No. 129/24, 33–45
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/129.03

Submitted: 24.11.2023
Accepted: 25.01.2024
Published: 28.03.2024

ANALYSIS OF THE EFFECT OF THE ADDITION OF ALUMINUM POWDER ON POLYESTER-GLASS COMPOSITE PROPERTIES IN TENSILE AND HARDNESS TEST

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Abstract: The study aimed to analyse the influence of aluminum powder on the mechanical properties of polyester-glass composites. Composite materials were made of glass fibres with random fibre direction and polyester resin with the addition of aluminum powder as a filler. The strength parameters of materials obtained during the static tensile test and hardness test were compared. The results were subjected to statistical analysis, taking into account the change in the amount of filler, microstructure was also observed using optical microscopy. An analysis of the results showed that the addition of aluminum powder amounting to 2% of the weight of the composites reduces their hardness and, at the same time, the longitudinal modulus of elasticity.The addition of aluminum powder amounting to 5% and 10% of the weight of the composites increased the hardness of the composites while reducing the Young's modulus. The values of hardness measurements were subjected to statistical analyses at significance level $\alpha = 95$. The Shapiro-Wilk test confirmed that the hardness variables for all tested samples were in normal distributions, and therefore the most powerful parametric tests were used to test the differences. Using the Student's t-test, it was confirmed that between pairs of variables in configurations: a standard sample with a modified sample, for all tested samples there are significant statistical differences in the distributions of hardness values. Studies have shown that the modification of the mechanical and strength properties of composite materials, through the use of an aluminum filler, makes it possible to obtain materials with variable parameters that can be useful and attractive in many new areas, depending on the application and user requirements.

Keywords: composites, aluminum powder, static tensile test, hardness, statistical analysis.

1. INTRODUCTION

Composites are materials that are used in many elements of construction in transport industry [Selvaraju and Ilaiyavel 2001]. Their wide application, high strength, stiffness, low density, high fatigue strength, high damping and low thermal coefficient (towards the fibres), as well as ease of modification compared to other materials, are associated with the development of newer and better materials in terms of strength parameters [Karbhari 2007; Pendhari, Kant and Desai 2008; Herakovich 2012; Tekinalpa et al. 2014; Kyzioł et al. 2020; Abramczyk et al. 2022]. There is enormous scope for modification [Lee, Nian and Tarng 2007; Singh and Samanta 2015; Gustin et al. 2020]. Over the years, new materials based on carbon fibre reinforcement have been developed [Lee, Nian and Tarng 2007], Kevlar [Singh and Samanta 2015], as well as glass fibres, and they have been combined to obtain the highest strength parameters [Gustin et al. 2020].

In recent years, there has been a growing interest in research and development in the field of natural fibre composites due to their better formability, abundance, renewability, cost-effectiveness and environmentally friendly properties [Saheb and Jog 1999; La Mantia and Morreale 2011; Misnon et al. 2014; Sanjay et al. 2016]. In addition to the modification of composites, through the use of various types of reinforcement, fillers and nanofillers are also used [Thostenson, Ren and Chou 2001]. Carbon nanotubes possess unique electric properties and thermal conductivity higher than diamond; to mechanical properties in which stiffness, strength and elasticity surpass any current material, carbon nanotubes offer great opportunities for the development of entirely new material systems. In particular, the unique mechanical properties of carbon nanotubes, combined with their low density, open the door to the development of nanotube-reinforced composite materials [Thostenson, Ren and Chou 2001].

The use of aluminum powders in combination with other materials allows for obtaining materials with completely new properties. Many factors affect the properties of the metal matrix composite, such as character reinforcement and the type of fibre warp. The degree of microstructural integrity is also quite important. This depends on the method of production used and the content of aluminum in the composite [Garga et al. 2019]. In the article [Garga et al. 2019] overview of synthesis pathways, mechanical behaviour and applications of aluminum matrix composites is presented. The focus was mainly on basic processing techniques for the production of these composites, as well as commercialisation challenges, industrial aspects and future research trends.

