Technologia i Automatyzacja Montażu

Volume 125, Issue 3/2024, Pages 21-28
https://doi.org/10.7862/tiam.2024.3.3

Original Research

ACCURACY OF ASSEMBLY HOLES AFTER DRILLING IN AL/CFRP LAYERED STRUCTURE

DOKŁADNOŚĆ WYKONANIA OTWORÓW MONTAŻOWYCH PO WIERCENIU KONSTRUKCJI WARSTWOWEJ TYPU AL/CFRP

Elżbieta DOLUK[1,*], **Izabela MITURSKA-BARAŃSKA**[1], **Oleksandra KRUPOVYCH**[1]

[1] Department of Production Computerisation and Robotisation, Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 36, 20–618 Lublin, Poland

* Corresponding author: e.doluk@pollub.pl, tel.: (+48) 507 666 485

Abstract

Layered structures consisting of CFRP composites and aluminum alloys are most commonly used in the aerospace, marine, construction and automotive industries. One of the most important aspects associated with their use is the difficulty of machining them due to the anisotropic nature of the structures. These structures are often jointed to each other by mechanical joints that require mounting holes. The purpose of this study was to determine the effect of drill bit diameter, cutting speed and the way the specimen is clamped during machining (drilling strategy) on the quality of holes drilled in a II-layer structure consisting of CFRP composite and aluminum alloy. The quality of the holes was expressed by the hole accuracy index D. A visual evaluation of the holes after the drilling process was also carried out. The most accurate holes (the lowest value of the hole accuracy index D) were obtained at the exit of the drill bits with Ø4 mm and Ø8 mm diameters, a cutting speed of v_c = 90 m/min and an Al/CFRP drilling strategy. The lowest dimensional accuracy of the hole was also obtained at the exit of the drill bit, but using a cutting tool with a diameter of Ø6 mm, a cutting speed of v_c = 30 m/min and an Al/CFRP drilling strategy. The values of the D index and visual evaluation of the holes also made it possible to note that for this type of material it is more favorable, considering the dimensional accuracy of the holes, to use a CFRP/Al drilling strategy.

Keywords: drilling, Al/CFRP stacks, assembly holes, cutting parameters

Streszczenie

Konstrukcje warstwowe składające się z kompozytów CFRP i stopów aluminium są najczęściej stosowane w przemyśle lotniczym, morskim, budowlanym oraz motoryzacyjnym. Jednym z najważniejszych aspektów związanych z ich zastosowaniem jest trudność ich obróbki wynikająca z anizotropowości konstrukcji. Konstrukcje te są często łączone ze sobą za pomocą połączeń mechanicznych, które wymagają wykonania otworów montażowych. Celem niniejszej pracy było określenie wpływu średnicy wiertła, prędkości skrawania i sposobu zamocowania próbki podczas obróbki (strategia wiercenia) na jakość otworów wykonywanych w II warstwowej konstrukcji składającej się z kompozytu CFRP i stopu aluminium. Jakość otworów wyrażono za pomocą wskaźnika dokładności wykonania otworu D. Przeprowadzono także ocenę wizualną otworów po procesie wiercenia. Najdokładniejszy otwór (najmniejszą wartość wskaźnika D) otrzymano na wyjściu otworów z wykorzystaniem wierteł o średnicach Ø4 mm i Ø8mm, prędkości skrawania vc = 90 m/min oraz strategii wiercenia Al/CFRP. Najmniejszą dokładność wymiarową otworu uzyskano również na wyjściu narzędzia, jednak z zastosowaniem wiertła o średnicy Ø6 mm, prędkości skrawania v_c = 30 m/min i strategii wiercenia Al/CFRP. Otrzymane wartości wskaźnika D oraz ocena wizualna pozwoliły zauważyć także, że dla tego typu materiałów korzystniejszym rozwiązaniem, biorąc pod uwagę dokładność wymiarową otworów, jest zastosowanie strategii wiercenia CFRP/Al (wejście narzędzia skrawającego w warstwę kompozytową, wyjście wiertła w warstwie metalowej).

Słowa kluczowe: wiercenie, konstrukcje warstwowe Al/CFRP, otwory montażowe, parametry skrawania

1. Introduction

One of the basic machining processes applied to heterogeneous materials, which include layered materials that are a combination of metal and polymer matrix composite, is the drilling process. Drilling holes in such structures is an important step in their assembly process – holes can be used to attach auxiliary units (e.g., bolts, rivets), introduce assembly components (e.g., adhesives, clamps, bushings) or carry out other assembly operations (Kausar et al., 2023). Layered materials are used in many industries due to their mechanical and physical properties, including light weight, bending and shear strength, ability to carry heavy loads, and impact resistance (Hosseinkhani et al., 2024). Performing the drilling process in structures that are a combination of materials with very different properties is a major challenge (Changze et al., 2023). Therefore, it is necessary to adapt the machining conditions to the specifics of the materials to ensure the desired surface quality after machining. This can be achieved by using appropriate cutting tools and cutting parameters (Kilickap, 2020).

