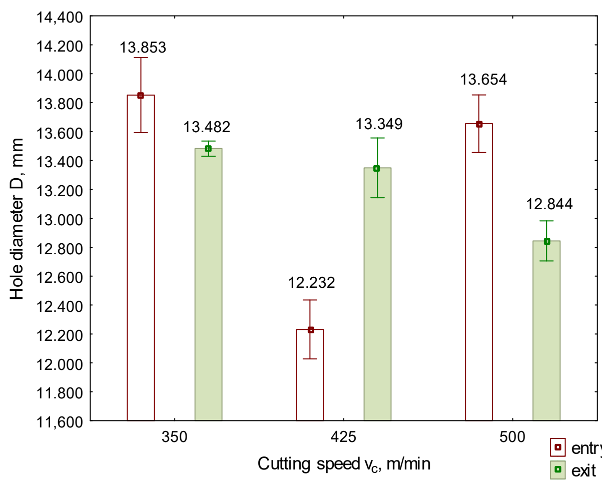

Fig. 7. Hole diameters for the CFRP/Al strategy after milling

Comparing the results shown in Fig. 8 it can be observed that for all the cutting speeds considered, lower F_R values were obtained in the cutting tool exit zone (metal layer). This is due to the better machinability of the aluminium alloy compared to the CFRP (Karataş & Gökkaya, 2018).

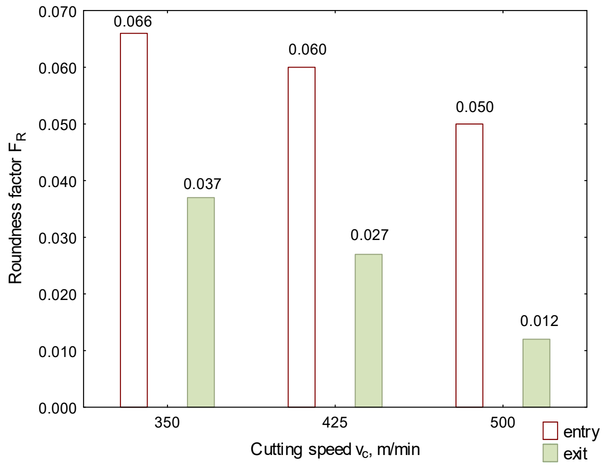

Fig. 8. Roundness factor F_R for the CFRP/Al strategy after milling

After the drilling process using the Al/CFRP strategy, the hole diameter closest to the nominal diameter (D = 13.241 mm, F_R = 0.019) was obtained in the tool entry zone using v_c = 15 m/min (Fig. 9). The hole with the lowest dimensional accuracy for this machining strategy (D = 12.127 mm, F_R = 0.067) was obtained in the tool exit zone after drilling with a cutting speed of v_c = 60 m/min (Fig. 9 and Fig. 10). For all cutting speeds considered in this case, holes with diameters lower than the nominal value were obtained in the drill exit zone. This is due to the presence of numerous defects in the composite layer in the tool exit zone, mainly in the form of undercut, pulled-out carbon fibres, which reduced the measuring area of the CMM.

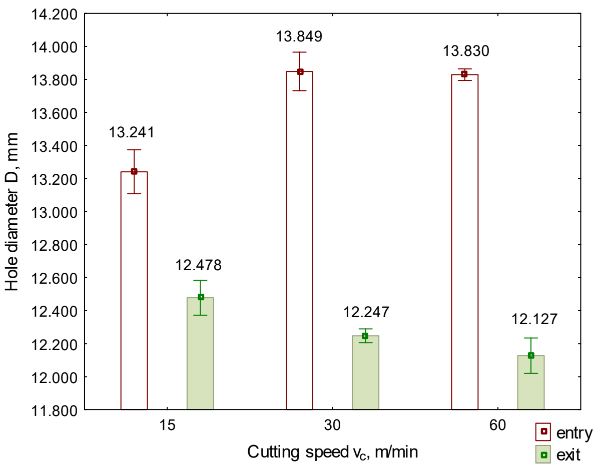

Fig. 9. Hole diameters for the Al/CFRP strategy after drilling

Smaller F_R values were obtained in the tool entry zone for most of the variables considered, indicating higher dimensional accuracy of the holes. The exception was a hole machined at a cutting speed of v_c = 30 m/min, where a lower F_R index value was obtained in the tool exit zone. In most cases, an increase in the v_c parameter resulted in an increase in the F_R value and thus a decrease in the dimensional accuracy of the holes (Fig. 10).

