Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2022, 16(2), 262–279
https://doi.org/10.12913/22998624/147524
ISSN 2299-8624, License CC-BY 4.0

Received: 2022.02.28
Accepted: 2022.03.19
Published: 2022.03.26

Strength of Epoxy-Bonded Aluminium Alloy Joints After Sandblasting

Anna Rudawska[1*], Magd Abde Wahab[2,3] , Miroslav Müller[4]

[1] Faculty of Mechanical Engineering, Lublin University of Technology, ul. Nadbystrzycka 36, 20-618 Lublin, Poland
[2] Faculty of Engineering, Van Lang University, 45 Nguyen Khac Nhu Street, Co Giang Ward, District 1, Ho Chi Minh City, Vietnam
[3] Faculty of Engineering and Architecture, Ghent University, Jozef Plateaustraat 22,9000 Gent, Zwijnaarde, Belgium
[4] Faculty of Engineering, Czech University of Life Science Prague, Kamýcká 129, 165 00 Prague, Czech Republic
* Corresponding author's e-mail: a.rudawska@pollub.pl

ABSTRACT
The purpose of this article is to investigate the effect of sandblasting surface treatment, before the bonding process, on the strength of the adhesive joints of the three types of aluminium alloy sheets. Three values of pressure were used during the sandblasting process, i.e. 0.41 MPa, 0.51 MPa and 0.56 MPa. After mechanical treatment, the samples of aluminium alloys sheets were degreased three times with acetone by immersion. The elements were bonded with single-lap joints using two components epoxy adhesive. After the curing process, the shear strength tests of the aluminium alloy adhesive joints were conducted, according to the DIN EN 1465 standard. The surface topography of all samples was measured, and the most important surface roughness parameter and its waviness were determined. Based on the experimental results, it was noticed that, among others, while using the same pressure value during sandblasting of different aluminium alloys, the roughness parameters *Ra* and *Rz* of the obtained surfaces differed depending on the type of alloy. It is also to notice that more than two times strength of the joints was obtained by those made of the aluminium alloy sheet, which was subjected to heat treatment.

Keywords: sandblasting; aluminium alloy; epoxy adhesive; adhesive joints strength; surface roughness, statistical analysis.

INTRODUCTION

The strength of adhesive joints of various materials depends on many of factors [1–7]. These factors are, most of all, determined by particular stages of the bonding technology together with their characteristic features. All types of factors are important, i.e. structural, technological, material, exploitation and economic ones, as well as, those related to the protection of environment [3, 8]. The bonded strength mostly depends on the first technological operation, i.e. surface treatment method [4, 5, 9–16]. This type of process increases the adhesive joints strength. Moreover de Barros et al. [5] underlined the importance of surface treatment of the substrate on the fatigue life. A proper preparation of the bonded surface includes the operations, thanks to which the surface layer will be characterised by very high activity [17–22]. This process enables to remove the dirt from the material, increase wettability, modify the surface's geometry, develop it properly, and increase the surface free energy [20–30]. Selection of the surface treatment method before the bonding process depends on, among others, the used material and its structure [2, 5, 12, 22, 27]. Other surface treatment methods are recommended for steel [26, 31–33], which is different for metals and metal alloys e.g. aluminium alloys [12, 18, 34–38] and titanium alloys [30, 39–42], and different for composites [43–45] and various polymer materials [2, 3, 46].

Adhesive joints of aluminium and aluminium alloys are used in many industries, e.g. aviation, building construction and others. Therefore, it is very important to properly develop appropriate bonding technology, including the selection of the right method of surface treatment. Aluminium and aluminium alloy surfaces are most often subjected to chemical and electrochemical treatments [2, 12, 21, 31, 47–51]. It should be mentioned that the first operation in the process of preparing the surface of aluminium and aluminium alloys is degreasing, which can be realized using various techniques and degreasing agents [2, 15, 34, 47]. Aluminium and aluminium alloy surfaces can also be machined, as reported in many articles [18, 52–56]. Among the mechanical treatments, the most recommended ones are to use sandblasting [2, 10, 20, 54, 56], grit blasting [19, 56, 57] and ice blasting [35]. In case of sandblasting, it is recommended to use alumina, silicon carbide and quartz as an abrasive, which, due to their irregular shape and sharp edges, effectively provides roughness to the surface to be treated. When using mechanical treatments, attention should be paid to the geometry of the surface formed during this treatment, which sometimes may hinder its wetting by the adhesive, which in turn leads to poorer mechanical properties of the joints. Elbing et al. [35] emphasized that the adhesive strength of aluminium components could essentially be improved with the application of dry ice blasting. However, dry ice blasting causes only small change in the topographic surface structure of adherends, but the improvement of the adhesive joint strength is because of the removal of the distributing lubricant, aluminium-oxide, and magnesium-oxide films. Bockenheimer et al. [18] showed that the surface treatment of the aluminium alloy surface by grit blasting, with glass beads or alumina grit, changed both, the aluminium alloy surface topography and the chemical state of this adherends surface. The authors underlined that the chemical state of adherend surface were resulted from influence of the curing reaction of the epoxy adhesive. Harris and Beevers [19] studied the effect of grit blasting on the surface characteristic aluminium alloy and mild steel adherends. They found that slight differences in grit types led to noticeable changes on surface characteristic. Rudawska et al. [20] presented the issues of sandblasting processing on the surface properties of steel sheets. It has been found that sandblasting medium has a greater effect than treatment pressure. Mandolfino et al. [21] investigated the influence of sandblasting parameters, e.g. type of sand, impact angle and pressure, on the surface roughness and mechanical characteristic of bonded joints steel sheets. The authors stated that the surface properties of adherends after sandblasting have an influence on the bonded joints mechanical behavior. Based on the analysis of the results of sandblasting and grit blasting studies, it was decided that in this article, research related to the use of sandblasting as surface treatment would be conducted for materials with a different degree of surface preparation after the manufacturing process. Spaggiari and Dragoni [13] investigated the effect of the mechanical surface treatments on the adhesive bonded joints and they noticed that that a simple correlation with the surface roughness is not sufficient to predict the best joint performances. The obtained results demonstrated that mechanical treatment (e.g. sandblasting) the adherends gives a strong improvement in terms of performance. Zhan et al. [52] presented that with the increase of surface roughness of Al–Li alloy the tensile-shear strength of the adhesive joints increased and the groove structures made during mechanical abrading were considered as being responsible for this strengthening behavior.

The aim of the article is to investigate the effect of sandblasting surface treatment before the bonding process on the strength of the adhesive joints of the three types of aluminium alloy sheets. Comparative analysis of the surface roughness parameters after sandblasting and the adhesive joints strength of the aluminium alloy sheets are also presented. Based on the tests, it can be underlined that a main technological factor that has an impact on the shear strength value is a proper surface treatment of the adherend. The technological parameters of sandblasting also have an influence on the adhesive joints' strength of aluminium alloys sheets. Moreover, the type of material and its technological surface treatment (heat treatment) after the production process also play a significant role both in terms of surface roughness and the strength of the adhesive bonds of these materials.

Table 1. Chemical composition of the aluminium alloys adherends [58, 59]

Compositions		EN AW-2024 TO	EN AW-2219 TO	EN AW-2014 T4
Al	wt.%	Remainder	Remainder	Remainder
Cu		3.80–4.90	8.80–6.80	3.90–5.00
Mg		1.20–1.80	≤0.02	0.20–0.80
Mn		0.30–0.90	0.20–0.40	0.40–1.20
Fe		≤0.50	≤0.30	≤0.70
Si		≤0.50	≤0.20	0.50–1.20
Zn		≤0.25	≤0.10	≤0.25
Cr		≤0.10	–	≤0.10
Ti		≤0.15	0.02–0.10	≤0.15
Zr		≤0.05	0.10–0.25	≤0.05
V		–	0.05–0.15	–
Total other		≤0.15	≤0.15	≤0.15

MATERIALS AND METHODS

Adherends

The single lap joints that were subjected to the tests were made of the following types of the aluminium alloy sheets: EN AW-2024 TO, EN AW-2219 TO and EN AW-2014 T4. The EN AW-2024 TO, EN AW-2219 TO and EN AW-2014 T4 aluminium alloys are recognised as cast alloys of the second series, which means that the main alloy addition is copper and, in small quantities, magnesium and manganese. They are characterised by high strength and an average susceptibility to corrosion. The EN AW-2014 T4 aluminium alloy had been subjected to supersaturating and a natural ageing until it obtained a steady state. The EN AW-2024 TO and EN AW 2219-TO alloys had been hardened and were not subjected to heat treatment. Table 1 presents the chemical composition of the alloys listed above [58, 59].