When drilling holes in sandwich structures consisting of aluminum alloy and CFRP (Carbon Fibre Reinforced Plastic) composite having abrasive fibers in its structure, various problems may arise due to the specific structure and properties of the material so formed. The anisotropic structure of fiber composites is the main factor that has a significant impact on their strength, but on the other hand it makes the process of their processing largely difficult (Zhang et al., 2020). Difficulties in obtaining holes with reproducible dimensional and shape accuracy, excessive cutting tool wear, the occurrence of typical machining defects such as delamination, fiber pullout, matrix cracking, undercut fibers, and frayed edges at the entrance and exit of the cutting tool are examples of phenomena that can occur when drilling holes in CFRP composites and layered materials formed on their basis (Ciecieląg, 2022). The main phenomenon that hinders the process of drilling holes in this type of structures is delamination, which leads to a loss of cohesion of the individual layers of the CFRP composite and the entire layered structure (Ergün et al., 2021). An enlargement of the delamination area can occur even when the cutting edges of the tools are slightly dulled. Delamination during drilling can occur at the entrance and exit of the drill bit from the workpiece material. In the entry zone, delamination is characterized by the winding of carbon fibers on the drill bit and their tearing before the material is removed. In the exit zone, delamination occurs as a result of the lower layers of the composite being pushed out and separated from the remaining fibers (Isbilir et. al., 2013). Delamination can lead to damage to the integrity of the structure and a reduction in strength. Studies have shown that proper adjustment of drilling conditions (rotational speed, cutting force and tool cooling system) can effectively reduce the risk of material delamination (Melentiev et al., 2016). In addition, improperly selected cutting tools, such as the use of brittle or vulnerable tool materials, can lead to the formation of micro-cracks in the surfaces, which reduces its strength and reduces the quality of the hole finish (Natarajan, et al., 2022; Alagan et al., 2023.).

A significant number of holes made in sandwich structures are assembly holes. After machining, the quality of the holes is often defined by the presence of defects on the machined surfaces. Delamination occurring between the inner layers, is caused by the tool passing through different cutting resistances (Yang et al., 2024). This type of delamination is a hidden material defect and is particularly dangerous from the point of view of structural safety. A significant problem that can be encountered when drilling metal-polymer composite layered materials is the insufficient quality of the machined hole, which can lead to difficulties in the assembly of structural components or a reduction in the aesthetics of the final product. A review of the literature indicates that the use of tools with appropriate geometries, such as rake angle and blade geometry, can significantly improve the quality of the hole (Isbilir et al., 2013; Saoudi et al., 2018).

The purpose of this study was to determine the effect of drill bit diameter, cutting speed and the way the specimen is clamped during machining (drilling strategy) on the quality of holes drilled in a II-layer structure consisting of CFRP composite and aluminum alloy. The work is a continuation of research conducted on the machinability and quality of holes drilled in layered structures.

2. Materials and methods

The subject of the study was a II-layer metal–polymer composite structure. The shape and dimensions of a spacement are shown in Fig. 1.

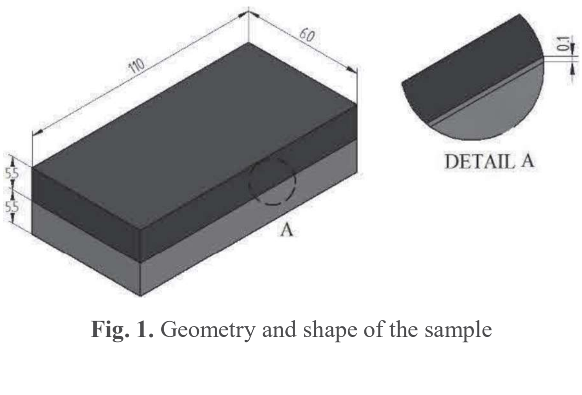

Fig. 1. Geometry and shape of the sample

The experiment investigated the effect of machining conditions on the dimensional accuracy of holes after the drilling process. Fig. 2 shows a diagram of the experiment conducted.

