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Original research article

Tensile-Shear Strength of a Single-lap Adhesive Joint of PA6 GF Composite: Effects of Fiber Orientation and Moisture

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ABSTRACT

One of the main features of additive manufacturing is the ability to produce parts with complex geometries that would be difficult or impossible to produce with minimal waste using conventional manufacturing technologies. A more massive implementation of additive technologies makes it possible to shorten supply chains and reduce the need to store parts. The use of composite materials is massive nowadays, first of all in the lightweight design. The aim of this study is to analyze the influence of fiber orientation and moisture on the strength of single-lap adhesive joints of parts produced by additive manufacturing. The test samples (adherends) were produced using FDM (Fused Deposition Modeling) technology, PA6 GF composite material and two-component epoxy adhesive. Results showed that the average failure load tends to increase the higher the percentage of absorbed moisture in the base material. With the selected combination of material and adhesive, the influence of fiber orientation cannot be observed independently of the amount of moisture absorbed. The best results are achieved with the highest percentage of absorbed moisture and the orientation of the fibers in the direction of the longitudinal axis of the samples.

Key words: *FDM; fiber orientation; moisture; PA6 GF; two-component epoxy adhesive.*

1. INTRODUCTION

In recent years, the use of composite materials for the development of lightweight structures has experienced remarkable growth in a variety of industries. Significant progress has been made in the aerospace, aircraft, marine, automotive, construction and sports industries, as well as in the chemical industry, road construction, agricultural and industrial buildings and renewable energy. The increasing use of composites in these areas underlines their crucial role in modern engineering practice and the continuous pursuit of innovative design solutions [1],[2]. Application of glass fiber reinforced composites (GFRP) can lead to a weight reduction in the range of 15-25% [3]. Requirements for high mechanical properties of structural parts and an excellent balance between price and mechanical properties have led to the wide use of the family of materials based on Polyamide 6 (PA6). However, the mechanical properties of polyamides are strongly dependent on the amount of water absorbed and the operating temperature [4].

One of the biggest challenges in the application of fiber-reinforced polymer composites is the process of joining individual components. Effective joining methods are critical to maintaining structural integrity. In addition, these methods must ensure efficient load transfer between the joined parts to maintain overall performance and durability [5].

Adhesive bonding represents a challenging and rapidly evolving area of research that has already gained significant attention from industry ([6]-[8]), and adhesive-bonded joints have become an excellent alternative to

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conventional joining methods [9]. The expansion of adhesive bonding in industry has been closely associated with the broader application of composite materials and the increasing demand for joining of dissimilar materials. Unlike conventional joining techniques, adhesive bonding does not require local heating of the substrates or the creation of holes and notches. Instead, it offers a continuous joining method that reduces regions of discontinuity and promotes a more uniform distribution of stress across the bonded structure [10].

The research [11] highlights the possibilities of joining 3D printed parts using two-component epoxy adhesives. The correct choice of adhesive can significantly facilitate the joining process and it is recommended to use materials with better mechanical properties compared to PLA. Volkan Kovan, Gurkan Altan and Eyup Sabri Topal [12] investigated the effect of layer thickness and print orientation on strength of 3D printed and adhesively bonded single lap joints. They've found that layer thickness and print orientation have significant influence on bonding strength of parts manufactured with Fused Deposition Modeling (FDM). In a study [13], a silane-based surface treatment with KH560 in combination with an abrasion pretreatment was developed for carbon fiber-reinforced PA6 composites with a fiber content of 30 (Cf/PA6) and the aluminum alloy AA6061-T4. The composition and structure of the applied silane coating were characterized and its influence on the mechanical strength and water resistance of the bonded Cf/PA6 and AA6061 joints was evaluated. The silane treatment increased the strength of Cf/PA6-to-Cf/PA6 and Cf/PA6-to-AA6061-T4 joints by 23% and 21%, respectively. However, immersion of both the untreated and pre-treated adhesive joints in water at 54 °C for one week resulted in a reduction in joint strength of approximately 50%. All samples subjected to water exposure exhibited adhesive failure mode. In a study [14], the effect of omitting annealing on the impact strength properties of PA6 GF composites was demonstrated. It was shown that the impact strength can be significantly increased if PA6 GF is not annealed after FDM. The paper examined samples stored at room temperature without a dry box system.