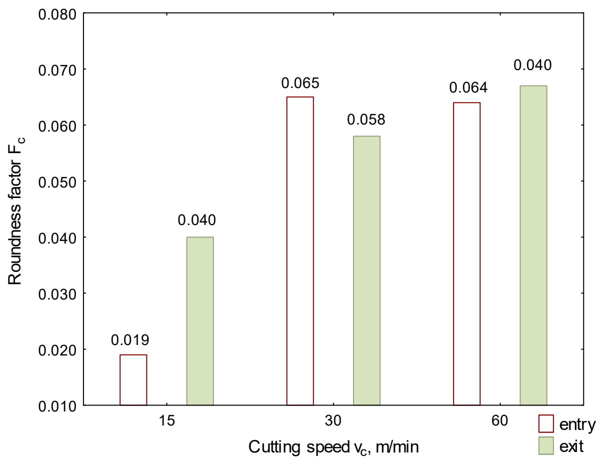

Fig. 10. Roundness factor F_R for the Al/CFRP strategy after drilling

When drilling the holes using the CFRP/Al strategy, the hole with the closest hole diameter (D = 13.160 mm, F_R = 0.012) to the nominal diameter was obtained in the tool entry zone using v_c = 15 m/min (Fig. 11). The hole with the lowest dimensional accuracy for this machining strategy (D = 13.720 mm, F_R = 0.055) was also observed in the drill entry zone when a cutting speed of v_c = 60 m/min was applied (Fig. 11 and Fig. 12). Increasing the v_c parameter resulted in breaking up the holes and reducing their dimensional accuracy (Hoffman Group Catalogue).

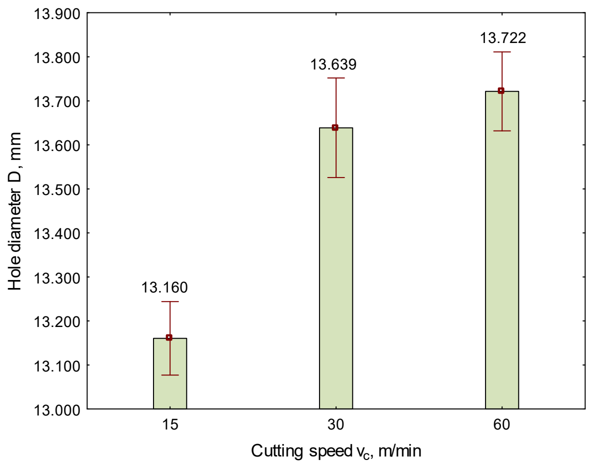

Fig. 11. Hole diameters in the tool entry zone for the CFRP/Al strategy after drilling

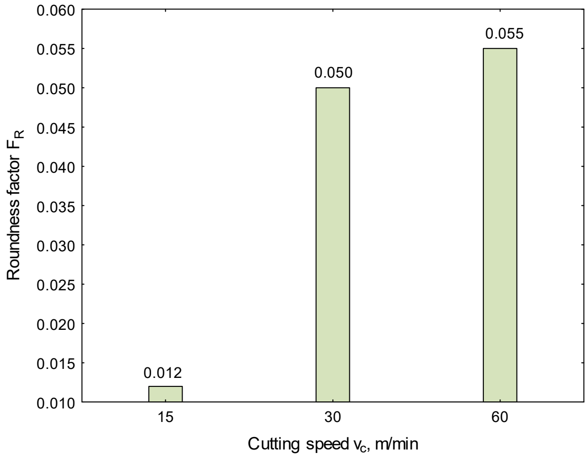

Fig. 12. Roundness factor F_R in the tool entry zone for the CFRP/Al strategy after drilling

For the CFRP/Al strategy, it was not possible to measure the hole diameter in the tool exit zone – the cutting tool did not punch the bottom of the hole for any of the adopted cutting speeds. The metal layer beneath the composite material underwent plastic deformation in the drill exit zone. The aluminium alloy was pressed deep into the hole, resulting in deformation of the metal and delamination of the entire structure (Fig. 13).

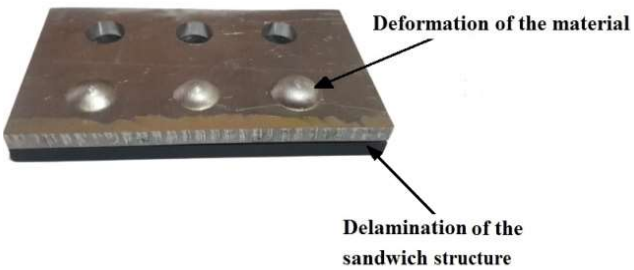

Fig. 13. Exit of the holes after drilling in the CFRP/Al strategy

Analysing the influence of the machining strategy on the machining effects, it can be seen that, for the milling process, the Al/CFRP strategy allowed a higher dimensional accuracy of the holes in the tool entry and exit zones. This is due to the stiffening effect of the metal layer, which increased the stability of the machining. In the case of drilling in the tool entry zone, higher dimensional accuracy was obtained when the CFRP/Al strategy was used. Similar conclusions were reached in (Zitoune et al., 2016; Isbilir and Ghassemieh, 2013). It was observed that the use of the CFRP/Al drilling strategy delays the delamination of the composite material.