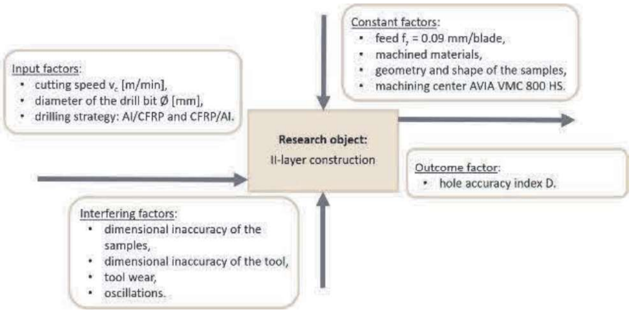

Fig. 2. Plan of the experiment

The structure consisted of two materials: a CFRP composite and an EN AW-2024 T3 aluminum alloy. The materials were chosen because of their frequent use in the aerospace and automotive industries. The layers were joined using an adhesive process. The characteristics and properties of the materials used and details of the bonding process are given in (Doluk, 2023).

The experiment examined the effects of cutting speed, drill bit diameter and drilling strategy on the dimensional accuracy of holes after the drilling process. The test was conducted using an AVIA VMS 800HS vertical machining center. The drilling process was carried out without the use of coolant due to the nature of the material to be machined (CFRP). The machining scheme is shown in Fig. 3.

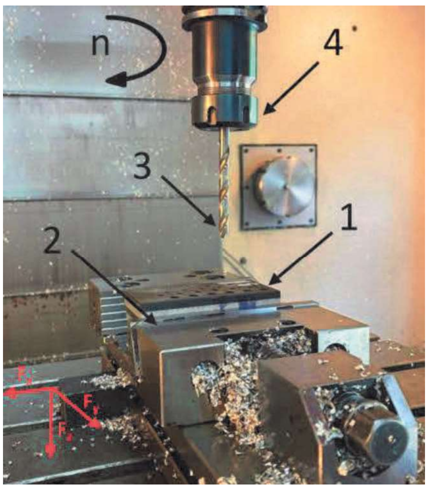

Fig. 3. Diagram of the drilling process: 1 – workpiece, 2 – machine vise, 3 – tool, 4 – spindle

Drill bits with diameters of Ø8 mm, Ø6 mm and Ø4 mm were used in the study. The manufacturer of the tools used is Kennametal. The drills were made of tungsten carbide and coated with TiAlN (*Titan Aluminum-Nitride*) tool coating. This coating has good resistance to large temperature ranges, which allows machining with high cutting speeds.

Two machining strategies were adopted in the study:

- drilling of holes in the II-layer aluminum alloy type structure EN AW-2024 T3composite CFRP, where the entry layer is aluminum alloy (Al/CFRP) (Fig. 4a),
- drilling holes in a II-layer CFRP-aluminum alloy EN AW-2024 T3 composite structure, where the entry layer is CFRP composite (CFRP/Al) (Fig. 4b).

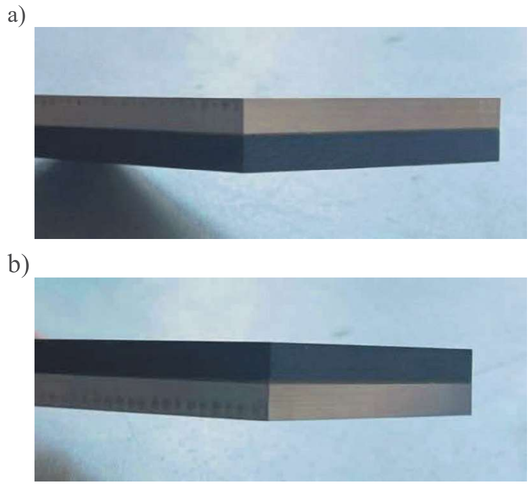

Fig. 4. Adopted drilling strategies: a) Al/CFRP strategy, b) CFRP/Al strategy

The values of the independent variables considered in this research are shown in Table 1. The study used a static, determined complete plan (PS/DC).

Table 1. Independent variables adopted in the experiment

Variable	Value		
Cutting speed v_c [m/min]	30	60	90
Drill bit diameter [mm]	Ø8	Ø6	Ø4
Drilling strategy	Al/CFRP	CFRP/Al	

The diameters of the treated holes were measured using a Keyence VHX-500 digital microscope. This device allowed recording the image with high accuracy (0.001). The dimensional accuracy of the holes was measured for all adopted machining variants at the entry and exit of the drill bit from the workpiece material. To determine the dimensional accuracy of the holes, the value of the hole accuracy index D was determined from the ratio of the arithmetic mean of the actual hole diameters D_{rz} obtained after machining and the nominal value of the hole in question. Hole diameters were measured using the Keyence VHX-

500 digital microscope. The quality of the machined holes was determined by the hole:

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

where: D – hole accuracy index, D_{rz} – diameter of the hole after machining [mm], D_N – nominal diameter of the hole [mm].