Adhesive

The epoxy adhesive with the designation Epidian 57/PAC/100:80 was used to make the joints. The epoxy adhesive contains epoxy resin based on Bisphenol A (Epidian 57 - commercial name, manufactured by CIECH Sarzyna, Nowa Sarzyna, Poland) and polyaminoamide curing agent (PAC - commercial name, manufactured by CIECH Sarzyna, Nowa Sarzyna, Poland). The adhesive preparation included mixing its ingredients in the proportion 100:80 (by volume). The Epidian 57 epoxy resin is an epoxy mixture created by the modification of the epoxy resin Epidian 5 with the saturated polyester resin Polimal 153. Table 2 presents the physicochemical properties of the Epidian 57 epoxy resin [60, 61].

The polyaminoamide curing agent (PAC) is a modified polyamide curing agent produced by the polycondensation of polyamine with diameters of unsaturated fatty acid methyl esters. Its use increases elasticity and impacts the joints strength and that is why it is used to create deformation-resistant adhesive joints. The curing time is from 4 to 7 days. However, it may be shortened to 8 hours by conducting the process at the temperature of 60°C. Table 3 presents the properties of the polyaminoamide curing agent [60, 61]. The adhesive preparation was conducted mechanically at the adhesive preparation stand, with use of a horseshoe mixer, with the mixer's rotational speed of 460 rpm for 2 minutes, at the ambient temperature of 25±1°C and ait humidity 24±1%. The electronic balance TP-2/1 (FAWAG S.A. manufacturer, Lublin, Poland), having an accuracy of 0.01 g, was used in order to weigh the ingredients properly and precisely. While preparing

Table 2. Physicochemical properties of the epoxy resin [60, 61]

Properties	Description/Value
Form	Dense, viscous, homogenous liquid
Epoxy number	≥ 0.40 mol/100 g
Combustibility	> 200°C
Density at 20°C	1.14–1.17 g/cm^3
Viscosity at 25°C	13000–19000 m·Pas
Solubility	Soluble in: ketones, esters, alcohols and aromatic hydrocarbons
Toxicity	May cause irritation and allergic reactions

Table 3. Physicochemical properties of the polyaminoamide curing agent [45, 47]

Properties	Description/Value
Form	Viscous liquid
Viscosity at 25°C	10 000–27 000 m·Pas
Density at 20°C	1.10–1.20 g/cm^3
Amino number	290–360 mg KOH/g
Gelling time at ambient temperature	180 minutes
Toxicity	May cause burns and allergic reactions on the skin

the epoxy adhesive, attention was paid to avoid creating the air bubbles as they could affect the joints strength.

Surface treatment

The surface preparation was conducted in two stages:

- The first stage – sandblasting of the aluminium alloys surface, which was performed in order to increase the surface roughness. The variable parameter of sandblasting was pressure of 0.41 MPa, 0.51 MPa and 0.56 MPa. Other parameters kept constant.
- The second stage – degreasing by immersion in acetone in order to remove the impurities created especially during the mechanical processing performed beforehand. After that the samples were left to dry completely.

Sandblasting

Sandblasting was performed with use of the abrasive blasting machine. The KC 1600 cabinet, thanks to a stable construction made of steel and a closed working space (1320×1320×950 mm), provides safety during processing. It needs to be pointed out that the blast cabinets ensure the best results possible in comparison to other construction tools aimed at sandblasting. It stems from the fact that the operation is conducted in a tight chamber that prevents the impurities from the outside to get in touch with the processed elements. The EB F54 aloxite, made of calcined bauxite, was used as a blasting medium [62]. The aloxite grit is very hard (9 in the Mohs hardness scale) and has very sharp edges that self-renew while working. The use of aloxite enables to clean the surface to a high extent. The F54 aloxite grit's size is between 355 to 300 µm. Due to the fact that aloxite is a reusable abrasive, the size of grit during processing of the aluminium alloys might have been slightly smaller.

The samples made of the aluminium alloy were placed inside the cabinet. During sandblasting the aloxite was getting out from the sandblasting machine's nozzle with use of the compressed air and was hitting against the processed materials' surface. After that, it was falling into the charging hopper; from there it was being poured to the abrasive pressure container again. Each aluminium alloy was subjected to sandblasting with use of three different pressure values, i.e. 0.41 MPa, 0.51 MPa and 0.56 MPa. This operation enabled us to obtain a clean and rough surface, even in hard-to-reach places, especially edges and corners. Table 4 presents the pressure variants used during sandblasting.

Degreasing method

A degreaser used in this stage was acetone, which dissolves fats, oils, lubricants, paints, as well as soft polymers. It is not toxic, however, when inhaled; it may cause headaches and irritation of the mucous membranes of the nose, mouth and eyes. Acetone is a colourless transparent liquid of a characteristic smell and high volatility.

After the sandblasting operation, the surface of the processed elements was covered with dust, which was removed during degreasing by immersion. The degreasing time was 4 seconds, and after that, the samples were left until acetone evaporated completely. This operation was conducted three times in order to remove all the impurities. Omission of that stage would result in weaker adhesive joints with low strength.

Table 4. Surface treatment variants

Variant of sandblasting	Technological parameters of sandblasting		
	Pressure, MPa	Time, s	Distance, mm
V1	0.41	60	200
V2	0.51	60	200
V3	0.56	60	200

Shape, dimensions and conditions of adhesive joints preparation

The EN AW-2024 TO, EN AW-2219 TO and EN AW-2014 T4 aluminium alloys were used to make 54 joints (6 single-lap joints made of all 3 aluminium alloys subjected to sandblasting with use of 3 pressure values) with use of the Epidian 57/PAC/100:80 two-component epoxy adhesive. Figure 1 shows the adhesive lap joint scheme. Table 5, in turn, presents the geometric dimensions of the real joints after curing. After the adhesive was prepared, it was instantly applied on the surface of one of the bonded elements. Then, the bonded elements were steadied in a locking special device. Instant application of the adhesive and bonding the elements right after the adhesive mass was prepared to preserve the adhesive's properties. The adhesive life, especially in case of the epoxy ones, changes with time. The curing process was performed at ambient temperature and under a pressure of 0.018 MPa. The curing time was 7 days. The pressure enabled the adhesive mass to flow in all pores and cracks and to distribute the adhesive on the whole surface. The processes of the adhesive compound preparation, application and conditioning were conducted in the conditions described in Table 6.

Tests and statistical analysis

The tests conducted for the purpose of the present article included determining both the geometrical structure of the adherends after the surface treatment, as well as, conducting the strength tests of different variants of the adhesive joints made of the aluminium alloy, taking into consideration different sandblasting variants.

The surface topography of all samples was measured with a tracer method with use of the Hommel-Etamic T8000 RC120-400 device (JENOPTIC Industrial Metrology Germany GmbH, Schweninngen, Germany). The most important surface roughness parameters and its waviness were determined. Also, a 3D topography of the surface prepared with use of sandblasting, during which different values of pressure were used, was prepared. All the tests were conducted as recommended with the standards: PN-EN ISO 11562, PN-EN ISO 4287 and PN-EN ISO 25178. The topographic structure measurements of the analysed surfaces consisted of mapping the material profile by passage of the measuring tip on the surface at the speed of 1.20 mm/s. The sheet surface scanning range was 4.80 mm × 4.80 mm and 1920 points of measurement were set. The following

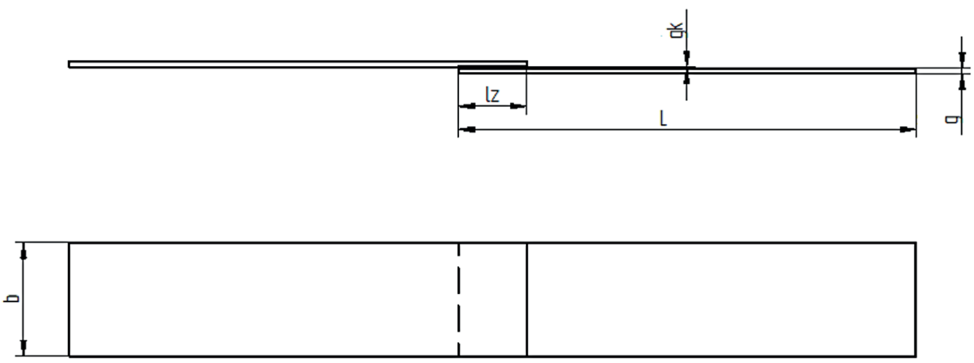


Fig. 1. Adhesive lap joint scheme

Table 5. Dimensions of the adhesive single-lap joints

Dimensions, mm		EN AW-2024 TO	EN AW-2219 TO	EN AW-2014 T4
Sample length	*L*	100 ± 1.00	100 ± 1.30	100 ± 0.90
Sample thickness	*g*	1.60 ± 0.02	1.30 ± 0.01	1.20 ± 0.01
Lap length	*lz*	15.32 ± 0.30	15.51 ± 0.27	15.40 ± 0.33
Sample width	*b*	25 ± 1.00	25 ± 1.10	25 ± 1.22
Adhesive joint thickness	*gk*	0.22 ± 0.05	0.25 ± 0.03	0.23 ± 0.02

Table 6. Conditions of preparing the single-lap joints

Temperature	Humidity	Pressure	Conditioning time	Curing time
25±1°C	24±1%	0.018 MPa	24 h	7 days

roughness parameters were analysed in both 2D and 3D systems:
- *Ra* – mean roughness profile deviation,
- *Rz* – ten-point mean roughness,
- *Sa* – arithmetical mean height,
- *Sz* – maximum 3D profile height,
- *Sku* – kurtosis.