This paper presents an experimental investigation of the influence of fiber orientation and moisture absorption on the strength of single-lap adhesive joints of PA6 GF composites produced using FDM technology. It is also a continuation of earlier research [11] and [14].

2. EXPERIMENTAL PROGRAM

For this study, Polymaker PA6 GF (glass fiber reinforced Nylon 6 filament) was used as a representative of composite materials with an excellent ratio of price and mechanical properties (Table 1). It is also a very demanding material in terms of production, as it requires constant temperature control (the nozzle temperature during printing must be above 280°C) and is very abrasive, which requires the use of abrasion-resistant nozzles. PA6 GF is very hygroscopic (tends to absorb moisture from the atmosphere), which greatly impairs its mechanical properties (Table 1).

Table 1 - *Mechanical properties of PA6GF (dry status and moisture conditioned) [15]*

	Dry status	**Moisture conditioned**
Young's modulus	4431 ± 184 MPa	2053 ± 243 MPa
Tensile strength	84.5 ± 2.1 MPa	50.8 ± 4.9 MPa
Charpy impact strength	136.4 ± 1.6 kJ/m^2	21.2 ± 1.1 kJ/m^2

The geometry and dimensions of the test samples are shown at Fig.1. The dimensions of the adherends are identical to those of the study [11], whereby the thickness of the adherends was increased to ensure that no fracture occurred in the base material.

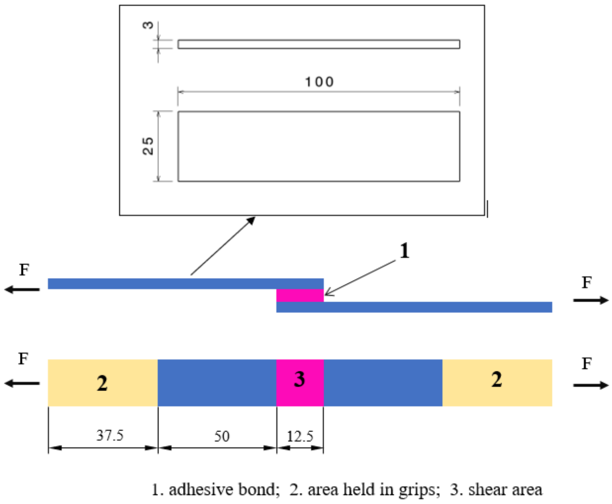

Fig. 1 *Dimensions of the adherends.*

The professional and industrial IDEX (Independent Dual Extrusion) 3D printer FlashForge Creator 3 Pro was used to produce the adherends. The using of this printer is possible to print two objects at the same time, either a copy or a mirrored version. One of the main features of this printer is a closed working chamber that prevents sudden temperature fluctuations due to external influences. The device also has an interactive display that allows the process to be constantly monitored and changed in terms of temperature. FlashPrint software was used to slice the 3D models and main printing parameters were:

1. Nozzle size: 0.6 mm
2. Layer height: 0.2 mm
3. Extruder temperature: 300°C
4. Build plate temperature: 50°C
5. Print speed: 60 mm/s
6. Fill density: 100%
7. Fill pattern: Line
8. Shell count (number of exterior walls): 3
9. Enable raft: Yes.

Fig. 2 shows the layout of the adherends for printing.

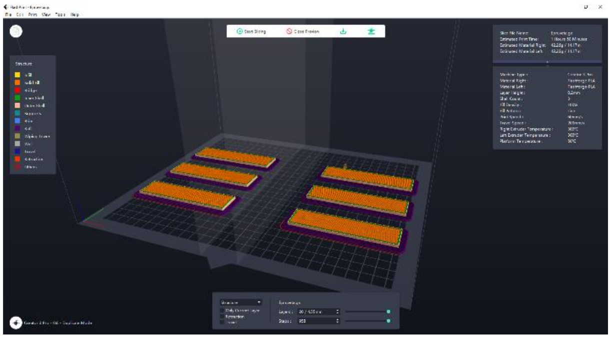

Fig. 2 *Layout of the adherends.*

The parameters that were varied in this experiment are the orientation of the fibers of the surface and the amount of moisture absorbed by the material before production. All specimens were divided into three groups according to the amount of moisture absorbed**:**

1. Group A - printing immediately after opening the material package;
2. Group B - printing 7 days after opening the material package;
3. Group C - printing 60 days after opening the material package.