The hole accuracy index D was assimilated to 0 – values closer to this digit indicated better dimensional accuracy of the hole. Each machining variate was performed three times to average the obtained diameter values, while each hole was expressed as the arithmetic average of three measurements.

When machining structures, comparing machining effects by dimensional accuracy alone may not be sufficient. It is also necessary to determine the condition of the hole edges. For this purpose, the holes were visually evaluated using the Keyence VHX-500 digital microscope with 100x magnification.

3. Results and discussion

Figures 5–10 show the effect of the tested machining conditions on the values of the hole accuracy index D at the entry and exit of the cutting tool.

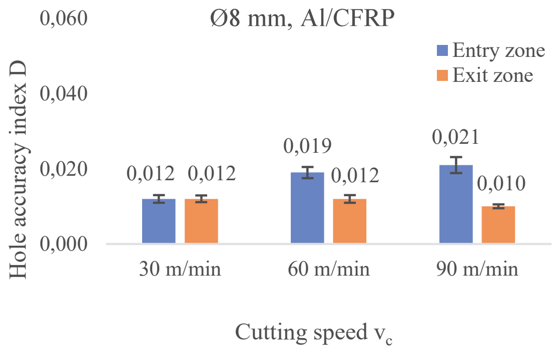

Fig. 5. Hole accuracy index D at the entry and exit of the cutting tool using Al/CFRP drilling strategy and drill bit diameter Ø8 mm

The maximum value of the D index (0.021) obtained after machining with the drill bit diameter Ø8 and the Al/CFRP drilling strategy was obtained at the entry of the cutting tool for the cutting speed of v_c = 90 m/min, while the minimum value (0.010) was obtained at the exit of the drill bit and the same cutting speed (Fig. 5). In the above case, higher values of the D index were observed at the entry of the cutting tool, indicating poorer hole accuracy than at the exit of the drill bit. Analyzing the above data, it can be observed that the values of the D index at the entry of the tool increased with an increase in the cutting speed v_c, while at the exit of the drill bit they remained at the same level or decreased with an increase in the cutting speed v_c.

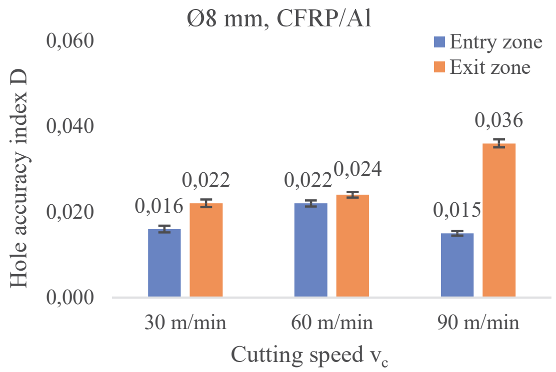

Fig. 6. Hole accuracy index D at the entry and exit of the cutting tool using CFRP/Al drilling strategy and drill bit diameter Ø8 mm

In the case of using the drill bit diameter Ø8 mm and the CFRP/Al drilling strategy (Fig. 6), the lowest value of the D index (0.015) was obtained at the entry of the cutting tool when using a cutting speed of v_c = 90 m/min. The highest value of the hole accuracy index D (0.036) for the adopted cutting conditions was obtained at the cutting speed v_c = 90 m/min at the exit of the cutting tool. The values of the D index obtained at the entry of the drill bit were equal to or higher than the values of the D index obtained at the exit of the cutting tool. Increasing the cutting speed in this case caused an increase in the value of the D index at the exit of the cutting tool.