The surface roughness measurement was conducted on three samples of each aluminium alloy (10 mm from every sample's edge, whereas the third measurement was made in the middle, i.e. 50 mm from the sample's edge), whose surface had been prepared according to three different variants. Each sample was measured at 1920 points, and this is why the tables present the mean measurement values. The shear strength tests of the aluminium alloys adhesive joints were performed on the Zwick/Roell Z150 testing device (ZwickRoell GmbH&Co. KG, Ulm, Germany), according to the DIN EN 1465 standard, at a constant speed of 5 mm/min. The adhesive joints were fixed at the testing machine with the screw-wedge clamps. TestExpert software was used to visualise the test results. After carrying out the strength tests, a visual analysis of the failure of adhesive joints was carried out based on the PN-EN ISO 10365 standard.

The shear strength (R_t) was determined on the basis of the obtained value of the failure force and the geometric bonding surface, using the basic formula for strength (1):

$$R_t = \frac{P}{A} \quad (1)$$

where: P – failure force, N;
A – geometric bonding surface, mm^2.

The strength test results were then subjected to a statistical analysis based on ANOVA due to the fact that the number of the analysed groups was higher than two. The analysis was conducted with use of the Statistica software. The statistical analysis of the obtained results enabled us to compare the mean strength value taking into consideration the analysed pressure variants applied during the mechanical processing. The Shapiro-Wilk test (normal distribution), Levene test (variance homogeneity) and the Tukey's HSD test at the assumed probability level $\alpha = 0.05$ was used. The probability level 0.05 is recognised as a boundary value of the acceptable error rate. The Tukey's HSD test is a post-hoc test (or a multiple comparison test) and may be used to find means that are significantly different from each other in a distribution of the analysis of variance.

RESULTS

Surface roughness

Figures 2 and 3, and Tables 7 to 9 present the results obtained during the topographic structure measurement of the materials, whose surface was subjected to sandblasting. However, for comparative purposes, Table 10 presents the results of surface roughness of aluminum alloy sheets before sandblasting. When analysing the data in Figure 2, it was observed that the higher the pressure value during sandblasting of the given material, the higher the arithmetical mean value of the profile

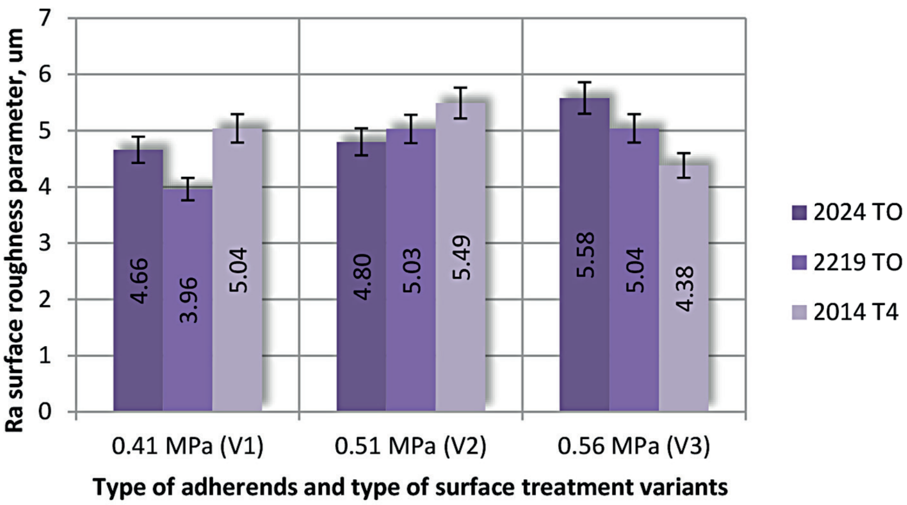


Fig. 2. Arithmetical mean value of the profile deviation of the aluminium alloys whose surface was sandblasted according to three different variants

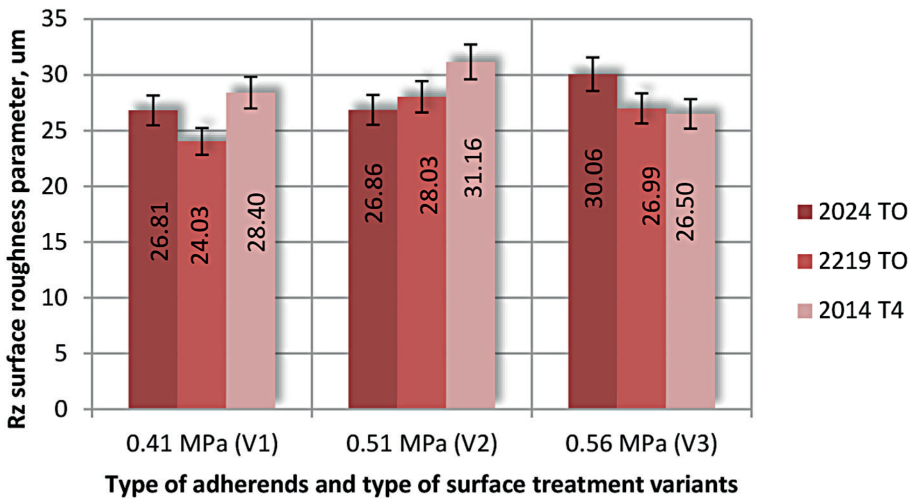


Fig. 3. Maximum roughness height of the aluminium alloys whose surface was sandblasted according to three different variants

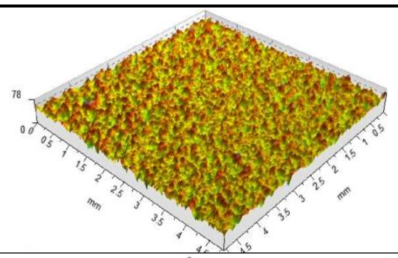
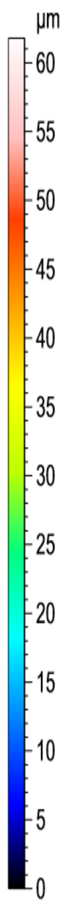
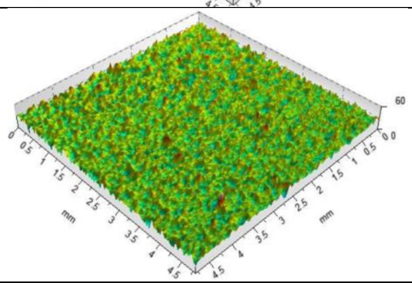
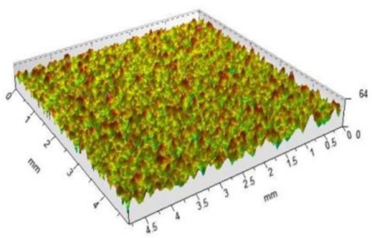
deviation is. However, it is not the case for the EN AW-2014 T4 aluminium alloy, i.e. the Ra parameter increased when the pressure values of 0.41 MPa (5.04 µm) and of 0.51 MPa (5.49 µm) were used. When the pressure increased to 0.56 MPa, the arithmetical mean of the profile deviation decreased to 4.38 µm. A more detailed analysis of the Ra parameter enabled us to observe that the increase of the pressure value from 0.41 MPa (V1 variant) to 0.56 MPa (V3 variant) caused the increase of the arithmetical mean of the profile deviation Ra of the EN AW-2024 TO aluminium alloy by 0.92 µm (19.74%). Even a higher change occurred in case of the EN AW-2219 TO alloy, as the Ra value increased by 1.08 µm (27.27%). In case of the EN AW-2014 T4 aluminium alloy, the Ra value increased by 0.45 µm (8.93%) after sandblasting with the pressure of 0.51 MPa (V3 variant) in relation to the V1 variant. However, in case of V3 variant, the arithmetical mean of the profile deviation decreased by 1.11 µm (20.22%) in relation to the V2 variant. During the surface preparation according to V1 variant, the highest value of the arithmetical mean of the roughness profile deviation was obtained by the EN AW 2014 T4, and the lowest one by the alloy EN AW-2219 TO. The difference between both values was 1.08 µm (27.27%). In case of V2 variant, the highest Ra value was obtained by the EN AW-2014 T4 aluminium alloy and the lowest one by the EN AW-2024 TO aluminium alloy, and the difference between both values increased to 0.69 µm (14.38%). During the surface preparation according to V3 variant, the highest value of the arithmetical mean of the roughness profile deviation was obtained by the EN AW-2024 T0 aluminium alloy, and the lowest one by the EN AW-2014 T4 aluminium alloy. The difference between both values was 1.20 µm (27.40%). Taking into consideration all aluminium alloys and all three pressure variants, the highest value of the Ra parameter was obtained by the EN AW-2024 TO aluminium alloy after surface preparation with use of V3 variant, and the lowest one by the EN AW-2219 TO aluminium alloy prepared with use of the V1 Variant. The difference between both values was 1.62 µm (40.91%).