The groups are then subdivided according to fiber orientation (Fig.3.):

1. Subgroup 1 - fiber orientation in the direction of the longitudinal axis of the specimen;
2. Subgroup 2 - fiber orientation at an angle of 45° in relation to the longitudinal axis of the specimen.

a) b)

Fig. 3 *a) Fiber orientation in the direction of the longitudinal axis of the specimen; b) fiber orientation at an angle of 45° in relation to the longitudinal axis of the specimen.*

Table 2 shows the indexing of all test specimens according to the degree of moisture absorption and fiber orientation. A total of 18 specimens were produced and the marking on each specimen stands for the group, subgroup and repetition.

It is important to note that the percentage of moisture absorbed is determined on the basis of the moisture absorption curve in the manufacturer's technical data sheet.

Table 2 – *Indexing of specimens*

	Mark	Moisture absorbed	Fiber orientation
Group A	A1.1	0%	0°
	A1.2	0%	0°
	A1.3	0%	0°
	A2.1	0%	45°
	A2.2	0%	45°
	A2.3	0%	45°
Group B	B1.1	2.25%	0°
	B1.2	2.25%	0°
	B1.3	2.25%	0°
	B2.1	2.25%	45°
	B2.2	2.25%	45°
	B2.3	2.25%	45°
Group C	C1.1	3.22%	0°
	C1.2	3.22%	0°
	C1.3	3.22%	0°
	C2.1	3.22%	45°
	C2.2	3.22%	45°
	C2.3	3.22%	45°

Before printing, the platform was cleaned with alcohol and a thin layer of Magigoo PA adhesive was applied to ensure sufficient adhesion between the platform and the specimens. The side of the specimen that was on the platform is referred to as the back, the opposite side is the front side (Fig.4). In order to determine the significance of the influencing parameters, only the front sides were bonded.

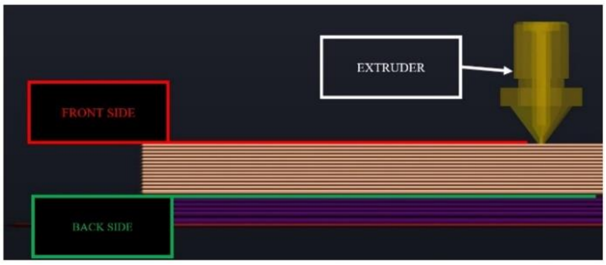

Fig. 4 *Front and back side of the specimen.*

The two-component epoxy adhesive Toolcraft (Toolcraft Epoxy transparent 5 Minuten) was used for the experiment. The characteristics of adhesive are given in the Table 3. After printing, the specimens were cleaned with Sika Cleaner P. The appearance of the specimens after 3D printing and cleaning is shown in Fig.5. Bonding was done at room temperature (approx. 23°C). To apply the adhesive, the provided Toolcraft gun was used with a nozzle for mixing the components in a 1:1 ratio. The nozzle recommended by the glue manufacturer was used. After joining the two materials together, additional plastic clamps were placed to prevent movement during curing. Curing took 24 hours at room temperature. The appearance of the bonded samples is shown in Fig.6a. The tensile - shear tests (Fig.6b) were carried out on the SHIMADZU AGS-X 20 kN testing machine. The speed of the crosshead was 2 mm/min.

