THE INFLUENCE OF THE DIRECTIVITY OF THE GEOMETRIC STRUCTURE ON THE LOAD CAPACITY OF SINGLE-LAP ADHESIVE JOINTS

Wpływ kierunkowości struktury geometrycznej powierzchni na nośność połączeń klejowych

Władysław ZIELECKI ORCID 0000-0002-7864-5525
Łukasz BĄK
Ewelina GUŹLA ORCID 0000-0002-7359-6007

DOI: 10.15199/160.2021.2.6

A b s t r a c t: The aim of the work was to investigate the influence of the directivity of the geometric structure obtained in the grinding process on the load capacity of single-lap adhesive joints made of steel S235JR and aluminum alloy 2024-T3. The research was carried out for five different variants of joints differing in the direction of grinding and the arrangement of the ground surfaces to each other. The test results show that in the case of steel joints, the most advantageous solution in terms of joint load capacity is grinding the adhesive surfaces at an angle of 45˚ to the direction of the force loading the joint and connecting them in such a way that the created texture crosses (joint load capacity Pt = 4667.36 N). However, in the case of joints made of aluminum alloy, the best solution is to grind the adhesive surfaces perpendicular to the direction of the force loading the joint (joint load capacity Pt = 3210.46 N). The results of the significant difference test (test-t) show that in the assumed range of variability of the input parameters, the directionality of the geometric structure has a significant impact on the load capacity of the adhesive joints.

K e y w o r d s: surface roughness, directivity of the geometric structure, texture, adhesive joint

S t r e s z c z e n i e: Celem pracy było zbadanie wpływu kierunkowości struktury geometrycznej, uzyskanej w procesie szlifowania, na nośność jednozakładkowych połączeń klejowych wykonanych ze stali S235JR oraz ze stopu aluminium 2024-T3. Badania przeprowadzono dla pięciu różnych wariantów połączeń różniących się kierunkiem szlifowania i ułożeniem szlifowanych powierzchni klejonych względem siebie. Wyniki badań wskazują, że w przypadku połączeń ze stali, najkorzystniejszym rozwiązaniem pod względem nośności złącza jest szlifowanie powierzchni klejonych pod kątem 45˚ względem kierunku działania siły obciążającej złącze i sklejenie ich w taki sposób, aby utworzona tekstura się krzyżowała (nośność połączeń Pt = 4667,36 N). Natomiast w przypadku połączeń ze stopu aluminium, najkorzystniejszym rozwiązaniem jest szlifowanie powierzchni klejonych prostopadle względem kierunku działania siły obciążającej złącze (nośność połączeń Pt = 3210,46 N). Wyniki testu znaczących różnic (test-t) wskazują, że w przyjętym zakresie zmienności parametrów wejściowych, kierunkowość struktury geometrycznej ma istotny wpływ na nośność połączeń klejowych.

S ł o w a k l u c z o w e: chropowatość powierzchni, kierunkowość struktury geometrycznej, tekstura, połączenie klejowe

Introduction

Adhesive technology has many advantages. One of them is the ability to combine almost all materials. Adhesives makes it possible to connect even materials that differ significantly in thermal expansion coefficient or electric potential. As a result, adhesive technology is successfully used, among others, in the automotive industry to combine various materials into so-called hybrid structures with reduced weight. Examples of materials that are used in such automotive construction are aluminum alloys and steels [2].

The strength of adhesive joints depends on many factors. One of them is the condition of the surface layer of the joined elements. An integral part of the surface layer is the geometric structure of the surface, which is composed of surface roughness, among others. Surface roughness is a set of irregularities repeating periodically or non-periodically, for which the ratio of the average width of the elements to the average height of these elements is less than 40 [1, 22].

The relationship between the surface roughness and the strength of the adhesive joints results from the mechanical theory of adhesion. According to this theory, the adhesive penetrates the microporosity occurring on the surface of the joined elements and creates mechanical anchors that enable the transfer of loads [7, 9, 18].

The influence of surface roughness on the strength of adhesive joints has been analyzed in numerous studies [5, 6, ,10, 24, 25, 26, 27]. In the work [5] the influence of the surface roughness on the shear strength of adhesive bonds joined with the Araldite epoxy resin was analyzed. Some of the joints were made of AA6063 aluminum alloy and some of the mild steel AISI1045. As a result of the research, it was found that with the increase of the Ra (arithmetical mean height) parameter the strength of joints made of both aluminum alloy and steel initially increased. The initial increase in the strength of the joints with the increase in roughness resulted from enhancing the contact surface between the adhesive and the bonded material and formation mechanical anchors. After exceeding the optimum roughness value, the strength of the joints began to decrease due to the reduction of the surface wettability. The maximum strength values were obtained for Ra = 2.05 ± 0.19 for aluminum alloy and Ra = 1.98 ± 0.10 for steel.

