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Comparison of the adhesive joints' strength of the similar and dissimilar systems of metal alloy/polymer composite

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Abstract

The aim of the present article is to compare the strength of the adhesive lap joints of the selected materials used in aviation. The joints were made in the similar and dissimilar systems with the use of three epoxy adhesives. Three different adherends were used: the EN AW-7075 aluminium alloy, the aramid-epoxy composite and the carbon-epoxy composite. Three adhesive compounds based on the Epidian 53 epoxy resin and three types of curing agents: two amine curing agents—Z1 (triethylenetetramine curing agent) and IDA, and one polyamide curing agent—PAC (polyaminoamide C) were used to make the adhesive joints. Three variants of similar joints and two variants of dissimilar joints were prepared for the tests. The shear strength was defined according to the ISO 4587 standard, with the use of Zwick/Roell 150 testing machine. In addition, the joined materials' surface roughness was measured. Based on the strength test's results, it was observed that the highest strength was obtained by the adhesive joints made with the Epidian 53/PAC/100:80 adhesive compound and that, in the majority of cases; similar joints show higher strength.

Keywords: Adhesive joints, Strength, Aluminium alloy, Polymer composite

Introduction

Bonding technology is one of the most popular methods of joining various constructional materials [1–3]. It plays a vital role in production of different types of machines and tools [2]. This fact results from numerous advantages of the adhesive joints. The most important ones include the capacity of joining construction materials of different physical and chemical properties [4–6], as well as of significantly different sizes (e.g. thickness) [4, 7–9].

A lot of advantages of the adhesive joints have contributed to the fact that they are widely used in aviation [8, 10–12], aeronautics [13] and automotive [14, 15]. One of the most important advantages is the ability to make dissimilar joints [5, 16–18]. He and Ge [4] tested the effect of similar versus dissimilar assembled adherends of adhesively bonded composite joints, on the dynamic strength of single-lap. Pinto et al. [16] investigated the tensile strength of single-lap joints between similar and dissimilar adherends (included polyethylene (PE), polypropylene (PP), carbon-epoxy (CFRP), and glass-polyester (GFRP) composites) bonded with an acrylic adhesive.

A fast-developing aviation industry introduces dynamic changes related to the airplanes' construction. As a result, it triggers profound research in this area. Construction of the modern airplanes that are able to carry heavy loads imposes the usage of different materials (like composite materials, and also aluminium, titanium etc.) that are light and extremely resistant at the same time [8, 19–24]. Continuous fiber composite/metal laminates (FMLs) offer significant improvements over currently available composite materials for aircraft structures due to their excellent fatigue endurance and low density [18]. Botelho et al. [18] presented the issue of surface treatment of glass fiber–epoxy composite laminate and aluminum foil (GLARE), which is commonly used to obtain these dissimilar laminates.

Moreover, dissimilar material joints with a structure such as composite materials combined with light-weight metals have been widely used in the automobile industries to deal with the issue of fuel efficiency and weight reduction [7, 17, 25]. Galvez et al. [14] investigated carbon fiber reinforced polymer (CFRP) adhesive joints and focused on the study of a structural adhesive for its application in this new type of joints. Hasheminia et al. [17] carried out the experiments and the finite elements analysis of single lap-shear bonded joints with metal-composite, similar composites and dissimilar composites components to investigate the factors that affect the joint failure load. In the work by Banea [25] the effect of material on the mechanical behaviour of adhesive joints was investigated experimentally and numerically by using single lap joints (SLJs) with different adherend materials (high strength steel, low strength steel and composite). In the other work, Banea et al. [26], considered the single lap joints (SLJs) using the following combinations of adherends: high-strength steel (HS), aluminum (Al), and carbon fiber reinforced plastics (CFRP), which were used in the automotive industry.

A lot of composite materials are based on epoxy resin [8, 22, 23, 27–30]. Lee and Wei [23] studied the effects of material and process variables on glass fabric-reinforced epoxy composites by the resin-transfer molding (RTM) process. Joining these materials requires extensive research and tests that will show which joining method is the most effective [2, 3, 31, 32].

Taking the above aspect into consideration, the present article presents the experimental studies related to the adhesive joints of the construction materials that are widely used in aviation [1, 9]. These materials include: aluminium alloy, carbon composite and aramid composite. Shear strength of two types of joints was determined for similar and dissimilar single-lap adhesive joints prepared with the epoxy adhesive.

Test method

Variants of joints

Three variants of similar joints (AL–AL, AC–AC and CC–CC) and two variants of dissimilar joints (AL–AC and AL–CC) were prepared for the strength tests. Their descriptions and designations are presented in Table 1.

Characteristics of adherends

Aluminium alloy

The tests described herein included EN AW-7075 aluminium alloy (according to the EN 573-1 and EN 485-2 standards). This material has very good strength properties: it is

Table 1 Adhesive joints' designation

Joint description	Joint designation
Similar joints	
Aluminium alloy/aluminium alloy	AL–AL
Aramid composite/aramid composite	AC–AC
Carbon composite/carbon composite	CC–CC
Dissimilar joints	
Aluminium alloy/aramid composite	AL–AC
Aluminium alloy/carbon composite	AL–CC

Table 2 Properties of the EN AW-7075 aluminium alloy (EN 485-2)

Tensile strength, Rm, MPa	Yield strength $R_{p0,2,}$ MPa	Elongation $A_{50,}$ %	Young's modulus, GPa
540	460	6	71.7

very hard, resistant to corrosion and it is characterised by good thermal conductivity. Some properties of the EN AW-7075 aluminium alloy are presented in Table 2.