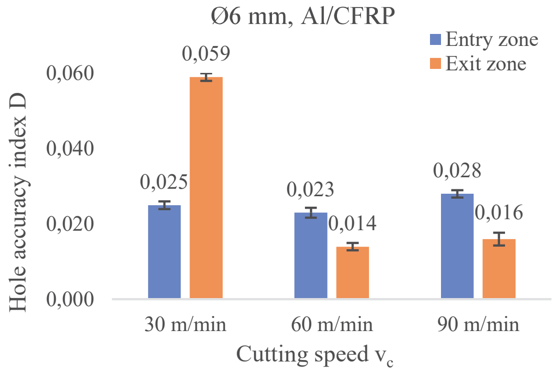

Fig. 7. Hole accuracy index D at the entry and exit of the cutting tool using Al/CFRP drilling strategy and drill bit diameter Ø6 mm

Fig. 7 shows the obtained results of the D index for the drill bit diameter Ø6 mm and the Al/CFRP drilling strategy. The highest value of the considered index (0.059) was obtained at the exit of the drill bit when using the cutting speed of v_c = 30 m/min. The lower value of the hole accuracy index D (0.014), and therefore the highest dimensional accuracy, was also observed at the exit of the cutting tool, but using the cutting speed of v_c = 60 m/min. Lower values of the D index were obtained at the exit of the cutting tool compared to the entry of the drill bit, except when using the lowest cutting speed, where the maximum value of the D index was obtained.

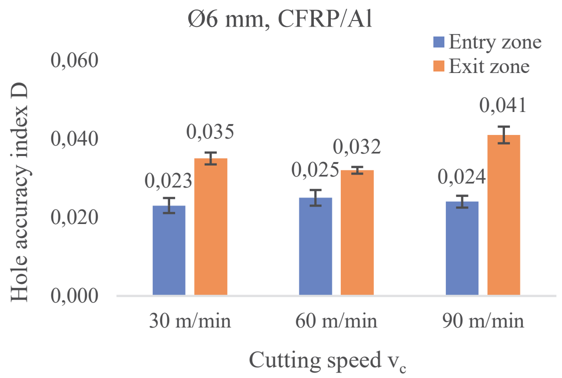

Fig. 8. Hole accuracy index D at the input and output of the cutting tool using CFRP/Al drilling strategy and drill bit diameter Ø6 mm

In Fig. 8 were presented the values of the hole accuracy index D for the drill bit diameter Ø6 mm and the CFRP/Al drilling strategy. The maximum value of the hole accuracy index D (0.041) was obtained at the exit of the cutting tool when using the cutting speed of v_c = 90 m/min, while the minimum value of the index D (0.023) was obtained at the entry of the drill bit for the cutting speed of v_c = 30 m/min. Comparing the results, it can be seen that the higher values of the D index were obtained at the exit of the cutting tool.

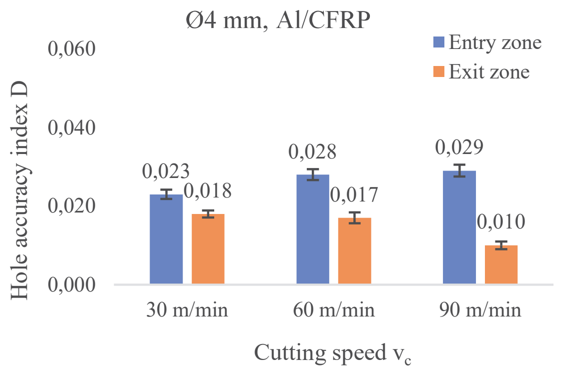

Fig. 9. Hole accuracy index D at the input and output of the cutting tool using Al/CFRP drilling strategy and drill bit diameter Ø4 mm

Analyzing Fig. 9, which presents the values of the hole accuracy index for the drill bit diameter Ø4 mm and the Al/CFRP drilling strategy, it is noted that for cutting speed v_c = 90 m/min, the lowest value of the hole accuracy index D (0.010) was obtained at the exit of the cutting tool, while the highest value (0.029) was obtained at the entry of the drill bit. Higher values of the D index were obtained at the entry of the cutting tool. Increasing the cutting speed in the analyzed case resulted in an increase in the value of the D index at the entry of the tool and a decrease in its value at the exit of the drill bit.

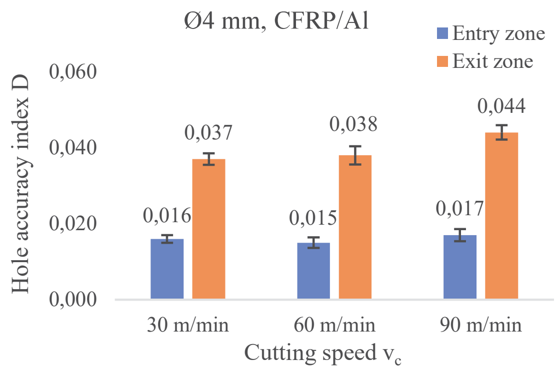

Fig. 10. Hole accuracy index D at the input and output of the cutting tool using CFRP/Al drilling strategy and drill bit diameter Ø4 mm

Considering the values of the hole accuracy index D obtained for the drill bit diameter Ø4 mm and the CFRP/Al drilling strategy (Fig. 10), it can be seen that the lowest value of the index D (0.015) was obtained at the entry of the drill bit at a cutting speed of v_c = 60 m/min, while the highest value was obtained at the exit of the tool using a cutting speed of v_c = 90 m/min. For all the considered cutting speeds, higher values of the D index were obtained at the exit of the cutting tool. For most of the results obtained, an increase in cutting speed resulted in an increase in the hole accuracy index D.