In research [Haldar, Modak and Sutradhar 2007] composites with and without aluminum powder were made using plant fibres (sisal-epoxy composite). Physico-mechanical properties were verified, the results obtained enabled us to conclude that aluminum powder increases the values of tensile strength, elastic modulus and impact strength, which was not observed in the material to which no aluminum powder was added [Mrówka et al. 2021]. The article undertakes to investigate the rate of wear of a polymer composite made of epoxy resin reinforced with glass fibre filled with aluminum powder. The influence of operating variables such as load and speed was observed. The rate of wear increased in line with the load by maintaining a constant speed and then a constant load.

Secondly, by observing worn surfaces with a microscope, basic wear mechanisms were observed and recorded as a function of fibre orientation. During the research, [Kumar et al. 2017] glass fibre-reinforced aluminum (GF) was produced using metallurgical synthesis, which is a non-standard and insufficiently tested production method. It was found that the electrical conductivity of samples obtained by metallurgical synthesis was higher than that which could be estimated using the principle of of mixture content and glass fibres. A similar situation was observed in terms of the hardness of the tested samples.

Aluminum oxide is a material often used as a filler or reinforcement in polymer composites. The interaction between Al powder and polymer resin in a composite material depends on several factors, including the surface chemistry of the Al particles, as well as the type of polymer resin and processing conditions used to make the composite.

For the purpose of this article, it has been decided that the effect of addition of aluminum powder on the mechanical properties of polyester – glass composites – should be verified. The properties of the material, depending on the amount of filler, were compared, and the structures were observed using an optical microscope. In addition, hardness tests of materials were carried out to determine the effect of the addition of aluminum powder on the hardness of the obtained composites.

2. MATERIALS AND METHODS

2.1. Material preparation

To carry out the research, the first step was to prepare the research material. Composites were made using the manual lamination method. An aluminum mould was used, and two layers of Honey Wax were used as a distributor. The matrix was Polimal 1094-AWTP polyester resin. Polimal 1094 AWTP-1 is a construction, medium-elastic, orthophthalic, accelerated, low-styrene emission resin. The reinforcement was a glass mat with a random direction of fibres with a density of 450g/m2. Acetyl brushes and rollers were used to properly saturate the reinforcement.

As an additive, WEST SYSTEM 420 aluminum powder was used, containing ≥ 99.5% pure aluminum with a density of 2.7 g/cm³ and a particle size < 160 μm. The aluminum powder was added directly to the matrix and mixed manually using a laboratory stirrer. The mixing process was carried out at a temperature of 18°C.

Composite materials with added aluminum powder amounting to 2%, 5% and 10% of the composite weight were made. By mixing the aluminum powder with the resin, a compact and bonded structure was obtained.

Table 1 presents the content of individual components in the composites examined.

Table 1. Content of individual components in the tested materials

Material	Aluminum powder [%]	Glass mat [%]	Resin content [%]	Number of layers
0	0	40	60	10
AP2	2	38	60	10
AP5	5	35	60	10
AP10	10	30	60	10

Figure 1 shows the composite material immediately after its manufacture.

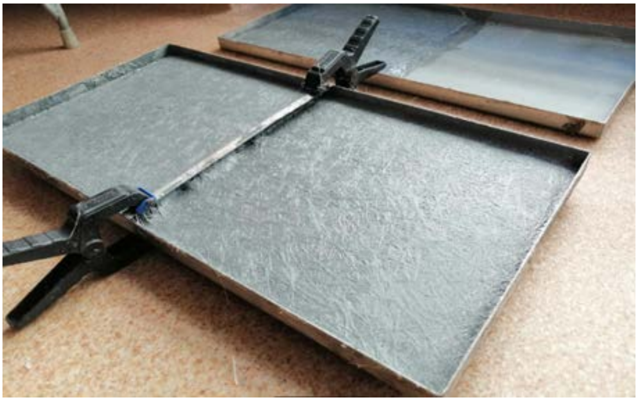

Fig. 1. Composite material produced by manual lamination technology

2.2. Static tensile test

Using EN ISO 527-4:2022-06 (Plastics – Determination of tensile properties – Part 4: Test conditions for fibre-reinforced isotropic and orthotropic composites), samples were prepared for static tensile testing. To obtain test samples, the water-cutting method was used to minimise the effect of the temperature during standard cutting on the structure of the tested materials. Five composite samples of each type of material were tested. For the purpose of the research, a universal testing machine with a Zwick Roell hydraulic drive, using Test Expert II software, was used.