Aramid-epoxy composite

The samples made of the aramid-epoxy composite were used in the tests. Kevlar, which is a very light and extremely resistant polymer material, is classified as an aramid fibre. Its invention has had significant influence on numerous branches of the contemporary industry due to its numerous advantages. The extraordinary properties of the aramid fibres result from terephthaloyl chloride (TCL). This substance gives kevlar fibres the appropriate mechanical resistance, external fire performance, as well as thermal and dimensional stability [5].

Kevlar is very light (five times lighter than steel); its density amounts to 1.44 g/cm$^{3.}$ It has also a high impact strength and it is wear resistant. Single aramid fibres that were subject to the tests in the laboratory conditions showed the tensile strength of ca. 3610 MPa. Kevlar does not melt in direct contact with fire. However, it decomposes at the temperature of above 500 °C. It preserves its properties at the temperature range from − 200 to 250 °C [31]. The aramid composite consisting of nine layers of kevlar fibres (designated as KV-EP 285 199-46-002) infiltrated with epoxy resin was used in the tests. The plain fibres with a weave of 0°/+90° were used. Such a fibre arrangement ensures good resistance but decreases the material's flexibility, contrary to the twill weave. The fibres were autoclave cured at 132 °C for 60 min.

Carbon-epoxy composite

The carbon-epoxy composite, with a twill weave 2/2 intersecting at right angles, was used in the tests. Such a fibre arrangement ensures higher strength, which is why it is used for the helicopters' production. The composite used in the tests was produced in the following way: 27 layers of carbon fabrics (designated as GR-EP 199-45-003) were joined with use of epoxy resin and then placed in an autoclave that enabled to conduct the curing process at 175 ± 5 °C for 60 min.

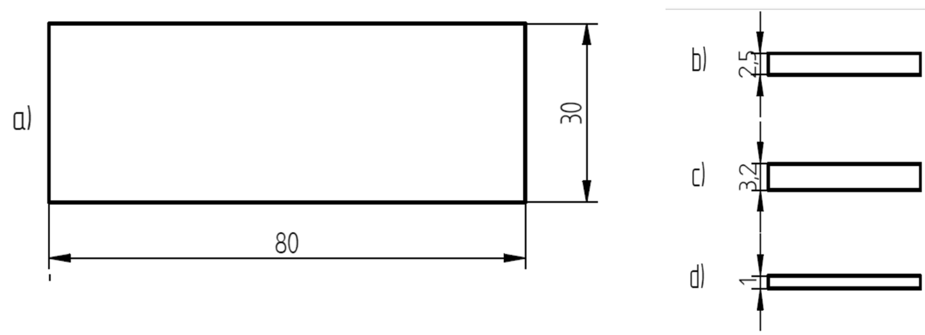

Fig. 1 Assumed dimensions of the samples used in the tests: **a** width and length, **b** carbon composite's thickness, **c** aramid composite's thickness, **d** aluminium alloy's thickness

Table 3 Technological parameters and the laser cutting-off machine's parameters during the composite samples' cutting

Parameters of cutting using the FIBER LASER LC 3015		
Parameter type	**Material type**	
	Aramid composite	**Carbon composite**
Cutting thickness	3.2 mm	2.5 mm
Cutting speed	6.35 m/min	6.45 m/min
Laser power when cutting	400 W	350 W

Samples preparation

Dimensions of the elements used to make the adhesive joints are presented in Fig. 1.

The samples were made in the process of cutting. The composite materials were cut with the use of a laser cutting-off machine CNC Fiber Laser LC 3015. The values of the technological parameters of cutting the samples made of the aramid and carbon composites are presented in Table 3.

The samples made of aluminium alloy were cut with the use of a guillotine shear equipped with CNC control, produced by Vimercati 3500. The tool used in the tests is able to cut the sheets of maximum length of 3050 mm and thickness of 6 mm. It has a 7.5 KW motor. The cutting speed of one cut is 85 mm/s.

Surface preparation

The surface of all samples was carefully prepared for the bonding process. They were cleaned of different impurities, such as lubricants, coolants or filings with use of a Loctite 7063 degreasing agent. After applying the degreaser on the samples' surface they were wiped thoroughly with a paper towel. This process was then repeated. The last stage of degreasing was to apply the Loctite 7063 degreasing agent (chemical base—aliphatic hydrocarbons) on the samples' surface and leave them to dry.

The samples made of aluminium alloy were the subject to mechanical working before degreasing. The abrasive paper P320 was used in the mechanical treatment. Every sample was being roughed with circular movements for ca. 30 s. After that the described above degreasing process was conducted.

Table 4 Adhesive compounds' types

Resin type	Curing agent type	Stoichiometric proportion of resin and curing agent	Compound's designation
Epidian 53	Polyamide: PAC	100:80	Epidian 53/PAC/100:80
	Amine: Z-1	100:10	Epidian 53/Z-1/100:10
	Amine: IDA	100:50	Epidian 53/IDA/100:50

Table 5 Adhesive compounds' properties [37]

Compound's designation	Tensile strength R_m, MPa	Tensile modulus Et, MPa	Elongation at break ε_M, %
Epidian 53/PAC/100:80	38.6	700	10.5
Epidian 53/Z-1/100:10	26.8	1500	2.6
Epidian 53/IDA/100:50	7.2[a]	1000	–

[a] The value for this compound in an approximate value, because in the Ref. [37] stoichiometric ratio of resin and curing agent used was 100:40

Adhesive compound

Three adhesive compounds based on the Epidian 53 epoxy resin and three types of curing agents: two amine curing agents—triethylenetetramine curing agent (Z-1 curing agent—trade name) and amine curing agent (IDA curing agent—trade name), and one polyamide curing agent—polyaminoamide C (PAC—curing agent—trade name)—manufactured by CIECH Sarzyna S.A. [33]—were used to make the adhesive joints. The ingredients of adhesive compounds were mixed in appropriate stoichiometric proportions. The epoxy adhesive compounds, presented in Table 4, were used in the tests.