In order to determine the influence of individual input factors (cutting speed v_c, drill bit diameter Ø and the drilling strategy S) and their interactions (v_c × Ø × S, v_c × Ø, v_c × S and Ø × S) on the dimensional accuracy of the machined holes, a multivariate analysis of variance (ANOVA) was conducted at the significance level of α = 0.05. Table 2 and Table 3 show the results of the statistical analysis.

Table 2. Three-factor ANOVA analysis of variance for the hole accuracy index D at the entry of the drill bit

Source	SS	DF	MS	F	*p-value*
v_c	0.004	2	0.002	5	0.024
Ø	98.652	2	49.326	146792	<0.001
S	0.002	1	0.002	7	0.017
v_c × Ø	0.004	4	0.001	3	0.064
v_c × S	0.002	2	0.001	4	0.039
Ø × S	0.004	2	0.002	5	0.022
v_c× Ø× S	0.002	4	<0.001	1	0.249

Table 3. Three-factor ANOVA analysis of variance for the hole accuracy index D at the exit of the drill bit

Source	SS	DF	MS	F	*p-value*
v_c	0.012	2	0.006	0.7	0.491
Ø	98.182	2	49.091	5778.7	<0.001
S	0.073	1	0.073	8.6	0.009
v_c × Ø	0.040	4	0.010	1.1	0.375
v_c × S	0.038	2	0.019	2.3	0.131
Ø × S	0.012	2	0.006	0.7	0.488
v_c× Ø× S	0.024	4	0.006	0.7	0.619

Based on the data presented in the tables, it can be seen that the dimensional accuracy of the holes at the entry of the cutting tool was most influenced by the drill bit diameter (F = 146792; *p-value* < 0.001). The interaction of all three independent variables (v_c x Ø x S), like the interaction of v_c x Ø, did not statistically affect the values of the index D. At the exit of the cutting tool, only two variables influenced the dependent variable: the drill bit diameter (F = 5779.7; *p-value* < 0.001) and the drilling strategy (F= 8.6; *p-value* = 0.009). The other factors had no effect from a statistical point of view on the obtained values of the hole accuracy index D.

a)

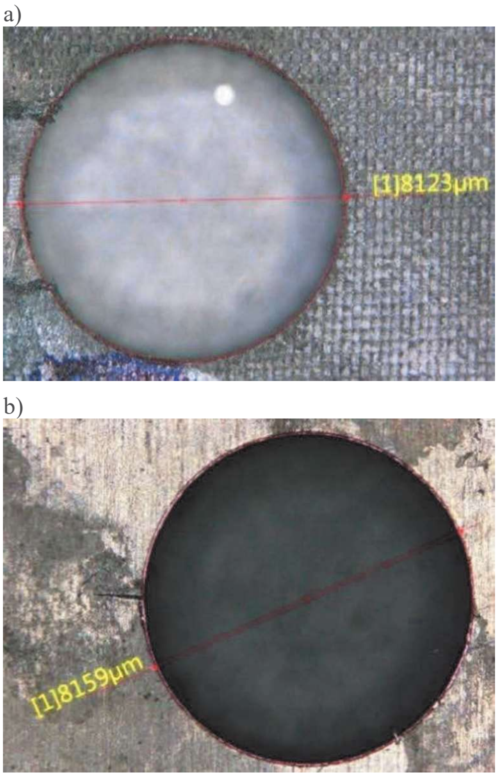

Fig. 11. Hole after drilling with drill bit diameter Ø8 for CFRP/Al drilling strategy and cutting speed v_c = 30 m/min: a) at the entry of the drill bit, b) at the exit of the drill bit

The quality of post-drilling holes in layered materials was also assessed visually to identify material defects after machining. Special attention was paid to holes drilled in the CFRP composite. Figures 11–13 show images of the holes for selected cutting conditions.

a)