Figure 2 shows an example of a sample during tensile test.

Fig. 2. Example composite sample (AP2) during static tensile test

2.3. Hardness measurement of composites

For the manufactured variants of composites with the addition of aluminum powder, hardness measurements were carried out using the Barcol Hardness Tester and the Qness Q250M Hardness Tester with a Vickers 5 kg indenter. For each variant of the material tested, 32 measurements were made. According to the instruction manual of the Barcol 934-1 hardness tester for glass fibre-reinforced plastics, the number of measurements. according to GB/T 3854-2005 for hardness 30 on the HBa scale is 29. The number of measurements made was therefore sufficient to determine the average hardness of the composite material tested.

Figure 3 shows an example of Barcol and Vickers hardness measurements.

a) b)

Fig. 3. Hardness measurement example: a) Sample B0, Qness Q250M, HV5, b) Sample AP5, Barcol 934-1

3. RESULTS AND DISCUSSION

3.1. Static tensile test

Figure 4 shows examples of tensile plots for all tested composite materials.

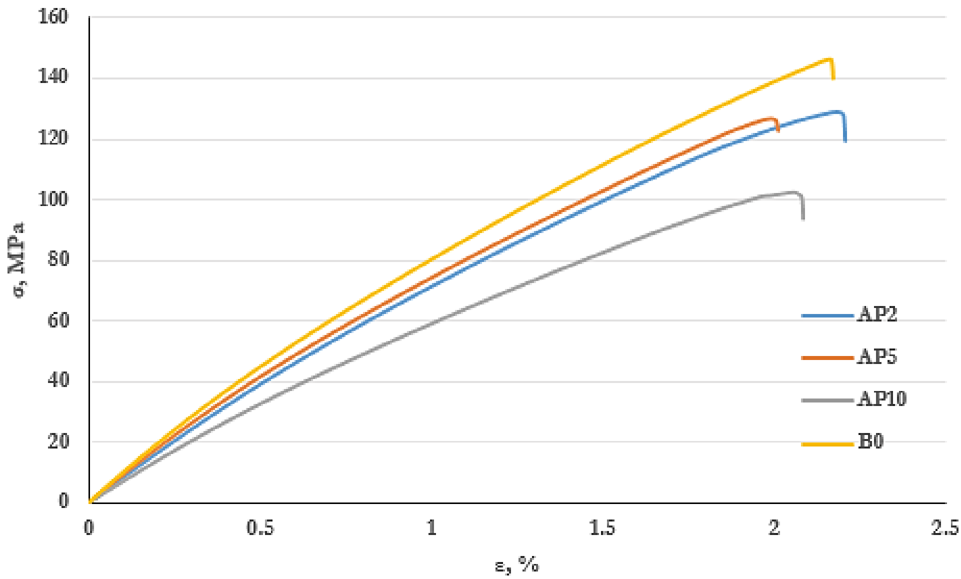

Fig. 4. Examples of tensile plots for all tested composite samples

Table 2 shows the results obtained (averaged) over five trials.

Table 2. Results obtained (averaged) over five trials of tested composites

Composite material	**σ_m [MPa]**	**ε [%]**	**E [MPa]**
B0	140	2.16	9208
Standard deviation	2.24	0.11	324
AP2	127	2.18	7906
Standard deviation	3.02	0.13	415
AP5	130	2.09	8529
Standard deviation	3.46	0.18	486
AP10	106	2.01	7142
Standard deviation	3.58	0.19	494

Based on the results obtained, the effect of aluminum powder on the properties of the composites tested is noticeable. However, the aluminum powder did not improve mechanical properties. In the case of the base material (without added aluminum powder), tensile strength values of approx. 140 MPa were obtained on average. In the case of the 2% of weight mass addition of aluminum powder, the tensile strength decreased by about 10%. However, the strain increased by approx. 1%.