Epidian® 53 epoxy resin is a compound consisting of a mixture of bisphenol A and epichlorohydrin, with an average molecular weight of less than 700 and with the addition of styrene. The properties of the Epidian 53 epoxy resin are described in [34]. The characteristics of the curing agents used in the tests are presented in [35]. The technology of preparing the adhesive compounds is described in [36]. After preparation, the adhesive compounds were applied on the joined surfaces (on one joined surface in particular joints) during so called 'compound's working life'.

The addition of polyamide curing agent—polyaminoamide C (PAC) to the resin results in greater flexibility of the adhesive layer than in case of the amine curing agent—triethylenetetramine (Z-1). Polyaminoamide C curing agent is a component of adhesives used to join adherends exposed to deformations, e.g. for joining thin sheets. However, the epoxy adhesive compounds containing the polyaminoamide C curing agent exhibit lower hardness and are less resistant to high temperature, compared to the epoxy adhesive compound containing the triethylenetetramine curing agent (Z-1).

Examples of selected properties of adhesive compounds in the cured state, obtained under specific curing conditions, are presented in Table 5.

The curing parameters of the epoxy adhesive compounds, for which the mechanical properties were determined, presented in Table 5, were as follows: curing temperature 23 ± 2 °C, relative humidity 27 ± 3%. Curing was carried out as a single-stage curing during 7 days. The properties of the cured epoxy adhesive compositions have been determined in accordance with DIN EN ISO 527-1 standard, using a Zwick/Roell Z150 testing machine. These properties were obtained during the tests presented in works [37, 38].

Adhesive joint

The adhesive joints for the strength tests were made as lap joints. The joints' scheme is presented in Fig. 2 and the theoretical dimensions of the similar adhesive joints in Table 6. Table 7 shows the theoretical and real dimensions of the dissimilar adhesive joints (obtained based on the measurements taken with a HARD L1500 electronic slide calliper).

After the samples' surface and the adhesive compound preparation, the samples elements were joined. The conditions in which the materials were joined played an important role in this process. The ambient temperature was of 22 ± 1 °C and the air humidity amounted to 25 ± 1%. A special locking device was used when sticking the joined elements together in order to keep the assumed lap length and to prevent the samples from moving, which could affect the joint's quality. The curing process was conducted in one stage for 14 days, at ambient temperature of 22 ± 1 °C and with feed force of 0.018 MPa. After that time the joints' quality was assessed visually. No irregularities were found for all the samples.

Strength tests

After the quality control of the hardened samples, the strength tests were conducted in accordance with the ISO 4587 standard. The Zwick/Roell Z150 testing machine was used during the strength tests.

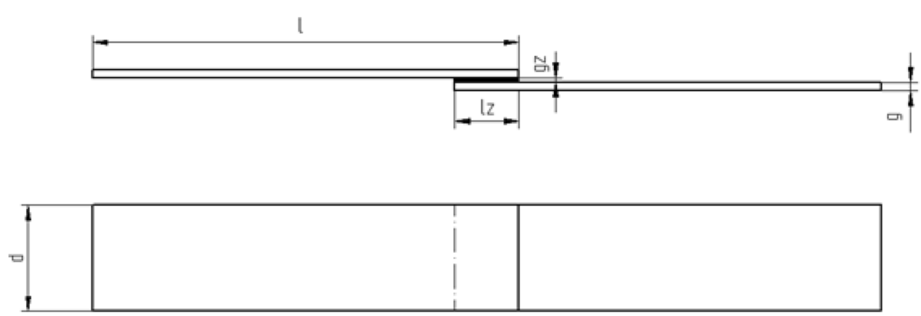

Fig. 2 Shape and dimensions of the adhesive joint: l—sample length, lz—lap length, gz—adhesive layer thickness, d—sample width, g—sample thickness

Table 6 Theoretical dimensions of the similar adhesive joints

Joint designation	Dimensions of the adhesive joints, mm				
	Sample length	Sample width	Sample thickness	Overlap length	Adhesive joint thickness
AL–AL	80	30	1 ± 0.02	12	0.15
AC–AC	80	30	3.2 ± 0.3	12	0.15
CC–CC	80	30	2.5 ± 0.2	12	0.15

Table 7 Theoretical dimensions of the dissimilar adhesive joints

Joint designation	Dimensions of the adhesive joints, mm				
	Sample length	Sample width	Sample thickness	Lap length	Adhesive joint thickness
AL–AC	80	30	1 ± 0.02/3.2 ± 0.3	12	0.15
AL–CC	80	30	1 ± 0.02/2.5 ± 0.2	12	0.15

Surface roughness measurement

After surface treatment and prior to the fabrication of the joint the surface roughness measurement was performed according to the PN-EN ISO 4287 standard. The following surface roughness parameters were determined: Ra, Rz, RSm and Rmax. HOMMEL TESTER T1000 device was used to this end. Its performance is based on a tracer method. The surface roughness measurement with the use of a tracer method is based on moving the sensor along the measured surface (continuously or with raising). The measuring length subjected to the tests was the one of the adhesive mass applied when making the adhesive joints (Fig. 3).

The purpose of the surface roughness measurement was to characterize the surfaces of the adherends.

Test results

Comparative analysis of the surface roughness parameters

Figures 4, 5, 6 and 7 present the comparison of the average roughness measurement results of the aluminium alloy, the aramid composite and the carbon composite.