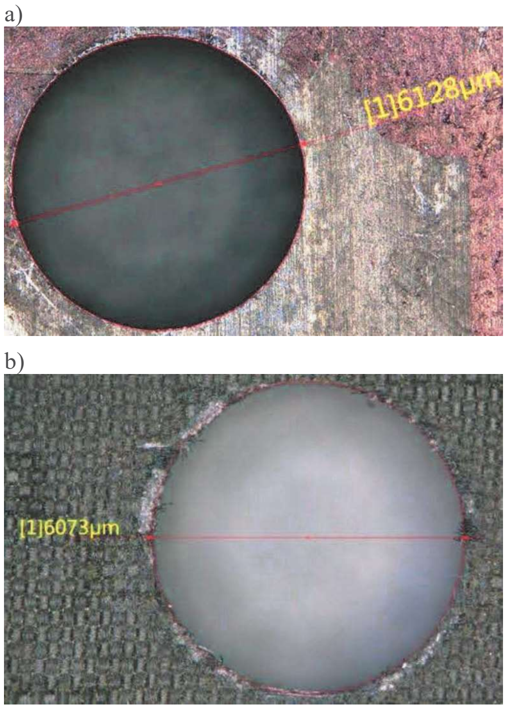

Fig. 12. Hole after drilling with drill bit diameter Ø6 for Al/CFRP drilling strategy and cutting speed v_c = 60 m/min: a) at the entry of the drill bit, b) at the exit of the drill bit

a)

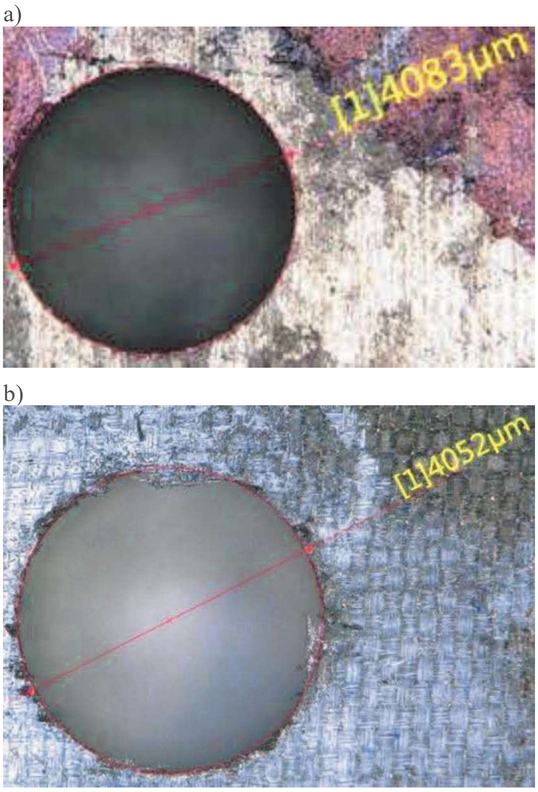

Fig. 13. Hole after drilling with drill bit diameter Ø4 for Al/CFRP drilling strategy and cutting speed v_c = 30 m/min: a) at the entry of the drill bit, b) at the exit of the drill bit

A visual evaluation of the holes after machining made it possible to note the occurrence of typical forms of destruction of polymer composites, During machining of the aluminum alloy there was mainly breaking of the hole, as a result of which in most cases holes with larger diameters were obtained in the metal layer than in the composite layer. Making holes in the CFRP composite was associated with the occurrence of typical forms of damage in fiber composites, i.e. torn and undercut fibers, matrix cracking, delamination and inclusions of aluminum chips. The occurrence of these defects led in many cases to a reduction in the diameter of the machined holes, resulting in lower value of the hole accuracy index D and misleadingly indicating holes with higher dimensional accuracy. This phenomenon can directly lead to difficulties in the implementation of the assembly process.

4. Conclusions

The aim of this study was to determine the effect of the cutting conditions on the quality of holes drilled in a layer structure. Based on the results obtained, it was found that the lowest value of the hole accuracy index D (0.010) indicating the best hole accuracy, was obtained at the exit of the cutting tool when using the drill bits with diameters Ø8 mm and Ø4 mm and the cutting speed v_c = 90 m/min and the Al/CFRP drilling strategy. The highest value of the D index (0.059) was observed at the exit of the drill bit diameter Ø6 mm using the cutting speed of v_c = 30 m/min and the Al/CFRP drilling strategy.

Both at entry and exit of cutting tools, the D index was most influenced by the drill bit diameter, while the interaction of the three considered independent variables (v_c x Ø x S) had no statistically significant effect on its values.

The CFRP/Al drilling strategy proved to be a better machining method compared to the Al/CFRP drilling strategy due to the avoidance of delamination of the composite material at the exit of the cutting tool.