It is interesting to note the results obtained from a 5% addition of aluminum powder, which are promising in comparison with the results for the base material without added aluminum powder. With a 5% addition of aluminum powder, the tensile strength and elastic modulus decreased by about 7%, while the strain decreased slightly. The 10% addition of aluminum powder decreased tensile strength by about 24%, and parameters such as strain and elastic modulus also decreased.

3.2. Analysis of material hardness

The distributions of the results obtained from the hardness measurement using the Barcol 934-1 hardness tester for samples B0, AP2, AP5 and AP10 are shown in Figure 5 a, b c and d.

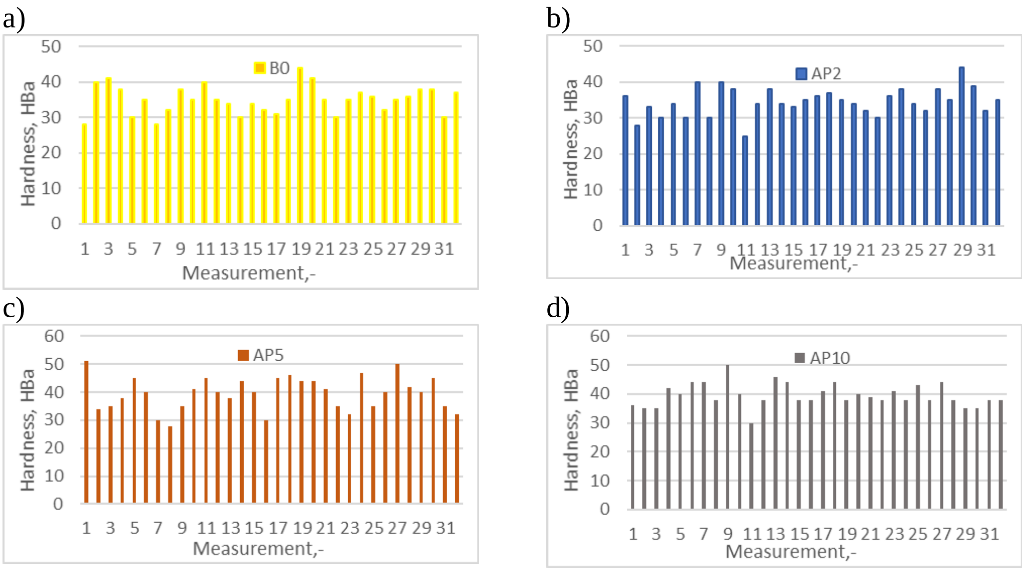

Fig. 5. Barcol hardness values for tested composite samples: a) Composite B0, b) Composite AP2, c) Composite AP5, d) Composite AP10

Figure 6 presents a collective summary of the results of the Barcol hardness measurements for all manufactured variants of materials, along with the course of the trend lines for the measurements. For greater readability, the measurements are ordered from the smallest to the largest value for each material variant.

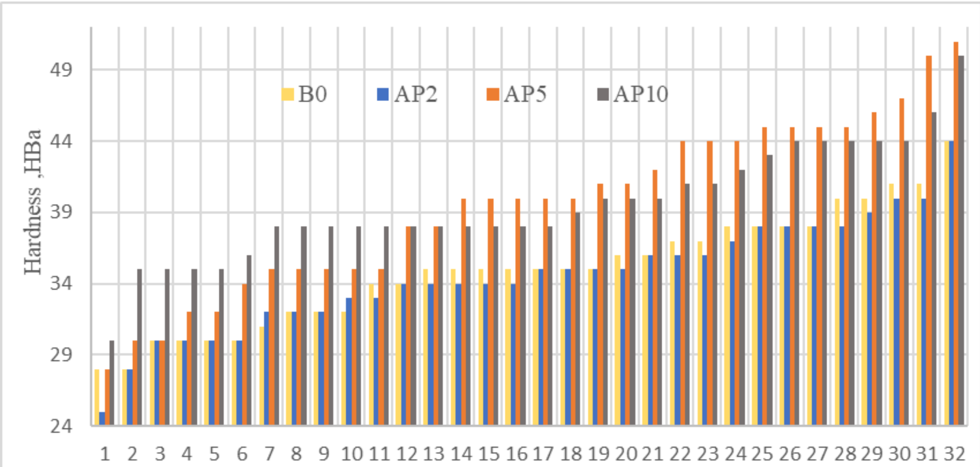

Fig. 6. Collective summary of the results of the Barcol hardness measurements for all manufactured variants of materials