After having analysed the aforementioned results, it was assumed that the aluminium alloy obtained the highest surface roughness. The Ra, Rz, Rmax and Rt parameters of this material had the highest value in comparison to other materials. The obtained roughness of the aluminium alloy samples may have been caused by the mechanical working that they were subject to. The samples made of other materials were only degreased.

In comparison to the aramid composite that obtained the smoothest surface, the results of aluminium alloy were twice higher. The Rz, Rmax and Rt parameters for the carbon composite were 40% lower than for the aluminium alloy. The difference for the Ra parameter was amounted to 50%. The aramid composite obtained the highest value of the RSm parameter, which was 18% higher than the one obtained by the carbon

Fig. 3 The place where the roughness measurement was performed

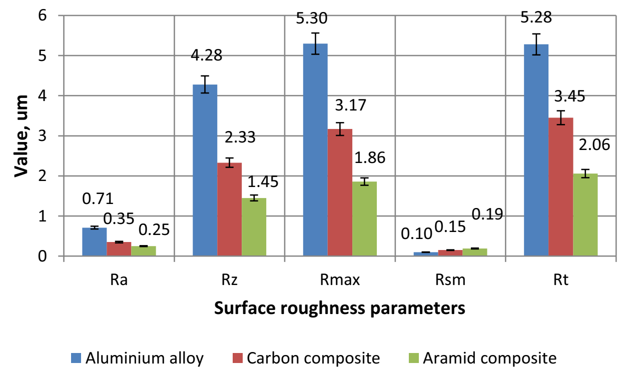

Fig. 4 Diagram of the surface roughness parameters of the examined samples subject

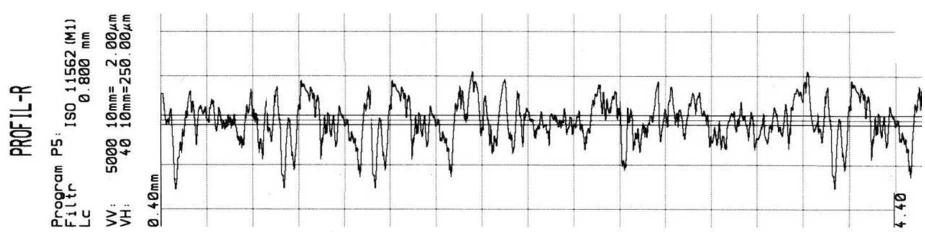

Fig. 5 An exemplary profilogram of the aluminium alloy samples surface

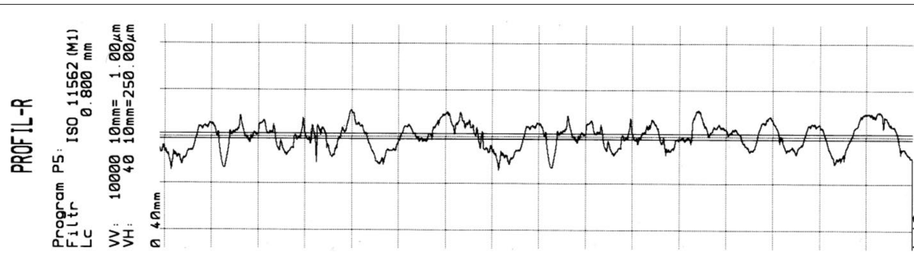

Fig. 6 An exemplary profilogram of the aramid composite samples surface

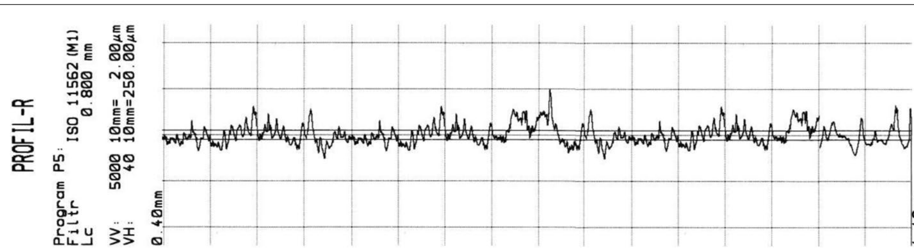

Fig. 7 An exemplary profilogram of the carbon composite samples surface

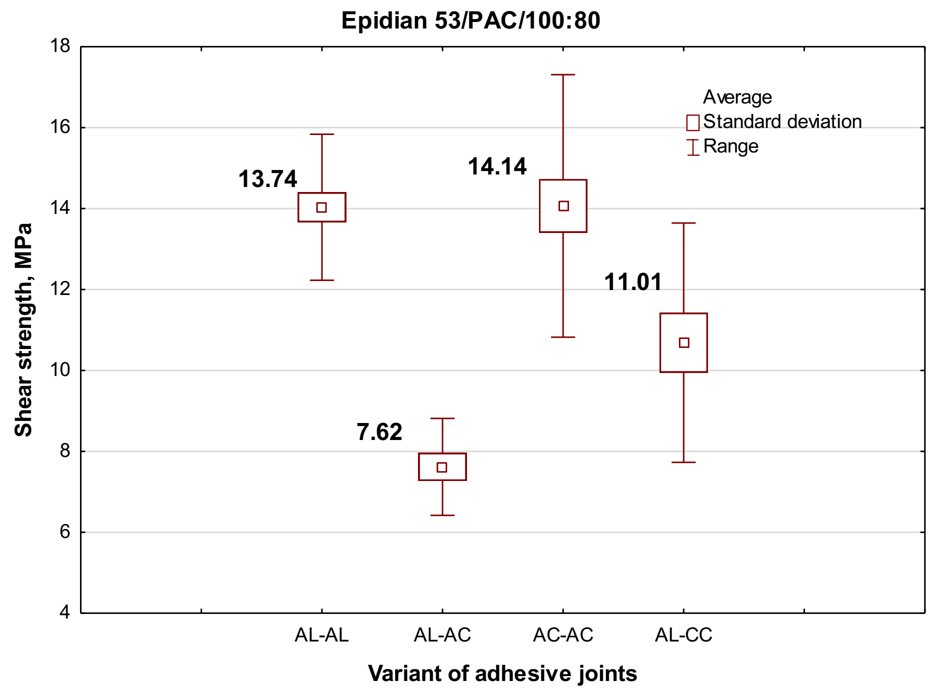

Fig. 8 The strength of the adhesive joints made with Epidian 53/PAC/100:80 adhesive compound