In paper [24], a relationship between the load capacity of adhesive joints and surface roughness parameters measured in the two-dimensional (2D) system was analyzed. Adhesive joints made of S235JR steel were used for the tests. The adherents (substrates) surfaces were milled or milled with the following abrasive treatment with corundum. The joints were made using two different compositions which resulted in flexible and rigid joints. It has been shown that the parameters lr (roughness profile length coefficient), Rda (arithmetic mean slope of the roughness profile), Rdq (mean square roughness profile inclination) are strongly related to the strength of elastic joints and can be used to predict the shear strength of lap joints.

The authors of the work [25] examined the relationship between the strength of adhesive joints and the roughness parameters measured in the three-dimensional (3D) system. The tests were carried out for joints made of S235JR steel using the Epidian 5 composition with the PAC curing agent. According to the results of the analysis, the parameters SqSpd (root-mean square density of peaks), Spc (arithmetic mean peak curvature), Sdr (developed interfacial ratio) and Sdq (root-mean square gradient) had the strongest influence on the shear strength of the adhesive joints.

In [10] the substrates surfaces of joints made of 5054 aluminum alloy were milled. It was shown that the highest shear strength was obtained when the roughness parameters of the adherents' surfaces were Ra = 1.226 μm, Sa = 3.242 μm.

The object of work [27] was the finite element analysis of the influence of the surface geometric structure on the stress state in the adhesive joint. The authors of the study pointed out that the surface irregularities such as indentations may become stress concentrators in the adhesive joint. They showed that the degree of stress concentration increases with an increase in the mean spacing of profile elements RSm and an increase in the maximum height of the profile Rz.

The subject of many studies was also the assessment of the influence of various methods of substrates surface treatment (resulting in different values of surface roughness) on the strength of adhesive joints [8, 14, 19, 23]. In the study [14] the effect of five types of surface treatment on the strength of single-lap joints made of AA 6082-T6 aluminum alloy made with the use of epoxy resin was investigated. The following types of treatments were used in the research: sodium dichromate–sulphuric acid etch, abrasive polishing, caustic etch, Tucker's reagent etch and acetone cleaning. It was found that the highest strength was obtained in the case of etching with sodium dichromate and sulfuric acid and in the case of abrasive polishing. Moreover, under the assumed conditions, increasing the roughness of the substrates surface resulted in a decrease in the strength of the joints.

In the work [19], adhesive joints made of the titanium alloy Ti6Al4V were tested. The applied methods of treating the substrates surface were: anodizing, alkaline degreasing, anodizing with vibrational shot peening and vibratory shot peening. As a result of the research, it was found that higher strength is obtained in the case of anodizing combined with vibration peening than in the case of using each of these techniques separately. The study also pointed out that the properties of the adhesive (mainly viscosity) and the geometric structure of the substrates surface have a significant impact on the strength of the joints, which results from the mechanical theory of bonding. Higher bond strengths were observed with the more flexible adhesive.

Some methods of treating the substrates surface may, under certain conditions, reduce the strength of the adhesive joints. According to the results of the research presented in [23], polishing the substrates surface resulted in a decrease in the strength of adhesive joints made of Mg AZ31B with the use of epoxy adhesive (Lord Versilok 253/254). The authors of the study suggested that changes in the surface morphology and surface chemistry of Mg AZ31B could be the reasons for the reduction in joint strength.

The applied method of preparing the substrates surface can also largely affect the impact strength of the adhesive joints. In [8], the impact strength of connections made of 2017A aluminum alloy was examined. Two types of adhesives were used in the research. The substrates surfaces were subjected to roughening with sandpaper or abrasive blasting. The conducted research showed that the applied methods of surface machining allowed to increase the impact strength of the joints. It has also been shown that the impact strength of the joints was also influenced by the properties of adhesive (in particular, the adhesive longitudinal modulus of elasticity).

In addition to the surface roughness, another feature of the surface layer that can also affect the strength of the adhesive bonds is texture. Texturing is a well-known method of improving the tribological properties of mechanical components. One of the most obvious examples of the use of surface texturing is cylinder liner honing [3].