Figure 3 presents the juxtaposition of the ten-point mean roughness' values of the aluminium alloys, whose surfaces were prepared according to the three different variants. For the EN AW-2024 aluminium alloy, the *Rz* roughness parameter value increased by 11% together with the increase of the pressure value during sandblasting. The highest value of the roughness height in case of the EN AW-2219 TO aluminium alloy during sandblasting with use of the pressure value of 0.42 MPa (V1) was 24.03 µm. When the pressure increased to 0.51 MPa (V2), the value of the Rz parameter increased to 28.03 µm. However, when the highest pressure value was applied (0.56 MPa in case of V3), the analysed parameter decreased to 26.99 µm. The same situation was observed in case of the EN AW-2014 T4 aluminium alloy. The highest value of the Rz parameter was obtained after sandblasting where the pressure value was of 0.51 MPa (V3).

Based on the results presented in Figure 3, it was observed that this parameter increases together with the increase of the pressure value during sandblasting from 0.41 MPa (V1 variant) to 0.56 MPa (V3 variant) for the EN AW-2024 TO aluminium alloy. The difference of the Rz parameter between the surfaces prepared according to these variants was 3.25 µm (Rz increased by 12.12%). In case of the EN AW-2219 TO aluminium alloy the roughness height increased only after using the V2 variant. The difference in relation from the V1 variant was of 4.00 µm (16.65%). The use of the V3 variant for this alloy resulted in the Rz parameter's value decrease to 1.04 µm (3.71%). For the EN AW-2014 T4 aluminium alloy, the results were similar, i.e. increase of the pressure value during sandblasting from 0.41 MPa to 0.51 MPa resulted in the roughness height's increase by 2.76 µm (9.72%). However, after using the V3 variant, this value decreased significantly by 4.66 µm (14.96%).

When analysing the results after the surface preparation with the V1 variant, it was found out that the highest value of the roughness height was obtained by the EN AW-2014 T4 aluminium alloy, whereas the lowest one was by the alloy EN AW-2219 TO. The difference in the Rz parameter value between these two alloys was 4.37 µm (18.19%). In case of V2 variant, the value of the roughness height was obtained by the EN AW-2014 T4 aluminium alloy and the lowest one by the EN AW-2024 TO aluminium alloy. The difference in the Rz parameter value increased to 4.30 µm (16.01%). During sandblasting where the pressure value was 0.56 MPa (V3 variant), the highest value of the roughness height was obtained by the EN AW-2024 TO aluminium alloy, whereas the lowest one by the EN AW-2014 T4 aluminium alloy. The difference in the Rz parameter value between these two alloys was 3.56 µm (13.43%). Taking into consideration all the aluminium alloys, whose surface was prepared by sandblasting with use of three different pressure values, it was observed that the highest value of the Rz parameter was obtained by the EN AW-2014 T4 aluminium alloy (V2 variant). Whereas the lowest one by the EN AW-2219 TO

Table 7. The 3D surface topography with the amplitude parameters for the spatial structure aluminium alloy, whose surface was prepared according to V1 variant

Adherend	3D imagine		3D parameter		
EN AW-2024 TO			*Sa*	[µm]	4.87
			Sz		78.60
			Sku		3.84
EN AW-2219 TO			*Sa*	[µm]	3.90
			Sz		60.60
			Sku		4.34
EN AW-2014 T4			*Sa*	[µm]	5.15
			Sz		64.40
			Sku		3.47

aluminium alloy (V1 variant), and the difference was of 7.13 μm (29.67%).

Table 7 presents the obtained results for the aluminium alloys, whose surface was subjected to sandblasting according to V1 variant.

The graphics presenting an exemplary topography of the alloys' surface showed the irregularities caused by sandblasting. The highest value of the arithmetical mean height, i.e. the Sa parameter, was obtained by the EN AW-2014 T4 aluminium alloy (5.15 μm), whereas the lowest one by the EN AW-2219 TO aluminium alloy (3.90 μm). The highest maximum 3D profile height (Sz) was obtained by the EN AW-2024 TO aluminium alloy (78.60 μm), whereas the lowest one by the EN AW-2219 TO aluminium alloy (60.60 μm). The surface kurtosis (Sku) obtained a positive value in all cases. It means that the individual results are very close to the arithmetical mean, especially in case of the EN AW-2219 TO aluminium alloy. It needs to be explicitly stated that the surfaces of the aluminium alloys: EN AW-2024 TO and EN AW-2014 T4 obtained a higher degree of surface development than the EN AW-2219 TO aluminium alloy.

Table 8 presents the results of the surface roughness measurements of the aluminium alloys, whose surface was prepared using V2 variant. The exemplary topographic maps show the micro irregularities caused by sandblasting. The highest values of the arithmetical mean height (*Sa*) and the maximum 3D profile height (*Sz*) were obtained by the EN AW-2014 T4 aluminium alloy (*Sa* = 5.58 μm, *Sz* = 73 μm). Slightly lower values were obtained by the EN AW-2219 TO aluminium alloy (*Sa* = 5.31 μm, *Sz* = 60.30 μm). The lowest values were obtained by the EN AW-2024 TO aluminium alloy (*Sa* = 4.97 μm, *Sz* = 56.20 μm). The best surface development was obtained by the EN AW-2014 T4 aluminium alloy.

Table 9 presents the results of the surface roughness measurements of the aluminium alloys, whose surface was prepared using V3 variant. The surface topography showed the irregularities

Table 8. 3D surface topography with the amplitude parameters for the aluminium alloy's spatial structure, whose surface was prepared according to the V2 variant

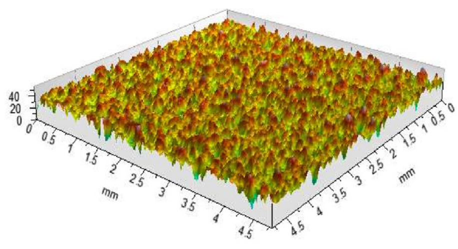
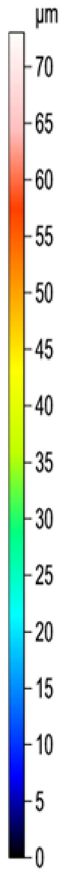
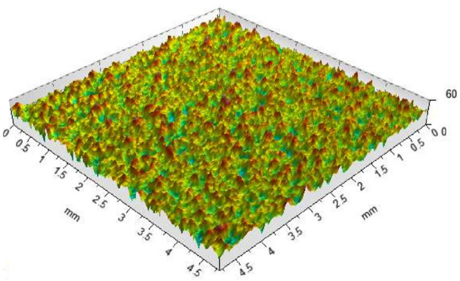
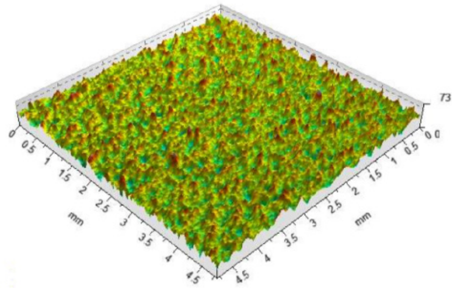
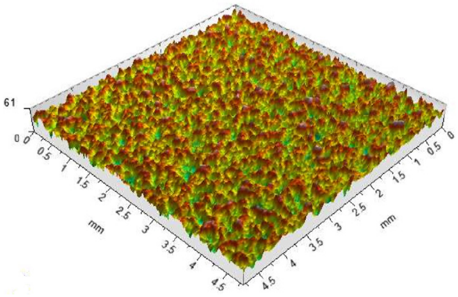
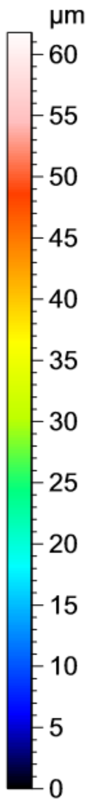
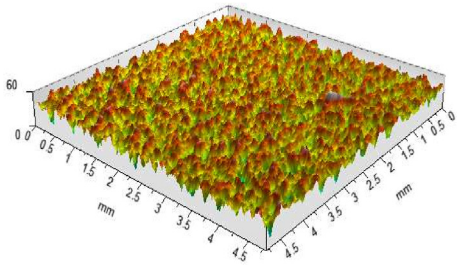
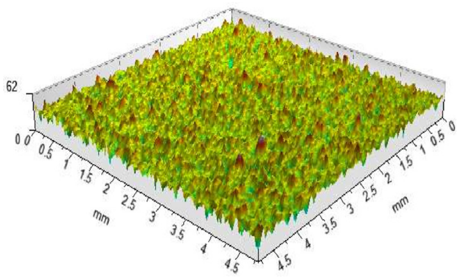
Adherend	3D images		3D parameter		
EN AW-2024 TO			*Sa*	[μm]	4.97
			Sz		56.20
			Sku		3.25
EN AW-2219 TO			*Sa*	[μm]	5.31
			Sz		60.30
			Sku		3.22
EN AW-2014 T4			*Sa*	[μm]	5.58
			Sz		73.00
			Sku		3.42