composite. The aluminium alloy obtained the lowest value of the RSm parameter, which was 46% lower than the one obtained by the aramid composite.

These results prove that the carbon composite's roughness is low. However, it is higher than in case of the aramid composite. Nevertheless, the values of the particular roughness parameters presented in Fig. 8 are very low. They are in the roughness grade 8 and can be compared to the values obtained after fine sanding.

The values of standard deviations for particular samples are low, which proves the high repeatability of results.

The analysis of the adhesive joints strength

The variants of adhesive joints versus the same type of adhesive

Figure 8 presents the comparison of the shear strength results of the particular joint types. The joints were made with the use of the Epidian 53/PAC/100:80 adhesive compound.

When analysing the results for the Epidian 53/PAC/100:80 adhesive compound, it may be observed that the highest strength was obtained by the AC–AC joints (14.14 MPa). Slightly lower values were observed for the AL–AL joints (13.74 MPa). This value was 3% lower than the one of the AC–AC joints. The AL–AC joints obtained 46% lower value than the AC–AC joints.

The AL–AC joints obtained much lower parameters: its strength value amounted to 7.62 MPa. In comparison to the AL–AL joints, the difference was of 45%. The results obtained by the AL–CC joints were 30% lower than of the AL–AC joints and 20% lower than of the AL–AL joints.

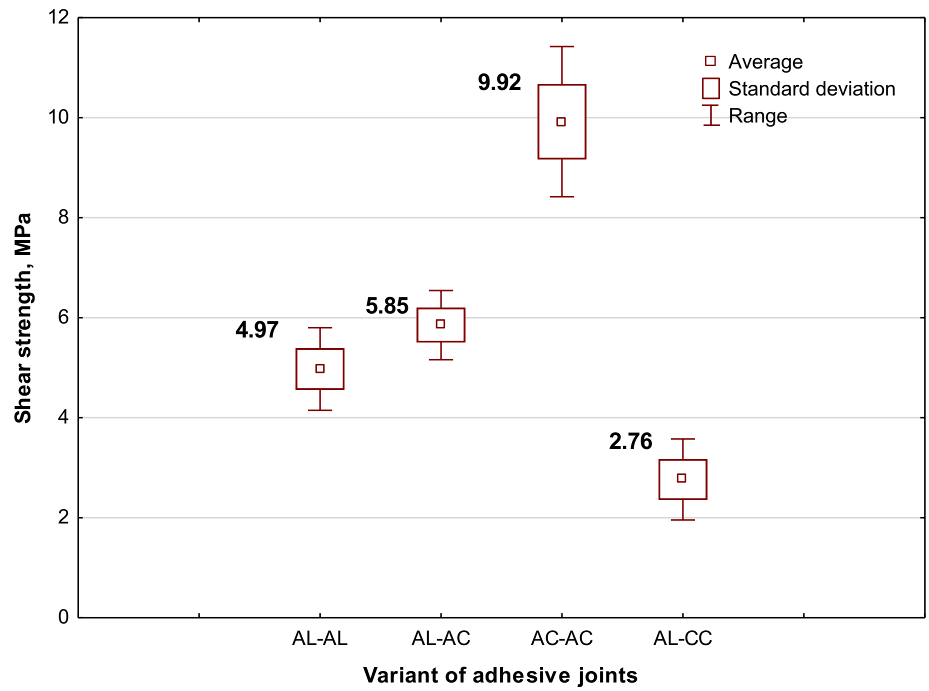

Fig. 9 The strength of the adhesive joints made with Epidian 53/Z-1/100:10 adhesive compound

According to the comparison presented above, the similar joints obtained higher values than the dissimilar joints. The difference between the strongest similar and dissimilar joints was 22%.

Figure 9 presents a diagram showing the shear strength values of the samples joined with the use of the Epidian 53/Z-1/100:10 adhesive compound.

When analysing the diagram below it was observed that the highest shear strength was obtained by the AC–AC joints. Its value was of 9.92 MPa. This value was highly distinctive among all the examined joints. When comparing the AC–AC joints to the AL–AC joints, the difference was of 41%. The AL–AL joints obtained 50% lower value than the AC–AC joints.

The value obtained by the AL–AL joints was 15% lower in comparison to the AL–AC joints. The AL–CC joints was the weakest (2.76 MPa). In comparison to the AC–AC joints, which obtained the highest value, the difference was very significant as it amounted to 72%. The result obtained by the AL–CC joints was 44% lower than the one of the AL–AL joints.

The results mentioned above prove that for the Epidian 53/Z-1/100:10 adhesive compound the strongest and the most distinctive joint was the similar joint made of the aramid composite. The dissimilar joint was also the weakest in this case.

Figure 10 presents the shear strength parameters related to the particular adhesive joints made with use of the Epidian 53/IDA/100:50 adhesive compound.