In order to determine the influence of the investigated independent variables (cutting speed v_c and strategy of the machining S) on the hole quality in the tool entry and exit zones (hole diameter D) after the milling and drilling processes an analysis of variance (ANOVA) was carried out (Table 3 and Table 4).

Table 3. Two-factor analysis of variance for the milling process

Impact	Entry				
	SS	DF	MS	F	*p*-value
v_c: cutting speed	4.41	2	2.20	271.31	< 0.01
S: strategy	2.05	1	2.05	252.77	< 0.01
v_c x S interaction	5.32	2	2.66	327.82	< 0.01
Error	0.24	30	0.01		
Total	12.02	35			
Impact	Exit				
	SS	DF	MS	F	*p*-value
v_c: cutting speed	0.91	2	0.45	93.30	< 0.01
S: strategy	1.47	1	1.47	302.84	< 0.01
v_c x S interaction	0.49	2	0.25	50.71	< 0.01
Error	0.15	30	0.01		
Total	3.02	35			

For the tool entry and exit zones after milling process all independent variables and their interaction had a significant effect on the dependent variable (Table 3). The $v_c \times S$ interaction had the highest effect ($F_{1,5} = 327.82$; *p*-value < 0.01) on the hole diameter values in the milling cutter entry zone. For the tool exit zone the highest influence on the dependent variable were the strategy of the machining ($F_{1,5} = 302.84$; *p*-value < 0.01), cutting speed ($F_{1,5} = 93.30$; *p*-value < < 0.01) and $v_c \times S$ interaction ($F_{1,5} = 50.71$; *p*-value < < 0.01), respectively.

Table 4. Analysis of variance for the drilling process

Impact	Entry				
	SS	DF	MS	F	*p*-value
v_c: cutting speed	2.35	2	1.17	115.63	< 0.01
S: strategy	0.15	1	0.15	15.14	< 0.01
v_c x S interaction	0.03	2	0.01	1.34	0.28
Error	0.29	30	0.1		
Total	2.82	35			
Impact	Exit				
	SS	DF	MS	F	*p*-value
v_c: cutting speed	0.38	2	0.19	23.52	< 0.01
Error	0.15	15	0.01		
Total	0.50	17			

The results of the analysis of variance carried out for the holes obtained after the drilling process are shown in Table 4. Based on the results obtained for the tool entry zone, it can be seen that the v_c x S interaction ($F_{1,5}$ = 1.34; p-value = 0.28) did not affect the dependent variable. The most significant influence on hole quality in this case was the cutting speed ($F_{1,5}$ = 115.63; p-value < 0.01). The strategy of the machining affected hole quality less than cutting speed ($F_{1,5}$ = 15.14; p-value < 0.01). As no holes were created at the drill exit zone using the CFRP/Al strategy, a one-way ANOVA was performed for the results obtained at the tool exit zone after drilling, where the independent variable was the cutting speed (with the Al/CFRP strategy of the machining held constant). In this case, the cutting speed had a significant effect on the dependent variable ($F_{1,2}$ = 23.52; p-value < 0.01).

Fig. 14 and Fig. 15 show selected images of the holes in the tool entry and exit zones after milling process.

For the cutting speeds and machining strategies considered, similar hole edge conditions were obtained in the tool entry and exit zones. However, in the metal layer, a more pronounced outline of the holes can be observed than in the composite layer (Fig. 14a and Fig. 15b). In the composite material, single, undercut fibres can be seen, as well as some metal chip inclusions and matrix defects (Fig. 14b and Fig. 15a). However, these defects should not adversely affect future assembly operations.

a) b)

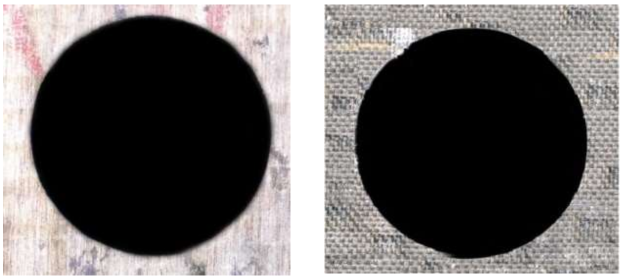

Fig. 14. Holes after milling with the Al/CFRP strategy and the cutting speed v_c = 350 m/min: a) tool entry zone, b) tool exit zone

a) b)