Table 9. 3D surface topography with the amplitude parameters for spatial structure of the aluminium alloy, whose surface was prepared according to the V3 variant

Adherend	3D images		3D parameter		
EN AW-2024 TO			*Sa*	[μm]	6.02
			Sz		61.80
			Sku		2.99
EN AW-2219 TO			*Sa*	[μm]	5.33
			Sz		60.70
			Sku		3.26
EN AW-2014 T4			*Sa*	[μm]	4.25
			Sz		62.70
			Sku		4.05

that were characteristic of the surfaces subjected to the abrasive blasting, specifically sandblasting. The EN AW-2024 TO aluminium alloy showed the highest value of the arithmetical mean height Sa (6.02 µm), whereas the lowest value of this parameter was obtained by the EN AW-2014 T4 aluminium alloy (4.25 µm). The highest maximum 3D profile height (Sz) was obtained by the EN AW-2014 T4 aluminium alloy (62.70 µm), whereas the lowest one by the EN AW-2219 TO aluminium alloy (60.70 µm). The most advantageous surface development, which is very important in the aspect of the adhesive anchoring during the adhesive bond formation and bonding process, was showed by the EN AW-2024 TO aluminium alloy.

Comparing the results presented in Figure 2, Figure 3 and Table 10, it was noticed that after the mechanical treatment of the surface of the aluminium alloy sheets, i.e. sandblasting, a significant increase of the considered surface roughness parameters Ra and Rz was observed, more than several times. This means that sandblasting influences the geometric development of the surface, which in the gluing processes is important; first of all, it increases the real surface of the bonding, and thus increases the share of the mechanical adhesion.

Adhesive joints strength

Shear strength results of the adhesive joints made of three types of the aluminium alloy sheets: EN AW-2024 TO, EN AW-2219 TO and EN AW-2014 T4, whose surface was subjected to

Table 10. Surface roughness parameters of aluminium alloys before mechanical treatment

Type of aluminium alloy	Surface roughness parameters, µm	
	Ra	*Rz*
EN AW-2024 TO	0.42	3.28
EN AW-2219 TO	0.35	2.46
EN AW-2014 T4	0.28	2.10

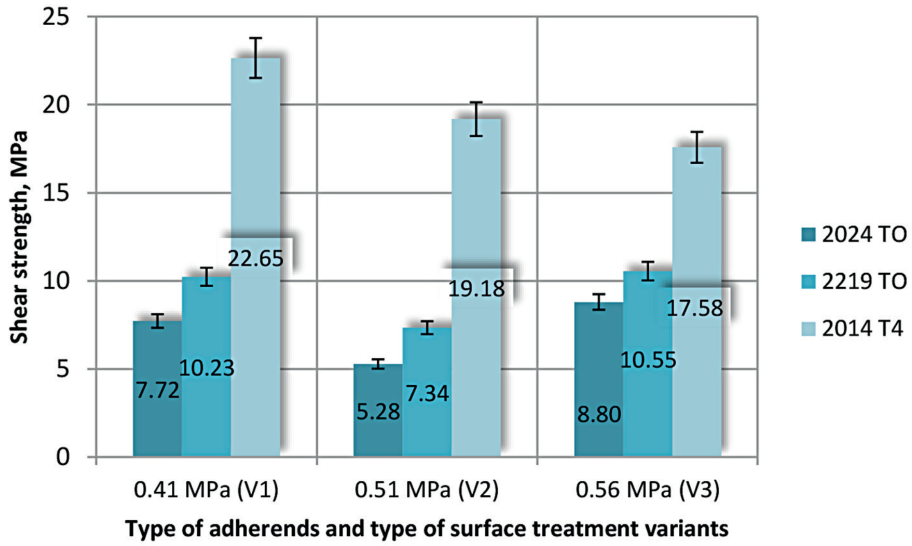


Fig. 4. Shear strength of the adhesive joints made of different aluminium alloys, whose surface was subjected to three variants of sandblasting

sandblasting with use of three pressure values before the bonding process, are presented in Figure 4.

Based on the presented shear strength results of the aluminium alloys (Fig. 4), whose surface was prepared using the three different variants of sandblasting, it may be stated that the adhesive joints of the EN AW-2024 TO aluminium alloy are characterised by the lowest shear strength. However, the highest shear strength of that alloy was obtained after sandblasting according to the V3 variant, whereas the lowest one was obtained using the V2 variant (0.51 MPa). The difference between the highest and the lowest shear strength values increased to 3.52 MPa (66.67%). In case of the joints made of the EN AW-2219 TO aluminium alloy, the highest strength value was obtained for the V3 variant, and the lowest one for the V2 variant. The difference was of 3.21 MPa (43.73%). The highest shear strength value was obtained by the joints made of the EN AW-2014 T4 aluminium alloy. The highest mean strength was obtained for the surfaces prepared according to the V1 variant, whereas the lowest one - according to the V3 variant. The increase of the pressure value during the sandblasting of the EN AW-2014 T4 aluminium alloy resulted in the shear strength decrease of the adhesive joints by 5.07 MPa (28.84%).

When analysing the strength of joints made of different aluminium alloys that were prepared using different pressure values, it was observed that there was a significant difference between the joints characterised by the highest and the lowest shear strength. The joints of the EN AW-2014 T4 aluminium alloy had more than three times higher

Table 11. Results of failure analysis of the adhesive joints aluminium alloys

Type of aluminium alloy adherends of adhesive joints	Variant of sandblasting	Type of failure inside adhesive layer			
		CF	SCF	AF	ACF(p)
		Amount of aluminium alloy adhesive joints			
EN AW-2024 TO	V1	+	++	+++	-
	V2		++	+++++	-
	V3		+++	+++	-
EN AW-2219 TO	V1	++	++	++	-
	V2	+	++	+++	-
	V3		++	++++	-
EN AW-2014 T4	V1	+	++++	+	-
	V2		+++	+++	-
	V3		+	+++++	-
Legend: CF – cohesion failure, SCF – special cohesion failure AF – adhesion failure, ACF (p) – adhesive and cohesive failure with peel					

strength than those made of the EN AW-2024 TO aluminium alloy.

Failure analysis of adhesive joints

The visual analysis of the failure of adhesive joints was carried out based on the DIN EN ISO 10365 standard. Based on failure analysis of adhesive joints after the mechanical tests, it can be observed that all the tested types of adhesive joints reveal the presence of failure inside the adhesive layer. None of the tested types of aluminium alloy sheets showed failure inside adherend – aluminium alloy sheets. The results of the different types of adhesive layer failure are shown in Table 11 and Figure 5.

When visually assessing the samples of adhesive joints in the place of joining after the mechanical strength tests, it can be seen that in any variant of surface preparation by sandblasting, the fourth type of failure of the adhesive joint did not occur - ACF (p) adhesive and cohesive failure with peel. It was also noted that in most cases there were two types of failure: adhesion failure (AF) and also special cohesion failure (SCF).