After analysing Fig. 10 it was observed that the strongest joints for the aforementioned adhesive compound were the AC–AC joints. The result of the AL–CC joints was 64% lower. The strength value obtained by the AL–AL joints was 65% lower than the value of

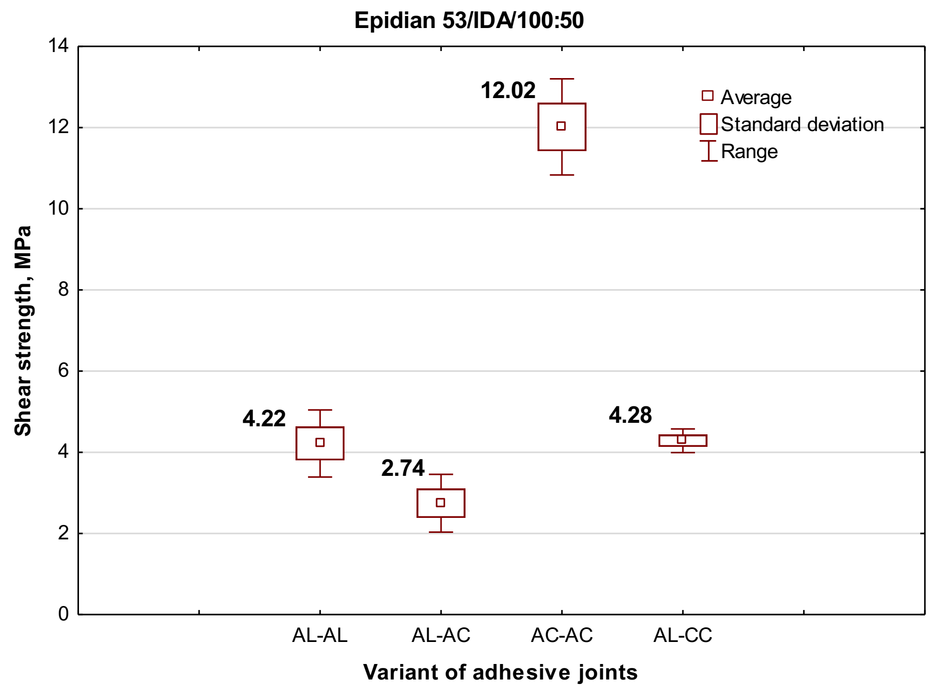

Fig. 10 The strength of the adhesive joints made with Epidian 53/IDA/100:50 adhesive compound

the AC–AC joints. The AL–AL joints obtained a similar, but 1% lower value in comparison to the AL–CC joints.

In this work, the use of this adhesive compound (Epidian 53/IDA/100:50) with stoichiometric proportions of resin and curing agent in the amount 100:50 allowed for high strength, although the tensile strength of the adhesive is the lowest (of the adhesive used). But Table 1 shows the adhesive strength results for the ratio of resin and curing agent 100:40, but it should be noted that the stoichiometric ratio of Epidian 53 epoxy resin and IDA curing agent in both 100:40 and 100:50 is the correct ratio. Here, it can be additionally noted that in the case of joining some of the adhesive joints analyzed in this work, increasing the mass proportion of this curing agent in the adhesive composition increases the strength of the adhesive joints.

The lowest value was observed for the AL–AC joints (2.74 MPa). This result was 77% lower than in case of the AC–AC joints. The AL–AL joints obtained 35% higher value than the AL–AC joints. The AL–CC joints obtained 36% higher value than the AL–AC joints.

For the analysed joints, the best shear strength parameters were obtained by the similar joint of the aramid composite. The dissimilar joint for the Epidian 53/IDA/100:50 adhesive compound was the weakest.

The variants of adhesives versus the same type of adhesive joints

Figure 11 presents the values of shear strength for the similar joints of the aramid composite, taking into consideration the type of curing agent added to the Epidian 53 epoxy resin. After analysing Fig. 11, it may be stated that the strongest AC–AC joints was obtained with use of the PAC curing agent (14.14 MPa), which is polyamide curing

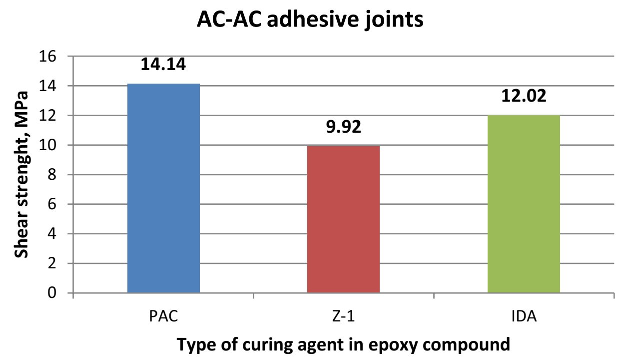

Fig. 11 Shear strength test results for the similar AC–AC joints with use of the curing agents: PAC, Z-1 and IDA

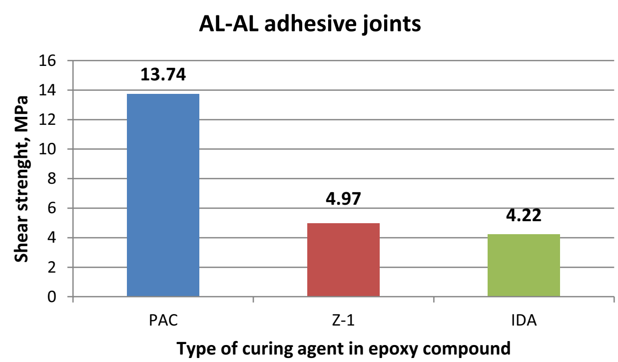

Fig. 12 Strength test results for the AL–AL joints made with use of the curing agents: PAC, Z-1 and IDA

agent. A 15% lower result was observed for the IDA curing agent. The lowest result was obtained by the Z-1 curing agent (9.92 MPa). These curing agents represent amine type curing agents. The difference between the strength values of the Z-1 and the IDA curing agents was 17%. The result obtained by the PAC curing agent was 30% higher than the value obtained by the Z-1 curing agent.