Currently, more and more studies are conducted on the influence of the texture on the strength of adhesive joints [4, 12, 13, 20, 21]. The authors of the work [4] investigated the effect of laser texturing on the strength of adhesive joints made of 30CrMnSiA steel. Three different patterns: dimple, groove and grid were performed on the substrates surfaces. It was shown that in the case of pits, the strength of the joints was not significantly improved. The samples with the groove and the grid increased the strength by 219% and 348%, respectively, compared to the samples whose surfaces were not texturized. Moreover, in the case of the grid pattern, the Ra value increased by 400% and the contact angle decreased from 65 degree to 24 degree.

The impact of the laser texturing on the mechanical behavior of the aluminium alloy 2024 adhesive joints was investigated in [21]. The authors of the study claim that the laser treatment of the adherents leads to comparable or even higher fracture energy values than a long sequence of mechanical, electrochemical and chemical treatment. What is more, the study also suggested that changes in the chemical composition occur on the treated surface as a result of laser treatment, may translate into the strengthening of interfacial bonds between the adhesive and the material.

In the work [12] a statistical optimization of the laser treatment process with a green fiber laser was carried out in order to improve the mechanical properties of adhesive joints of the aluminum alloy 2024.

The paper [20] showed an 80% increase in the strength of adhesive joints made of CFRP and epoxy adhesive as a result of CO_2 laser texturing. The positive effect of laser surface texturing on the load capacity of adhesive joints was also proven in the case of joining polymeric materials [13].

Summarizing, the surface roughness and texture may affect the strength of the adhesive bonds. Most of the research currently being conducted focuses on the analysis of the effect of laser texturing on the strength of adhesive joints. However, in addition to beam methods, mechanical methods, for example grinding, lapping or polishing, can also be used for texturing the surface layer. The aim of the research presented in this article was to assess the influence of the directivity of the geometric structure obtained in the grinding process on the load capacity of adhesive joints made of steel S235JR and aluminum alloy 2024-T3.

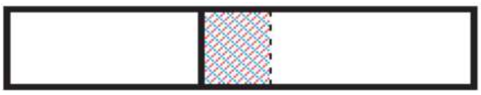
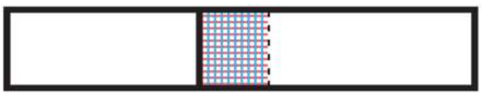
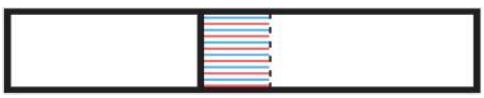
Methodology

The analysis was carried out for single-lap adhesive joints. The first group of connections was made of S235JR non-alloy structural steel. The chemical composition and properties of this steel can be found in the PN-EN 10025-1:2007 standard [15]. The second group of connections is made of the aluminum alloy 2024-T3. The chemical composition of this alloy and its basic properties are presented in the PN-EN 3997:2016-02 standard [17]. Steel plates and aluminum alloy plates were cut from a 2 mm thick rolled sheet.

The adhesive surfaces of the plates were ground in order to obtain the appropriate surface roughness and directivity. The grinding process was carried out with the use of a tool grinder EUROMET SN-200 (manufacturer - Eurometal Sp. z o.o, Poland) with a 80x30x6 mm P40 flap disc (manufacturer – Klingspor, Poland). The treatment was carried out at a rotational speed of 3000 rpm. The adopted grinding directions for individual pairs of the plates are presented in Table 1.

Residues left after the grinding process were removed with compressed air. Then, the plates were cleaned with

Table 1. Grinding directions and variants of the adhesive joints

Adhesive connection variant - steel S235JR	Adhesive connection variant - aluminum alloy 2024-T3	Grinding directions	Scheme
ST45	AL45	Post-machining marks at an angle of 45˚ to the direction of the force loading the joint on both joined surfaces	
ST45K	AL45K	Cross direction - post-machining marks at an angle of 45˚ to the direction of the force loading the joint on both joined surfaces	
STK	ALK	Cross direction – post-machining marks perpendicular on one joined surface, and parallel on the other	
STP	ALP	Perpendicular arrangement of the post-processing marks in relation to the direction of the force loading the joint	
STR	ALR	Parallel arrangement of the post-machining marks in relation to the direction of the force loading the joint	

acetone. The next stage of the research was to measure the surface roughness of the plates subjected to grinding. The parameters Rz (maximum peak to valley height of the profile within a sampling length), Ra (arithmetic mean of the absolute departures of the roughness profile from the mean line), RSm (mean spacing between profile peaks at the mean line) and Rda (arithmetic mean slope of the profile) were measured. The surface roughness was measured using a Taylor Hobson SURTRONIC 25 contact profilometer (manufacturer - Taylor Hobson, England) and TalyProfile Lite software.