The photos in Fig. 5 show examples of EN AW-2014 T4 aluminium alloy adhesive joints, because for this material it will obtain the highest shear strength of adhesive joints. It has been found that for the adhesive joints of this alloy, increasing the pressure value during sandblasting caused a greater amount of failure to the adhesive joint. Perhaps the higher pressure causes the unfavourable shape of the surface roughness and considering the mechanical adhesion. After the V3 variant, no greater real bonding surface was obtained, and thus the adhesive was less anchored in the surface micro-unevenness and the failure image was rather classified as adhesive failure (AF). On the other hand, in the V1 variant surface treatment for this type of aluminium alloy sheet, a greater number of samples were noticed showing the properties of the cohesive failure (SCF) of the adhesive joint. On this basis, it can be assumed that the sandblasting variant with lower nozzle pressure may contribute to obtaining a more favourable stereometrics structure of the surface of the analysed aluminium alloy sheets. As a result, a larger real bonding surface (wetted by the adhesive) is obtained. This can be confirmed by the strength results for those joints, where the adhesive joints of aluminium alloy sheets made in the first surface treatment condition (V1) are characterized by greater strength. It should be noted that the authors are aware that the visual assessment of the failure character of adhesive joints based on the DIN EN ISO 10365 standard may be a subjective assessment, but efforts were made to make the presented results as objective as possible.

Statistical analysis of adhesive joints strength results

The first stage of the analysis includes preparing the descriptive statistics that characterise the analysed variables. The results are presented in Tables 12 to 14.

The next stage of the statistical analysis includes verification of adjustment of the empirical research of the analysed variables' result to the normal distribution with use of Shapiro-Wilk (S-W) normality test. The statistical analysis (at the

a) c) b) d)

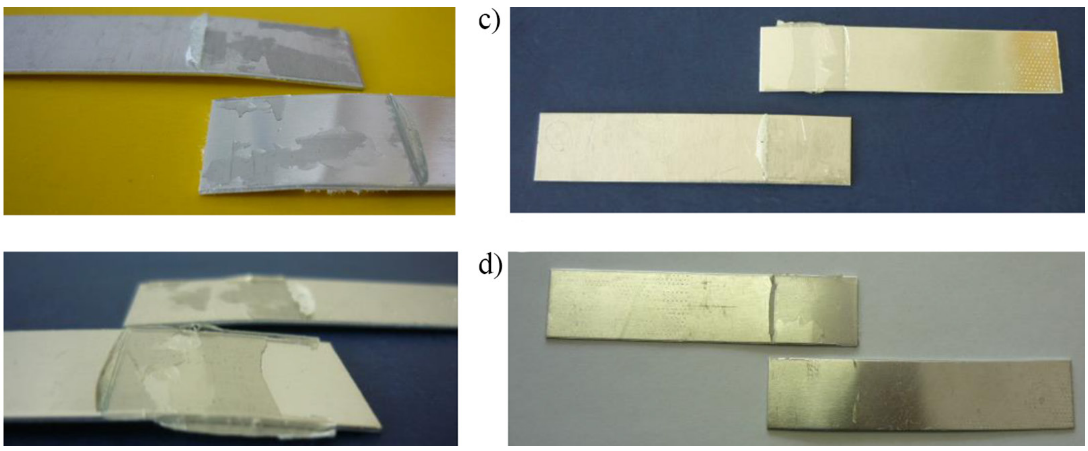


Fig. 5. Failure patterns of EN AW-2014 T4 aluminium alloys adhesive joints: a) special cohesion failure (SCF) for V1 variant, b) and c) adhesion failure (AF) and also special cohesion failure (SCF) for V2 variant, b and c) and d) adhesion failure (AF) for V3 variant

Table 12. Results of the descriptive statistics of the adhesive joints shear strength EN AW-2024 TO aluminium alloy

Variant	Mean	Median	Variance	Standard deviation	Skewness	Kurtosis
V1	7.72	8.58	3.37	1.84	-0.68	-1.86
V2	7.45	7.81	3.60	1.90	-0.20	-2.18
V3	8.80	8.45	1.30	1.14	1.05	0.10

Table 13. Results of the descriptive statistics of the adhesive joints shear strength EN AW-2219 TO aluminium alloy

Variant	Mean	Median	Variance	Standard deviation	Skewness	Kurtosis
V1	10.23	10.50	1.09	1.04	-1.77	3.46
V2	7.74	7.92	0.40	0.63	-0.43	-2.29
V3	10.55	11.10	2.28	1.51	-0.41	-1.31

Table 14. Results of the descriptive statistics of the adhesive joints shear strength EN AW-2014 T4 aluminium alloy

Variant	Mean	Median	Variance	Standard deviation	Skewness	Kurtosis
V1	22.65	22.50	1.86	1.36	0.50	-0.86
V2	19.18	19.80	2.91	1.70	-1.46	1.95
V3	17.58	17.85	2.41	1.55	-1.51	2.97

Table 15. Results of the Shapiro-Wilk normality test for the EN AW-2024 TO aluminium alloy shear strength test results

Variant	Number of samples, N	Shapiro-Wilk statistics, *W*	Probability level, *p*	Normal distribution
V1	5	0.893798	0.376563	YES
V2	6	0.881915	0.277968	YES
V3	6	0.880145	0.269725	YES

Table 16. Results of the Shapiro-Wilk normality test for the EN AW-2219 TO aluminium alloy shear strength test results

Variant	Number of samples, N	Shapiro-Wilk statistics, *W*	Probability level, *p*	Normal distribution
V1	5	0.817403	0.111485	YES
V2	6	0.836403	0.121684	YES
V3	5	0.949550	0.733976	YES

Table 17. Results of the Shapiro-Wilk normality test for the EN AW-2014 T4 aluminium alloy shear strength test results

Variant	Number of samples, N	Shapiro-Wilk statistics, *W*	Probability level, *p*	Normal distribution
V1	6	0.931033	0.588102	YES
V2	6	0.856359	0.177021	YES
V3	6	0.873222	0.239354	YES

Table 18. Results of the Levene's homogeneity of variance test for the shear strength results in division taking into consideration the material type

Adherend	Levene's test *F*	Probability level, *p*	Homogeneity of variance
EN AW-2024 TO	2.222721	0.145102	YES
EN AW-2219 TO	2.381391	0.131465	YES
EN AW-2014 T4	0.154601	0.858105	YES

assumed significance level α=0.05) of adjustment of the empirical distribution to the normal distribution showed that the distribution of the shear strength results obtained for all the sandblasting pressure variants and all the materials was consistent with the normal distribution. The obtained results are presented in Tables 15–17.

The next stage of the statistical analysis included verification of the assumption of the variance homogeneity, with use of the Levene's test. The Levene's test results are presented in Table 18.

As the assumptions of the normality of distribution and the homogeneity of variance were proved to be true, the parametric tests (Tukey's HSD) were used in the next stage of the statistical analysis. Its results were presented in Tables 19–21.

For the EN AW-2024 TO alloy, considering three values of pressure used during sandblasting, the multiple comparison analysis did not show any statistically significant differences between the mean values of the obtained results (Table 19). The results presented in Table 20 show that there were some differences between V1 and V2 variants and V2 and V3 variants of sandblasting. There were no statistically significant differences between the V1 and V1 variants. In case of the results for the EN AW-2014 T4 aluminium alloy (Table 21), the significant differences between the mean values were observed in case of the sandblasting variants V1 and V2, as well as V1 and V3. There were no significant variances between the mean values of the results obtained for variants V2 and V3.

Table 19. Results of the post-hoc Tukey's test of the significant differences of the shear strength values for the joints of the EN AW-2024 TO aluminium alloy

Variant	V1	V2	V3
V1		0.961062	0.537600
V2	0.961062		0.357008
V3	0.537600	0.357008	

Table 20. Results of the post-hoc Tukey's test of the significant differences of the shear strength values for the joints of the alloy EN AW-2219 TO aluminium alloy

Variant	V1	V2	V3
V1		0.006265	0.890670
V2	0.006265		0.002658
V3	0.890670	0.002658	

Table 21. Results of the post-hoc Tukey's test of the significant differences of the shear strength values for the joints of the alloy EN AW-2014 T4 aluminium alloy

Variant	V1	V2	V3
V1		0.004072	0.000278
V2	0.004072		0.206053
V3	0.000278	0.206053	

DISCUSSION

A main technological factor that has an impact on the strength of adhesive joints is a proper surface treatment of the adherends. The method used during the tests described herein was sandblasting, which caused some irregularities, cracks and pores on the adherends surface. Thanks to that, the adhesive-adherend contact surface was increased and the anchor points for the adhesive were created. Comparative analysis of the surface roughness' parameters and the adhesive joints strength of the aluminium alloy sheets were based on the correlation coefficient of two values: shear strength and surface roughness parameters (*Ra* and *Rz*). The correlation coefficient (ρ) serves to determine the relations between two values and it may be defined with a following dependence as reported in Ref. [20]. Table 22 presents the selected *Ra* and *Rz* surface roughness parameters of the surface of adherends, whose surfaces were subjected to sandblasting according to three variants (Table 4) and the shear strength of the adhesive joints of the analysed sheets.