Table 3 shows the mean values of the hardness measurements using the Barcol 934-1 hardness tester for the composite panels tested by adding aluminum powder to the matrix.

Table 3. Average Barcol hardness and standard deviation measurements of composites with added aluminum powder

Material	B0	AP2	AP5	AP10
Average Hardness [HBa]	35.0	34.5	39.6	39.6
Standard deviation	3.98	3.90	5.95	3.96

In view of the results of hardness measurements obtained it was concluded that the addition of aluminum powder to polyester-glass composites increases the hardness parameter of these materials. However, what matters is the percentage of aluminum powder added to the composite. For the composite without added aluminum powder, the average hardness measurement was 35 HBa. A 2% addition of aluminum powder to the resin lowers the hardness of the material by 1.4%, while 5% and 10% additions of aluminum powder increase the hardness of the composite by 13% compared to the base material without added aluminum powder.

An increase in the addition of aluminum powder to a polyester-glass composite may affect its hardness for several reasons. Aluminum powder can act as a filler, filling the spaces between the glass fibres and the polymer matrix. This, in turn, can improve the compaction of the composite structure, which affects the hardness of the material. The addition of aluminum powder increases the overall amount of filler in the composite. Fillers such as aluminum powder can improve mechanical properties of the composite, including its hardness. If evenly distributed, aluminum powder particles may cause micro-disturbances in the composite structure, which affects its hardness. These micro-disturbances can provide additional points of resistance, which increases the hardness of the material.

Aluminum powder can affect the mixing and curing process of the composite. If properly distributed and hardened, it can help create a more compact and durable structure.

3.3. Microstructure of composites

Using Axiovert 25 optical microscopy, the microstructure of composite materials was observed. Figure 7 shows the microstructures of composites with added aluminum powder. As a result of an analysis of photographs of microstructures, the approximate size of pores formed in the production process of the material was determined. These values range from 400 μm to 456 μm for AP2 material, from 96 to 304 μm for AP5 composite and from 221 μm to 810 μm for AP10 material.

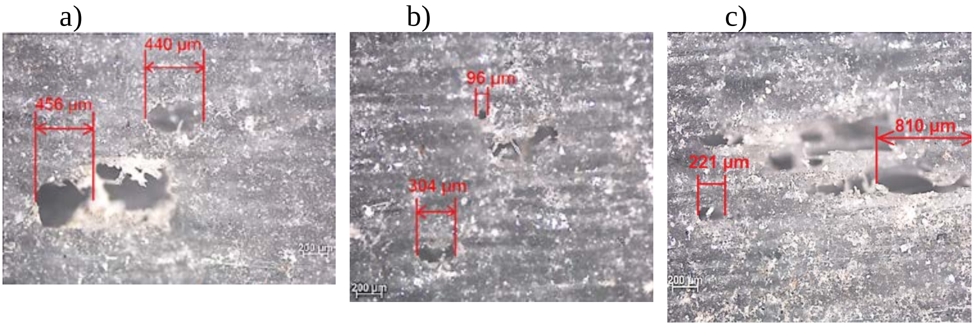

Fig. 7. Exemplary structures of composite materials with the addition of aluminum powder: a) AP2, b) AP5, c) AP10

The changes observed in internal structures coincide with the results obtained from the static tensile test. This is because it is noticeable that with a 5% addition of aluminum powder, a much smaller number of pores and air voids appear, and they are also smaller than in the case of materials with 2% and 10% additions of aluminum powder. On the basis of the microstructures observed, it is clear that as the percentage of added aluminum powder increases, the number of air pores and voids between the layers increase.