Increasing the cutting speed for most of the cases considered resulted in an increase in the dimensional accuracy of holes made in the composite layer and its deterioration in the metal layer.

The dimensional accuracy of holes made in metal–polymer composite layered materials should not be analyzed solely by means of the index D. A visual assessment taking into account post-machining defects on the machined surfaces should also be considered.

References

Alagan, NT., Sajja, NT., Gustafsso, A., Savio, E., Ghiotti, A., Brusch, S., & Bertolini, R. (2023). Investigation of the quality of Al-CFRP stacks when drilled using innovative approaches. *CIRP Journal of Manufacturing Science and Technology, 43,* 260–272. doi.org/10.1016/j.cirpj.2023.04.011.

Changze Sun, Ch., Albustani, H., Phadnis, VA., Saleh, MN., Cantwell, W.J., & Guan, Z. (2023). Improving the structural integrity of foam-core sandwich composites using continuous carbon fiber stitching. *Composite Structures, 324,* 117509. doi.org/10.1016/j.compstruct.2023.117509.

Ciecieląg, K. (2022). Study on the Machinability of Glass, Carbon and Aramid Fiber Reinforced Plastics in Drilling and Secondary Drilling Operations. *Advances in Science and Technology Research Journal, 16(2),* 57–66. doi.org/10.12913/22998624/146079.

Doluk, E. (2023). Comparison of hole quality after drilling and helical milling of the Al/CFRP stacks. *Technologia I Automatyzacja Montażu (Assembly Techniques and Technologies), 122(4)*, 3–12. doi.org/10.7862/tiam.2023.4.1.

Ergün, E., Uzun, G., & Altaş, S. (2021). Evaluation of the effects of drilling parameters, tool geometry and core material thickness on thrust force and delamination in the drilling of sandwich composites. *Surface Review and Letters, 28(12),* 2150112. doi.org/10.1142/S0218625X21501122.

Hosseinkhani, H., Zhang, X., Liu, Q., & Nasiruddin, M. (2024). Enhancing impact energy absorption in composite sandwich structures through synergistic smart material integration. *Results in Engineering, 21(3),* 101902. doi.org/10.1016/j.rineng.2024.101902.

Isbilir O., & Ghassemieh, E. (2013). Numerical investigation of the effects of drill geometry on drilling induced delamination of carbon fiber reinforced composites. *Composite Structures, 105,* 126–133. doi.org/10.1016/j.compstruct.2013.04.026.

Kausar, A., Ishaq A., Rakha, SA., Eisa, MH., & Diallo, A. (2023). State-Of-The-Art of Sandwich Composite Structures: Manufacturing–to–High Performance Applications. *Journal of Composites Science, 7(3),* 102. doi.org/10.3390/jcs7030102.

Kilickap, E. (2020). Optimization of cutting parameters on delamination based on Taguchi method during drilling of GFRP composite. *Expert Systems with Applications, 37(8),* 6116–6122. doi.org/10.1016/j.eswa.2010.02.023.

Melentiev, R., Priarone, PC., Robiglio, M., & Settineri, L. (2016). Effects of Tool Geometry and Process Parameters on Delamination in CFRP Drilling: An Overview. *Procedia CIRP, 45,* 31–34. doi.org/10.1016/j.procir.2016.02.255.

Natarajan, E., Markandan, K., Sekar, SM., Varadaraju, K., Nesappan, S., Albert Selvaraj, AD., Lim, WH., & Franz, G. (2022). Drilling-Induced Damages in Hybrid Carbon and Glass Fiber-Reinforced Composite Laminate and Optimized Drilling Parameters. *Journal of Composites Science, 6(10),* 310. doi.org/10.3390/jcs610031.

Saoudi, J., Zitoune, R., Gururaja, S., Salem, M., & Mezleni, S. (2018). Analytical and experimental investigation of the delamination during drilling of composite structures with core drill made of diamond grits: X-ray tomography analysis. *Journal of Composite Materials, 52(10),* 1281–1294. doi:10.1177/0021998317724591.

Yang, B, Wang, H., Chen, Y., Fu, K., & Li, Y. (2021). Experimental evaluation and modelling of drilling responses in CFRP/honeycomb composite sandwich panels. *Thin-Walled Structures, 169,* 108279. doi.org/10.1016/j.tws.2021.108279.

Zhang, Z., Myler, P.; Zhou, E., & Zhou, R. (2020). Strength and Deformation Characteristics of Carbon Fibre Reinforced Composite Wrapped Aluminium Foam Beams. *Journal of Composites Science 6(10),* 288. doi.org/10.3390/jcs6100288.