Then, the surfaces of the plates were degreased with acetone. After the adhesive surface has dried, single-lap adhesive joints were made. The length of the overlap was 12.5 mm. The joining variants are shown in Table 1. The joints were created using the Loctite 3430 two-component epoxy adhesive (manufacturer – Henkel, Germany), which fills the gaps well, therefore it can be used on rough and poorly adhering surfaces [11]. The samples were placed in a mechanical clamping device and loaded with a one-kilogram weight. The cross-linking time was 48 hours. The cross-linking temperature ranged from 23±2˚C and the humidity was 35%.

The adhesive joints have been subjected to a static tensile test in accordance with PN-EN 1465:2009 (Adhesives - Determination of the shear strength of lap joints) [16]. The tests were carried out on the Zwick / Roell Z030 testing machine (manufacturer - Zwick Roell, Germany). The connections were loaded until they were broken. The breaking force was taken as the load capacity Pt [N] of the adhesive joint.

Results and discussion

Table 2 and Table 3 contain the mean values of the measured roughness parameters as well as selected surface profilograms and the corresponding photos of microstructures made with a microscope with 10x magnification.

As a result of machining with a 80x30x6 mm P40 flap disc, the geometric structure of the surface with unidirectional directivity was constituted. Based on Table

Table 2. Selected microstructures and profilograms of ground surfaces for S235JR steel

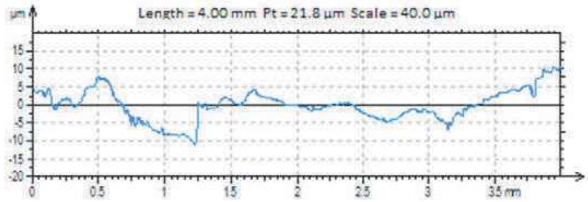
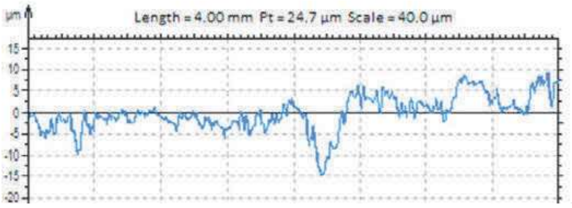
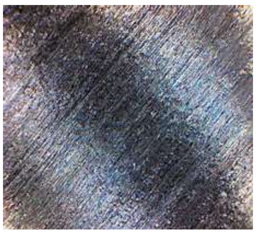
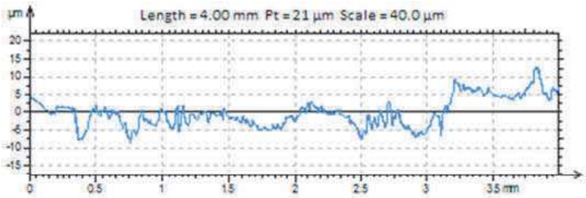
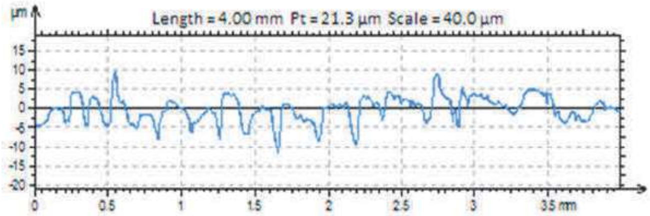
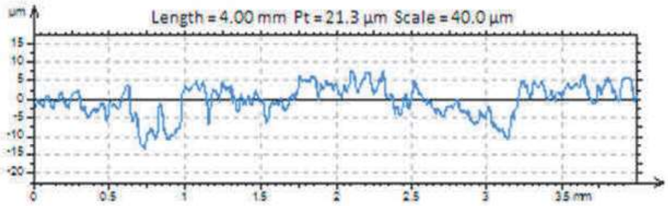
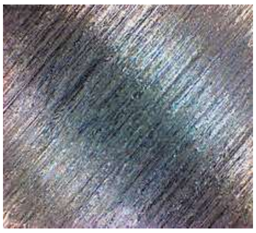
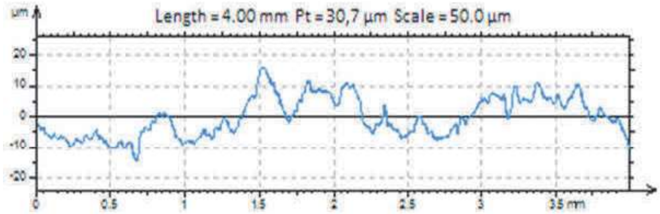
Parallel direction (S235JR steel)							
Rz [µm]	7.41	Ra [µm]	1.16	RSm [mm]	0.278	Rda [˚]	2.88
							