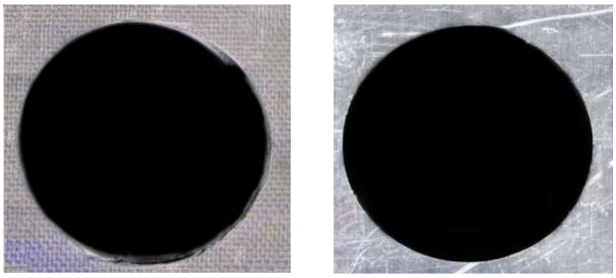

Fig. 15. Holes after milling with the CFRP/Al strategy and the cutting speed v_c = 350 m/min: a) tool entry zone, b) tool exit zone

For the cutting speeds and machining strategies considered, similar hole edge conditions were obtained in the tool entry and exit zones. However, in the metal layer, a more pronounced outline of the holes can be observed than in the composite layer (Fig. 14a and Fig. 15b). In the composite material, single, undercut fibres can be seen, as well as some metal chip inclusions and matrix defects (Fig. 14b and Fig. 15a). However, these defects should not adversely affect future assembly operations.

Fig. 16 and Fig. 17 show a comparison of the holes in the tool entry and exit zone after the drilling process using the Al/CFRP strategy. In the drill entry zone (metal layer), when the lowest value of the parameter v_c is used (v_c = 15 m/min), a similar hole condition can be observed as after the milling process. However, as the cutting speed increases, the material plasticises and settles on the edges of the holes (Fig. 16b and Fig. 16c). Increasing the cutting speed causes an increase in cutting temperature, resulting in a chemical reaction between the drill material and the aluminium alloy being machined. This causes build-up at the edge of the hole (Zitoune et al., 2016).

a) b) c)

Fig. 16. Tool entry zone after drilling with the Al/CFRP strategy and cutting speeds: a) v_c = 15 m/min, b) v_c = 30 m/min, c) v_c = 60 m/min

In the drill exit zone (composite layer), a decrease in hole diameter can be observed with an increase in the v_c parameter (Fig. 17). Numerous defects can be seen on the surface of the CFRP: pulled and undercut fibres, matrix chipping and delamination. The occurrence of these defects intensifies as the v_c parameter increases (Angelone et al., 2019). The condition of the machined holes would make it very difficult or impossible to make the joint. The resulting holes require additional finishing operations. Moreover, delamination of the entire sandwich structure was also observed at the layer boundary.

The images (Fig. 16 and Fig. 17) show that for such strongly anisotropic structures as the Al/CFRP stacks, the dimensional and shape accuracy of the holes should not be considered separately. Fig. 17 does not present the same hole quality as the results in Fig. 9 and Fig. 10.

a) b) c)

Fig. 17. Tool exit zone after drilling with the Al/CFRP strategy and cutting speeds: a) v_c = 15 m/min, b) v_c = 30 m/min, c) v_c = 60 m/min

This shows that determining the quality of holes machined in this type of structure also requires consideration of the condition of the hole edges and damage to the composite material in the cutting tool entry and exit zone.

4. Conclusions

The following conclusions were drawn from the research:

1. The highest dimensional accuracy of the hole (the hole with the diameter closest to the nominal diameter and the lowest F_R value) was obtained after milling process in the tool entry zone using the Al/CFRP strategy and the cutting speed of v_c = 500 m/min.
2. The lowest dimensional accuracy of the hole was obtained in the drill exit zone using the Al/CFRP strategy and the cutting speed of v_c = 60 m/min.
3. Considering the selection of cutting conditions for the machining of holes in sandwich structures, one cannot be guided solely by the criterion of dimensional accuracy. The condition of the hole edges after machining (shape accuracy) must also be considered.
4. In most cases, the milling process has made it possible to obtain higher dimensional accuracy of the holes than the drilling process.
5. Each use of the drill, irrespective of the machining strategy or the value of the v_c parameter, resulted in delamination of the sandwich structure.
6. Increasing the cutting speed during the milling process produced holes with higher dimensional accuracy, while the reverse was true for the drilling process.
7. For both tools tested, a higher dimensional accuracy of the holes was obtained for the metal layer.
8. The use of high v_c values (v_c = 80 – 320 m/min) during drilling with the Al/CFRP strategy caused deformation of the aluminium alloy in the tool entry zone and led to delamination of the entire structure.
9. The use of the CFRP/Al strategy and the drill, regardless of the v_c parameter value adopted, resulted in deformation of the hole in the tool exit zone (no punched hole) and delamination of the entire structure.
10. The Al/CFRP strategy was more suitable for the milling process and the CFRP/Al strategy for the drilling process.
11. On the basis of the analysis of variance carried out, it can be concluded that, depending on the tool entry and exit zones and its type (milling cutter, drill bit), the independent variables studied have a different impact on the quality of the holes.
12. In the milling cutter entry zone, the v_c x S interaction had the highest influence on the hole diameter, while in the exit zone the machining strategy had the highest effect. For the drilling process the highest influence on the dependent variable for both zones had the cutting speed.

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