Table 3 – *Properties of Toolcraft two-component adhesive [16]*

Mixing ratio	1:1
Processing time:	5 minutes
Curing time:	2-3 hours
Temperature resistance:	-40 °C to +120 °C
Tensile shear strength:	20 N/mm²

Fig. 5 *The appearance of the specimens after 3D printing and cleaning with Sika Cleaner P.*

a) b)

Fig. 6 *a) Appearance of bonded samples b) The tensile shear test.*

3. RESULTS AND DISCUSSION

The failure load values achieved during the test are given in Table 4. The failure load for all specimens ranged from approximately from 700 N to 1700 N and all specimens failed in AF (Adhesive Failure) mode (Fig.7).

Table 4 – *Failure load of specimens*

	Mark	Failure load *N*	Average failure load *N*
Group A	A1.1	850.849	934.907
	A1.2	989.691	
	A1.3	964.181	
	A2.1	796.948	785.521
	A2.2	699.145	
	A2.3	860.469	
Group B	B1.1	1244.32	1203.543
	B1.2	1308.91	
	B1.3	1057.40	
	B2.1	1469.23	1315.796
	B2.2	1284.91	
	B2.3	1193.25	
Group C	C1.1	1702.48	1538.796
	C1.2	1545.14	
	C1.3	1368.77	
	C2.1	1533.38	1240.956
	C2.2	1050.77	
	C2.3	1138.72	

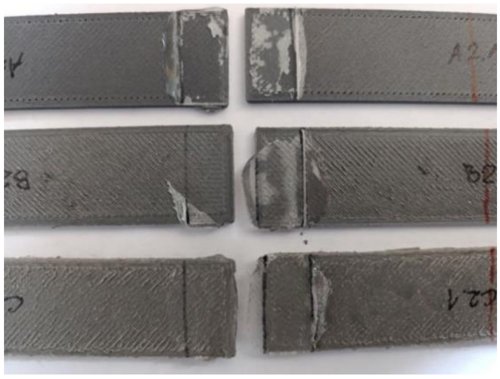

Fig. 7 *AF mode of A2.1, B2.1 and C2.1 specimens.*

It can be observed that the average failure load tends to increase the higher the percentage of absorbed moisture in the base material. In terms of the amount of absorbed moisture, the samples in group C proved to be the best. With regard to the orientation of the fibers in the surface layer, it can be determined that the orientation of the fibers in the direction of the longitudinal axis of the specimen leads to a higher load capacity for group A and group C. The higher load capacity for group B was achieved when the fibers were at an angle of 45° in relation to the longitudinal axis of the specimen.

Fig.8 shows the stress-strain curves for the samples from both subgroups of group A, which showed the best results. The maximum stress value of 3.17 MPa was recorded for sample A1.2.

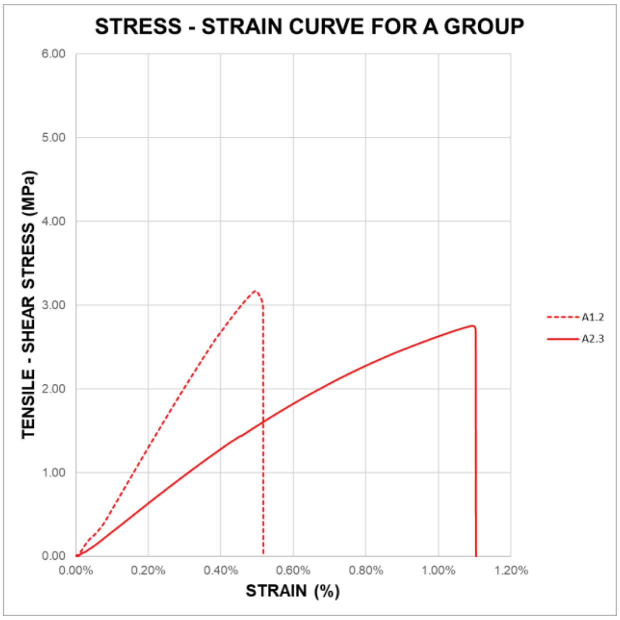

Fig. 8 *Stress-strain curves for group A.*

Fig.9 shows the stress-strain curves for the samples from both subgroups of group B, which showed the best results. The maximum stress value of 4.7 MPa was recorded for sample B2.1.