When considering the dependence between the values of the *Ra* and *Rz* surface roughness parameters of the aluminium alloy sheets and the strength of the adhesive joints of the analysed sheets, in case of the variant 1 a positive correlation between these values may be observed. However, it is not as strong as for the variant 2. The correlation coefficient for the distribution for the compared parameters *Ra* and *Rt* is 0.66, and for the compared parameters *Rz* and *Rt* it is 0.67.

In case of the second variant (V2), when comparing the analysed surface roughness parameters, it was observed that together with the increase of these parameters' value, the strength of the adhesive joints of the aluminium alloy sheets increases as well. The correlation coefficient for the distribution for the compared parameters *Ra* and *Rt* is 0.98, and for the compared parameters *Rz* and *Rt* it is 0.99.

For the third variant of sandblasting V3), an inverse correlation may be observed: together

Table 22. Surface roughness parameters of the aluminium alloy sheets, whose surfaces were subjected to sandblasting according to three variants and the strength of the adhesive joints of the analysed sheets

Pressure value during sandblasting, MPa	Variant	Adherend	Surface roughness parameter, μm		Strength, MPa
			Ra	*Rz*	
0.41	V1	EN AW-2024 TO	4.66	26.81	7.72
		EN AW-2219 TO	3.96	24.03	10.23
		EN AW-2014 T4	5.04	28.40	22.65
0.51	V2	EN AW-2024 TO	4.80	26.86	5.28
		EN AW-2219 TO	5.03	28.03	7.34
		EN AW-2014 T4	5.49	31.16	19.18
0.56	V3	EN AW-2024 TO	5.58	30.06	8.80
		EN AW-2219 TO	5.04	26.99	10.55
		EN AW-2014 T4	4.38	26.50	17.58

with the decrease of the roughness parameters value, the strength of the joints increases. The correlation coefficient is negative and for the cpmapred parameters *Ra* and *Rt* it is -0.96, and for the compared parameters *Rz* and *Rt* it is -0.74.

de Barros et al. [56] in their research showed that the influence of individual average surface roughness parameters (e.g. after mechanical treatment in the form of grit-blasting and sandblasting) is not statistically significant when it is correlated with the bond strength. In turn, Bockenheimer et al. [18] emphasized that the effect of mechanical surface treatment for aluminium alloy bonding was very complex, compromised the topography structure of adherends surface and changed the chemical state of the adherends surface. On the basis of the present tests, it can be added that technological factors of machining can shape a specific surface structure, which ultimately affects the strength of adhesive joints, considering the aspect of mechanical adhesion. This statement was also supported by the results of research presented in the study prepared by Rudawska et al. [20]. Moreover Boutar et al. [53] and Harris and Beevers [19] concluded that the changes in the adhesive joints properties associated with the roughened surfaces cannot be explained simply by the increased roughness characteristic, such as mechanical anchoring and increased effective real bond area. The properties and changes of both physical and chemical surfaces of joined materials should be considered simultaneously. Spaggiari and Dragoni [13] underlined that that a simple correlation with the surface roughness is not sufficient to forecast the best adhesive joint execution.

With regard to the results obtained, it is also important to notice that more than two times the strength of the joints was obtained by those made of the EN AW-2014 T4 aluminium alloy, which had been subjected to heat treatment, i.e. solution heat treatment and natural ageing until obtaining a stable state. This procedure resulted in the material's hardening, and this was the only material that was not deformed after sandblasting. The adhesive joints of the EN AW-2014 T4 aluminium alloy obtained more than three times higher strength than those made of the EN AW-2024 TO aluminium alloy. In case of the two other aluminium alloys sheets, i.e. EN AW-2024 TO and EN AW-2219 TO (not subjected to heat treatment), many samples were deformed during sandblasting. This proves the fact that sandblasting of these materials, is not recommended due to lower hardness and high susceptibility to deformation. For these materials it is recommended to use a different surface preparation method.

CONCLUSIONS

Based on the conducted tests, it can be underlined that a main technological factor that has an impact on the shear strength of adhesive joints is a proper surface treatment of the adherend. The technological parameters of sandblasting have an influence on the adhesive joints strength of the aluminium alloys sheets. The type of material and its technological surface treatment (heat treatment) after the production process also play a significant role both in terms of surface roughness and the strength of the adhesive bonds of these materials. When using the same pressure value during sandblasting of different aluminium alloys surface, the roughness parameters *Ra* and *Rz* of the obtained surfaces differed depending on the aluminium alloy type. The adhesive joints of the aluminium alloy sheets, the surface of which has been heat treated after the production process, showed a much higher strength than the other joints for which sheets were not subjected to heat treatment.

The conclusion is that an important element in the bonding technology is not only the surface treatment prior the bonding process, but also the surface treatment of adherends after the production process (temper state). However, the surface treatment method should be selected for each type of the material individually, depending on its properties.

Acknowledgments

The authors would like to thank Faculty of Mechanical Engineering, Lublin University of Technology, Lublin, Poland. Funding: Lublin University of Technology**,** Award Number: FD-20/IM-5/093 | Recipient: Prof. Anna Rudawska, Ph.D., D.Sc. Eng.

REFERENCES

1. da Silva L.F.M., Carbas R.J.C., Critchlow G.W., Figueiredo M.A.V., Brown K. Effect of material, geometry, surface treatment and environment on the shear strength of single lap joint. International Journal of Adhesion and Adhesives. 2009; 29: 621–632.
2. Ebnesajjad S., Ebnesajjad C. Surface Treatment of Materials for Adhesive Bonding. 2nd ed. Inc. Norwich, William Andrew; 2013.
3. Adams R.D., Comyn J., Wake W.C. Structural Adhesive Joints in Engineering Book. Springer; 1997.
4. Rudawska A. Pressure during curing and the strength of 2024, 2017A and 1050 aluminium alloy sheet adhesive joints. Advances in Science and Technology Research Journal. 2015; 9(26): 96–103.
5. de Barros S., Kenedi P.P., Ferreira S.M., Budhe S., Bernardino A.J., Souza L.F.G. Influence of mechanical surface treatment on fatigue life of bonded joints. Journal of Adhesion. 2017; 93: 599–612.
6. Rudawska A., Bociąga E., Olewnik-Kruszyńska E. The effect of primers on adhesive properties and strength of adhesive joints made with polyurethane adhesives. Journal of Adhesion Science and Technology. 2017; 31: 327–344.
7. Müller M., Valasek P., Rudawska A. Mechanical properties of adhesive bonds reinforced with biological fabric. Journal of Adhesion Science and Technology. 2017; 31: 1859–1871.
8. Rudawska A., Wahab M.A. The effect of cataphoretic and powder coatings on the strength and failure modes of EN AW-5754 aluminium alloy adhesive joints. International Journal of Adhesion and Adhesives. 2019; 89: 40–50.
9. Prolongo S.G., Ureña A. Effect of surface pre-treatment on the adhesive strength of epoxy-aluminium joints. International Journal of Adhesion and Adhesives. 2009; 29: 23–31.
10. Wang, X., Lin J.-p., Min J.-y., Wang P.Ch., Sun, Ch.-ch. Effect of atmospheric pressure plasma treatment on strength of adhesive-bonded aluminum AA5052. Journal of Adhesion. 2018; 94: 701–722.
11. Kinloch A.J., Smart N.R. Bonding and failure mechanisms in aluminium alloy adhesive joints. Journal of Adhesion. 1981; 12: 23–35.
12. Critchlow G.W., Brewis D.M. Review of surface pretreatments for aluminium alloys. International Journal of Adhesion and Adhesives. 1996; 16: 255–275.
13. Spaggiari A.E., Dragoni E. Effect of mechanical surface treatment on the static strength of adhesive lap joints. Journal of Adhesion. 2013; 89: 677–696.
14. Lunder O., Lapique F., Johnsen B., Nisancioglu K. Effect of pre-treatment on the durability of epoxy-bonded AA6060 aluminium joints. International Journal of Adhesion and Adhesives. 2004; 24: 107–1170.
15. Goglio L. Rezaei M. Effect of different substrate pre-treatments on the resistance of aluminum joints to moist environments. Journal of Adhesion. 2013; 89: 769–784.
16. Leena K., Athira K.K., Bhuvaneswari S., Suraj S., Lakshmana Rao, V. Effect of surface pre-treatment on surface characteristic adhesive bond strength of aluminium alloy. International Journal of Adhesion and Adhesives. 2016; 70: 265–270.
17. Bhatt R.D., Radhakrishnan V. Evaluation of some machining process as adherend surface treatments in bonding aluminium. Journal of Adhesion Science and Technology. 1989; 3: 383–396.
18. Bockenheimer C., Valeske B., Possart W. Network structure in epoxy aluminium bonds after mechanical treatment. International Journal of Adhesion and Adhesives. 2002; 22: 349–356.
19. Harris A.F., Beevers A. The effect of grit-blasting on the surface properties for adhesion. International Journal of Adhesion and Adhesives. 1999; 19: 445–452.
20. Rudawska A., Danczak I., Müller M., Valasek P. The effect of sandblasting on surface properties for adhesion. International Journal of Adhesion and Adhesives. 2016; 70: 176–190.
21. Fondeur F., Koenig J.L. FT-IR characterization of the surface of aluminum as a result of chemical treatment. Journal of Adhesion. 1993; 40: 189–205.
22. Wang Y., Chai P., Ma H., Zhang Y. Characteristics and strength of hybrid friction stir welding and ad-

hesive bonding lap joints for AA2024-T3 aluminium alloy. Journal of Adhesion. 2022; 98: 325–347.