In the manual lamination method, a common problem resulting from the manufacturing technology used is air pores causing voids in the material. These can be partially eliminated using acetyl rollers, but even when they are used, voids are still visible in the microstructure of the composite. The addition of aluminum powder does not have a positive effect on their minimisation or adhesion between subsequent layers of reinforcement. The addition of aluminum powder to the resin in polyester-glass composites acts as a filler. An increase in the amount of this additive may lead to an increase in porosity and the number of voids between the layers of the composite. There may be several reasons for such a phenomenon. Aluminum powder has a different thermal expansion from resin and glass fibres. During the composite hardening and cooling process, differences in thermal expansion may lead to the formation of voids. An increase in the amount of aluminum powder may lead to difficulties in distributiing particles in the resin evenly. Uneven distribution of the filler may cause local clusters, which in turn may lead to the formation of voids. Aluminum powder is lightweight, which means adding it to a composite increases the overall lightness of the material. This lightness may contribute to the formation of voids, especially if the mixture is not properly compacted. The introduction of aluminum powder may cause a synergistic phenomenon, i.e. mutual interaction between the components of the composite. This may affect the hardening processes and cause changes in the structure of the material, which lead to the formation of voids.

4. CONCLUSIONS

Composite materials provide a wide spectrum of possibilities to modify mechanical properties achieved by changing their composition and technology. The basic objective of designing new composite materials is to obtain a composite with specific physicochemical properties adapted to its intended purpose, with specific ranges of strength parameters. The composites market is constantly growing with the addition of new materials and fibres; at the same time, there are no sufficiently reliable calculation models enabling the optimum composite to be selected for theconditions under which it is expected to be applied. Tests of materials representing the proposed material solutions are carried out.

The article attempts to demonstrate the effect of added aluminum powder on the mechanical properties of polyester-glass composites. In view of the results obtained during the research, it can be concluded that the addition of aluminum powder to the matrix of composites reduces the tensile strength of composites but slightly increases their hardness.

Taking into account the commonly known strength properties of aluminum, these results can be considered reliable. In both cases, the hardness of the composites tested was measured in the appropriate number of measurements made to ensure real final values could be obtained for anisotropic materials, such as polyester-glass composites. Both when using the Barcol hardness tester and the Vickers indenter with a load of 5 kg, it showed that a 2% addition of aluminum powder to the resin reduces the hardness of the material, while adding a greater amount of aluminum powder to the matrix of the composite (5% and 10%) increases the hardness of the composite compared to the material without added aluminum powder. Increasing the hardness of the composites tested after adding aluminum powder to their matrix enables us to consider using such materials for structures or elements requiring slightly more hardness than ordinary polyester-glass composites. This material can be used for various types of coatings to increase hardness and for structural elements. It is also noteworthy that a 5% addition of aluminum powder has a positive effect on the internal structure of the polyester-glass composite, which has been confirmed by microscopic studies.

The authors of the article intend to continue their research by modifying the amounts of aluminum powder added and the composition of the composites studied to obtain better strength parameters, with a simultaneous increase in hardness and improvement of the internal structure. Adhesive properties between the resin and glass fibres and between the resin and aluminum powder are crucial to maintaining the integrity of the structure. In order to minimise problems with porosity and voids in composites, it is important to properly adjust the proportions of ingredients, control the mixing process, use appropriate hardening techniques and take care to maintain an even distribution of additives in the resin.

The authors of the research also intend to introduce modifications to the chemical composition of the materials, which may improve the adhesion and cohesion of the polyester-glass composite with added aluminum powder. The proposed solutions are the so-called adhesion promoters, i.e. chemical substances that increase adhesion between the fiber surface and the polymer matrix. They can improve the adhesion between the glass fibers and the resin, which will contribute to better bonding of the composite. The authors will also consider subjecting aluminum powder to chemical modifications that will improve its ability to combine with the resin.

It is also planned to use Acoustic Emission Analysis to detect individual changes during the material destruction process under stress. To do this, both the measuring system and the coupling of the sensor to the sample must be optimised.

The evaluation of the signals may be supported by artificial intelligence.

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