Figure 12 presents the strength results of the similar joints of the aluminium alloy obtained with use of the curing agents: PAC, Z1 and IDA.

After analysing the figure above (Fig. 12), it may be stated that the strongest joint AL–AL was obtained with use of the PAC curing agent (13.74 MPa). A significantly lower result was observed for the Z-1 curing agent. The difference was 64%. The lowest result was obtained by the IDA curing agent (4.22 MPa). The difference between the strength values of the Z-1 and the IDA curing agents was 15%. The result obtained by the PAC curing agent was 69% higher than the value obtained by the IDA curing agent.

Figure 13 presents the strength results of the dissimilar joints of the aluminium alloy with the aramid composite (AL–AC) obtained with use of the curing agents: PAC, Z-1 and IDA.

After analysing the results presented above, it was stated that the highest strength result was obtained by the joint with the PAC curing agent. The strength value of this

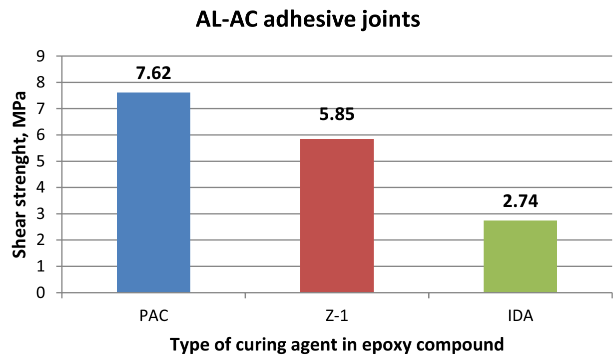

Fig. 13 Strength test results for the dissimilar AL–AC joints made with the use of the curing agents: PAC, Z-1 and IDA

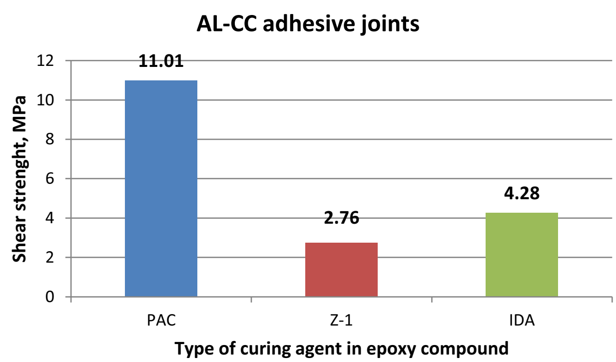

Fig. 14 Strength test results for the dissimilar AL–CC joints with the use of the curing agents: PAC, Z-1 and IDA

joint was 7.62 MPa. A 23% lower result was observed for the Z-1 curing agent. The lowest result was obtained by the IDA curing agent (2.74 MPa). The difference between the strength values of the Z-1 and the IDA curing agents was 53%. The result obtained by the PAC curing agent was 64% higher than the value obtained by the IDA curing agent.

Figure 14 presents the strength results of the dissimilar joints of the aluminium alloy with the carbon composite (AL–CC) obtained with use of the curing agents: PAC, Z-1 and IDA.

After analysing the results presented above, it was stated that the highest strength result was obtained by the joint with the PAC curing agent. The strength value of this joint was 11.01 MPa. A 61% lower result was observed for the IDA curing agent. The lowest result was obtained by the PAC curing agent (2.76 MPa). The difference between values obtained by the IDA and Z-1 curing agents was 31%. When comparing the joint strength obtained with the use of the PAC and the Z-1 curing agents, a substantial discrepancy between the results may be observed. The difference was 73%.

It can be noticed that in all considered cases of adhesive joints, the use of more flexible adhesive (with addition of the PAC curing agent) is the most advantageous as it allows for obtaining the highest strength of these joints. This epoxy compound is especially useful for adhesive joints of aluminum alloys (Fig. 12) and those containing aluminum alloys in dissimilar joints, as a significant increase in strength was observed compared to the same types of joints but made with more rigid adhesive.

Discussion

According to the comparison of strength results the similar and dissimilar adhesive joints contain aluminium adherend (Fig. 8), the dissimilar joints obtained the lower values than the similar joints (AL–AL or AC–AC). The similar material joints perform better than the dissimilar ones considering that the latter are unbalanced in terms of stiffness. Similar results were obtained for the adhesive joints prepared with other adhesive, both more flexible and more rigid ones (except for one case—Fig. 9: AL–AC). These results relate to the comparison of the strength of adhesive joints containing aluminium alloy and composite. In this case of dissimilar adhesive joints a more rigid adhesive allowed for a greater strength than other adhesives.

The results presented by Pinto et al. [16] indicated a positive effect of joining different adherends, but this applies to the same material group, i.e. polymer materials (polyethylene, polypropylene, carbon-epoxy and glass-polyester composites). The authors noticed that increasing the adherend stiffness leads to reduction of the joint bending, which diminished stresses at the overlap edges and, therefore, increased the strength of the joints. Based on the results obtained by Pinto et al. [16] it can be seen that in most analyzed cases in of dissimilar adherends joints, i.e. composites and aluminum alloy, lower strength was obtained, because the aluminum alloy has less rigidity than the composite, and lower rigidity does not reduce the joint bending, which diminished stresses at the overlap edges-and. In addition, the issue of stiffness of connected elements was presented by Cândido and Almeida [22] and the mentioned above authors have observed that the strength of composite laminates with molded edges is about 10 percent lower than that of laminates with machined edges.