23. Rudawska A. Adhesive properties, Chapter 7. Scanning Electron Microscope, Ed. V, Kazmiruk, 2012, 101–126, INTECH, Rijeka, Croatia.
24. Sancaktar E., Gomatam R. A study on the effects of surface roughness on the strength of single lap joints. Journal of Adhesion Science and Technology. 2001; 15: 97–117.
25. Mandolfino Ch., Lertora E., Gambaro C. Effect of surface pretreatment on the performance of adhesive-bonded joints. Key Engineering Materials. 2013; 554–558: 996–1006.
26. Rudawska A. Selected aspects of the effect of mechanical treatment on surface roughness and adhesive joint strength of steel sheets. International Journal of Adhesion and Adhesives. 2014; 50: 235–243.
27. Rudawska A., Głogowska K., Vitenko T., Stančeková D., Čuboňová N., Kasperek D.: The impact of selected technological and material parameters on the strength of adhesive steel sheets joints. Advances in Science and Technology Research Journal. 2017; 11(2): 8–16.
28. Baldan A. Adhesion phenomena in bonded joints. International Journal of Adhesion and Adhesives. 2012; 38: 95–116.
29. Akiyama H., Fukata T., Sato T., Horiuchi S., Sato C. Influence of surface contaminants on the adhesion strength of structural adhesives with aluminium. Journal of Adhesion. 2020; 96: 1311–1325.
30. Carre A., Schultz J. Polymer-aluminium adhesion. I. The surface energy of aluminium in relation to its surface treatment. Journal of Adhesion. 1983; 15: 151–161.
31. Ebnesajjad S. Handbook of Adhesives and Surface Preparation, Chapter 6. Surface Preparation of Metals. Plastic Design Library, Elsevier Inc. 2011, 83–106.
32. Rotella G., Alfano M., Schiefer T., Jansen I. Evaluation of mechanical and laser surface pre-treatments on the strength of adhesive bonded steel joints for automotive industry. Journal of Adhesion Science and Technology. 2016; 30: 747–758.
33. Rudawska A., Reszka M., Warda T., Miturska I., Szabelski J., Skoczylas A., Stancekova D. Milling as method of surface pretreatment of steel for adhesive bonding. Journal of Adhesion Science and Technology. 2016; 30: 2619–2636.
34. Rudawska A. Surface free energy and 7075 aluminium bonded joint strength following degreasing only and without any prior treatment. Journal of Adhesion Science and Technology. 2012; 26: 1233–1247.
35. Elbing F., Anagreh N., Dorn L., Uhlmann E. Dry ice blasting as pretreatment of aluminium surfaces to improve the adhesive strength of aluminum bonding joints. International Journal of Adhesion and Adhesives. 2003; 23: 69–79.
36. Rechner R., Jansen I., Beyer E. Influence on the strength and aging resistance of aluminium joints by laser pre-treatment and surface modification. International Journal of Adhesion and Adhesives. 2010; 30: 295–601.
37. Guo S., Carlson B.E., Hector L.G. Jr., Xia Y., Zhou Q. Increasing strength and fracture toughness of AA7074-T6 adhesively-bonded joints with laser ablation. Journal of Materials Processing Technology. 2018; 259: 368–379.
38. Brack N., Rider A.N. The influence of mechanical and chemical treatments on the environmental resistance of epoxy adhesive bonds to titanium. International Journal of Adhesion and Adhesives. 2014; 48: 20–27.
39. Takeda T., Yasuoka T., Sugimoto S., Iwahori Y. Strength enhancement of adhesively bonded Ti-6Al-4V alloy joints by flame-based surface treatment. Journal of Adhesion. 2021, DOI: 10.1080/00218464.2020.1870106
40. Molitor P., Barron V., Young T. Surface treatment of titanium for adhesive bonding to polymer composites: a review. International Journal of Adhesion and Adhesives. 2001; 21: 129–136.
41. Smith T. A surface treatment for Ti-6AI-4V. Journal of Adhesion. 1983; 15: 137–149.
42. Kurtovic A., Brandl E., Mertens T., Maier H.J. Laser inducted surface nano-structuring of Ti-6Al-4V for adhesive bonding. International Journal of Adhesion and Adhesives. 2013; 45: 112–117.
43. Wahab M.A. Joining composites with adhesives. DEStech Publications Inc; 2016.
44. Kim J.G., Choi I., Lee D.G., Seo I.S. Flame and silane treatments for improving the adhesive bonding characteristics of aramid/epoxy composites. Composite Structures 2011; 93: 2696–2705.
45. Leone C., Genna S. Effects of surface laser treatment on direct co-bonding strength of CFRP laminates. Composite Structures. 2018; 194: 240–251.
46. Xiao G.Z. Effects of solvent on the surface properties of oxygen plasma-treatment polyethylene and polypropylene films. Journal of Adhesion Science and Technology. 1997; 11: 655–663.
47. Rudawska A., Nalepa J., Müller M. The effect of degreasing on adhesive joint strength. Advances in Science and Technology Research Journal. 2017; 11(1): 75–81.
48. Dodiuk H., Buchman A., Kenig S., Rotel M., Zahavi Reinhart T.J. Preadhesion laser treatment of aluminum surfaces. Journal of Adhesion. 1993; 41: 93–112.
49. Comrie R., Affrossman S., Hayward D., Pethrick R.A., Zhou X., Thompson G.E. Ageing of adhesive bonds with various surface treatments, Part 1: Aluminium–dicyandiamide cured epoxy joints. Jour-

nal of Adhesion. 2005; 81: 1157–1181.

50. Allen K.W., Smith M. A cold chromate etch treatment for some aluminium alloys. Journal of Adhesion. 1985; 18: 111–129.
51. Prolongo S.G., Horcajo K.F., Del Rosari G., Ureña A. Strength and Durability of Epoxy-Aluminum Joints. Journal of Adhesion. 2010; 86: 409–429.
52. Zhan X., Chen J., Gu Ch., Peng Q., Chen J., Wei Y. Study on effects of pre-treatment and surface roughness on tensile-shear strength of 2060 Al–Li alloy adhesive joints. Journal of Adhesion. 2017; 93: 613–625.
53. Boutar Y., Naïmi S., Mezlini S., Ali M.B.S. Effect of surface treatment on the shear strength of aluminium adhesive single-lap joint for automotive applications. International Journal of Adhesion and Adhesives. 2016; 67: 38–43.
54. Miturska-Barańska I., Rudawska A., Doluk E. The influence of sandblasting process parameters of aerospace aluminium alloy sheets on adhesive joints strength. *Materials.* 2021; *14*: 6626.
55. Xing Y., Yang S., Lu S., Zhang P., An Y., Zhai J. Effect of bonding parameters on compression mechanical properties of bi-directional corrugated honeycomb aluminum. Journal of Adhesion. 2022; 98: 348–366.
56. De Barros S., De Souza J.R., Gomes K.C., Sampaio E.M., Barbosa N.P., Torres S.M. Adhesion of geopolymer bonded joints considering surface treatments. Journal of Adhesion. 2012; 88: 364–375.
57. Flanagan J., Schütze P., Dunne C., Twomey B., Stanton,K.T. Use of a blast coating process to promote adhesion between aluminium surfaces for the automotive industry. Journal of Adhesion. 2020; 96: 580–601.
58. PN-EN 573-3:2019-12. Aluminium and aluminium alloys - Chemical composition and form of wrought products - Part 3: Chemical composition and form of products.
59. PN-EN 1706. Aluminium i stopy aluminium – Odlewy – Skład chemiczny i własności mechaniczne.
60. Folder of Chemical Ciech Grup. Available online at: http://ciechresins.com/files/katalogi/EPIDIAN_CATALOG_PL_PAGE_BY_PAGE.pdf (accessed on 20.12.2021).
61. Chemical Ciech Grup. Available online at: http://www.ciechzywice.pl/pl/produkty/chemia-organiczna/zywice/zywice-epoksydowe (accessed on 20.12.2021).
62. Available online at: https://www.alumetal-technik.com/scierniwa/elektrokorund-zwykly-brazowy (accessed on 03.11.2021).