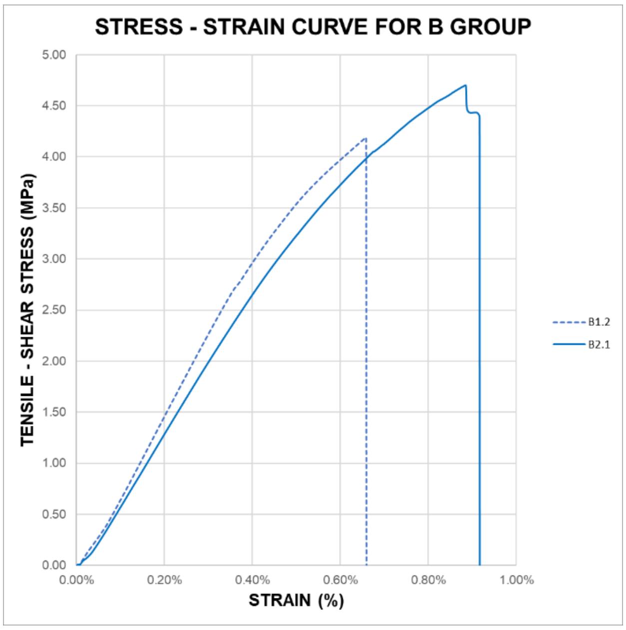

Fig. 9 *Stress-strain curves for group B.*

Fig.10 shows the stress-strain curves for the samples from both subgroups of group C, which showed the best results. The maximum stress value of 5.44 MPa was recorded for sample C1.1.

It can be seen that the values are well below the values defined by the adhesive manufacturer. Due to the low value of the tensile shear stress achieved and the failure of the adhesive, it can be concluded that the bonded joint made of PA6 GF material and Toolcraft adhesive does not have satisfactory mechanical properties.

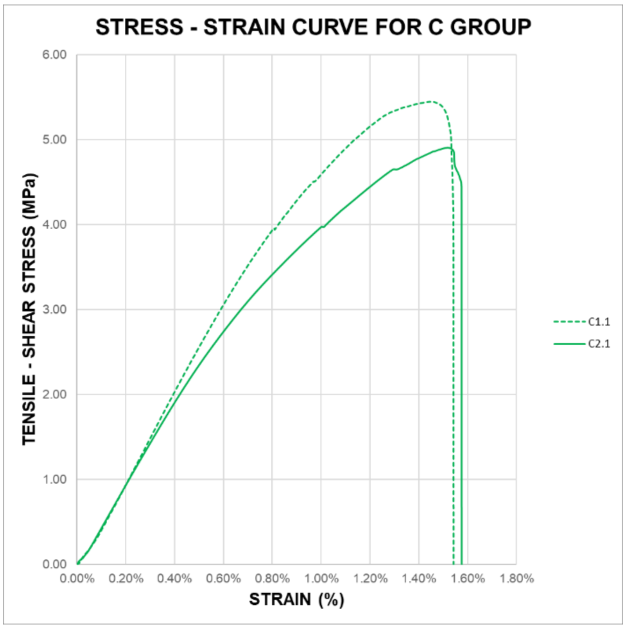

Fig. 10 *Stress-strain curves for group C.*

3. CONCLUSIONS

In this study, the effects of fiber orientation and moisture absorption on the strength of single-lap adhesive joints in PA6 GF composites were investigated. The main results are as follows:

1. The failure load of all samples ranged from approximately 700 N to 1700 N, with higher moisture content correlating with higher average failure load.
2. Bonded joints made with PA6 GF material and TOOLCRAFT adhesive showed insufficient mechanical performance.;
3. Due to the material–adhesive combination used, the influence of fiber orientation could not be isolated from the effects of moisture absorption. The best performance was observed at maximum moisture absorption and fiber orientation along the longitudinal axis, with a peak stress of 5.44 MPa being achieved. Future researches will investigate adhesives with improved mechanical properties and extend the range of influencing parameters.

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[15] PRODUCT DATA SHEET – PolyMide PA6 GF Version 5.1.

[16] PRODUCT DATA SHEET – TOOLCRAFT Epoxy transparent 5 Minuten Version 03 (15.02.2016.)

NOTE

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