At the same time, the influence of the type of adhesive on the strength of the analysed joints was also shown in this work. Botelho et al. [8] emphasized that the combination of metal and polymer composite laminates can create a synergistic effect on many properties. The results presented by Machado et al. [39] presented the positive effect of preparing the dissimilar adhesive joints, using composite and aluminum substrates, by the modern crash resistant adhesives.

It can be also seen that the use of a more flexible adhesive with much higher strength (among those tested, Rm = 38.6 MPa, which is a higher value by 27% compared to Epidian 53/Z-1/100:10 adhesive and about 80% compared to the Epidian 53/IDA/100:50 adhesive) in comparison to other adhesives, in case of adhesive joints made of both the same and different materials, enables to obtain higher strength of adhesive joints than the use of adhesives with lower tensile strength (Epidian 53/Z-1/100:10 adhesive—26.8 MPa and Epidian 53/IDA/100:50 adhesive—7.2 MPa). It can be emphasized that the high strength of the adhesive itself contributes to the high strength of the joint. However, one should not forget about other factors affecting the strength of adhesive joints. Moreover, it should be noted that the adhesive compound constituting the adhesive joint has slightly different properties, resulting from not only of the adhesive's characteristics (e.g. cohesion), but also of the properties at the interface (e.g. adhesive properties and surface roughness properties). In this case, among others, the elements made of aluminum alloy of relatively low thickness and the selection of a more flexible adhesive contributed to obtaining higher strength of such joints than in case of using more rigid adhesive.

Taking into consideration the results of tests performed on the adhesive joints, it can be noticed that the most frequent type of failure was the special cohesion failure (SCF), or cohesion failure (CF)—mainly in case of similar adhesive joints, according to the PN-EN ISO 10365 standard. During the analysis of the nature of the failure of adhesive joints, no plastic deformation of aluminium alloy sheets was observed. The yield strength of this material is 460 MPa (Table 2). The surface roughness parameters of aluminium alloy adherends are much higher than those of the composite adherends. And in case of these adherends, higher strength is additionally due to the greater mechanical adhesion, resulting from the greater wetting surface by the adhesive and the creation of mechanical anchors, although this is also associated with the viscosity of the adhesive. Probably for this reason, in case of joints made of aluminium alloys, the second type of cohesive failure—special cohesion failure (SCF), was obtained. In this case the failure of the adhesive joint does not run evenly along the middle of the thickness of the adhesive joint, but it varies along the thickness of the adhesive joint. At the same time, a greater rest of the adhesive layer was observed on the aluminium alloy adherends.

Conclusions

The present article was aimed at comparing the strength of the dissimilar and the similar joints made with use of three different adhesive compounds. Four joint systems were made: AL–AL, AL–AC, AL–CC, AC–AC. Each system was joined with the adhesive compound: Epidian 53/PAC/100:80, Epidian 53/Z-1/100:10 and Epidian 53/IDA/100:50. The shear strength tests were conducted on the testing machine. Moreover, the surface roughness of adherends was measured.

After having analysed the strength test results, it was concluded that the samples joined with the Epidian 53/PAC/100:80 adhesive compound obtained the best strength results. The joints made of the aramid composite showed the highest average results, in turn. Their shear strength was amounted to 14.14 MPa. The joints of the aramid composite and the aluminium alloy, in which the IDA curing agent had been added to the adhesive compound, obtained the lowest value (2.74 MPa). The difference between the strongest and the weakest joint was 80%.

For the similar AC–AC joints, the 53/PAC/100:80 adhesive compound let obtain the best results. The lowest value for this joint type was observed when the Epidian 53/Z-1/100:10 adhesive compound was used. The difference was 29%.

The similar AL–AL joints made with use of the Epidian 53/PAC/100:80 adhesive compound obtained the highest strength value. The lowest value for this joint type, in turn, was observed when the Epidian 53/IDA/100:50 adhesive compound was used. The difference between the highest and the lowest values for the AL–AL joints was 69%.

The dissimilar AL–AC joints obtained the highest strength with the use of the 53/PAC/100:80 adhesive compound. The lowest value, in turn, was observed when the adhesive compound Epidian 53/IDA/100:50 was used. The difference was 64%.

The dissimilar AL–CC joints made with the use of the Epidian 53/PAC/100:80 adhesive compound showed the highest strength value. The lowest strength for this joint type was observed when the Epidian 53/Z-1/100:10 was used as the adhesive compound. This value was 61% lower than in case of the samples joined with the Epidian 53/PAC/100:80 adhesive compound.

With regard to the type of adhesive, the summary can be found that the use of a more flexible adhesive in comparison to other adhesives, in case of similar and dissimilar adhesive joints, results in a greater strength.

The construction materials analysed in the present article showed different strength properties. Similar material joints perform better than the dissimilar ones considering that the latter are unbalanced in terms of stiffness. In addition, it was concluded that the choice of adhesive compounds adapted to the type of adherends and its surface roughness, is of high importance as it may significantly improve the particular strength of joints. Moreover, if the adhesive is suitable for the materials to be joined, it is possible to obtain dissimilar joints with the same strength as the similar ones made of the material presented in the first joints with the weakest joint strength.

Abbreviations

Z-1: triethylenetetramine—amine curing agent (aliphatic amine)—trade name; IDA: amine curing agent—trade name; PAC: polyaminoamide C—polyamide curing agent—trade name.

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Authors' contributions

The author conceived, designed and performed the experiments; analyzed the data; wrote final manuscript. The author read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The author declares that she has no competing interests.

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