Perpendicular direction (S235JR steel)							
Rz [µm]	10.10	Ra [µm]	1.74	RSm [mm]	0.140	Rda [˚]	6.96
							
Post-machining marks at an angle of 45˚ (steel S235JR)							
Rz [µm]	9.60	Ra [µm]	1.52	RSm [mm]	0.137	Rda [˚]	6.13
							

Table 3. Selected microstructures and profilograms of ground surfaces for aluminum alloy 2024-T3

Parallel direction (aluminum alloy 2024-T3)							
Rz [µm]	14.4	Ra [µm]	2.32	RSm [mm]	0.193	Rda [˚]	6.39
							
Perpendicular direction (aluminum alloy 2024-T3)							
Rz [µm]	12.8	Ra [µm]	2.27	RSm [mm]	0.114	Rda [˚]	8.08
							
Post-machining marks at an angle of 45˚ (aluminum alloy 2024-T3)							
Rz [µm]	13.9	Ra [µm]	2.60	RSm [mm]	0.233	Rda [˚]	6.03
							

2, it can be concluded that in the case of steel S235JR the highest values of the Rz, Ra and Rda parameters were obtained for the surface that was ground perpendicular to the plate length (Rz = 10.1 µm, Ra = 1.74 µm, Rda = 6, 96˚). In turn, the highest value of the RSm parameter was obtained for the parallel direction (RSm = 0.278 mm). By analyzing the roughness parameters obtained for the samples from the aluminum alloy 2024-T3, it can be concluded that the highest value of the Rz parameter was obtained in the case of the parallel direction (Rz = 14.4 µm), the highest value of the Ra and RSm parameters was obtained for grinding at an angle of 45˚ (Ra = 2.60 µm, RSm = 0.233 mm), and the highest values of the Rda parameter were obtained for the perpendicular grinding direction (Rda = 8.08˚). Moreover, the aluminum alloy surfaces are characterized by much higher values of Rz and Ra parameters. The reason for the greater surface roughness of the aluminum alloy plates may be greater softness and better machinability of this alloy compared to the steel used in the tests.

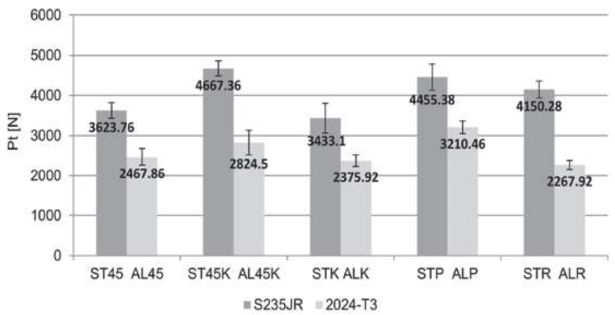


Fig. 1. Comparison of the load capacity of adhesive joints

The average values of the load capacity of adhesive joints and the standard deviations are presented in Figure 1.

The average values of the load capacity were calculated from the measurement results for five samples made for each material and joint variant. Based on the results of the load capacity of the adhesive joints, it can be concluded that the joints made of S235JR steel are

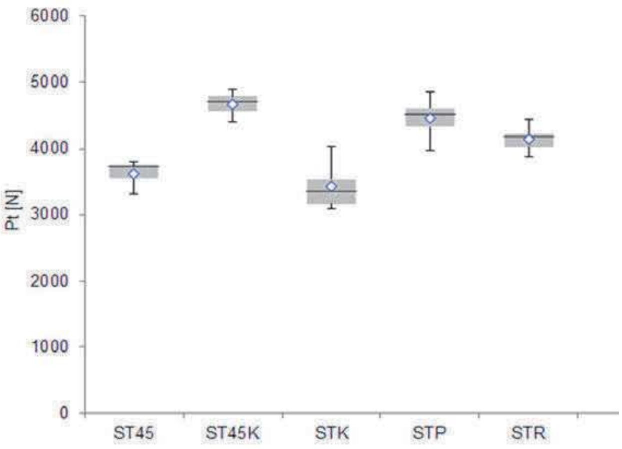


Fig. 2. Box plot - connections made of S235JR steel

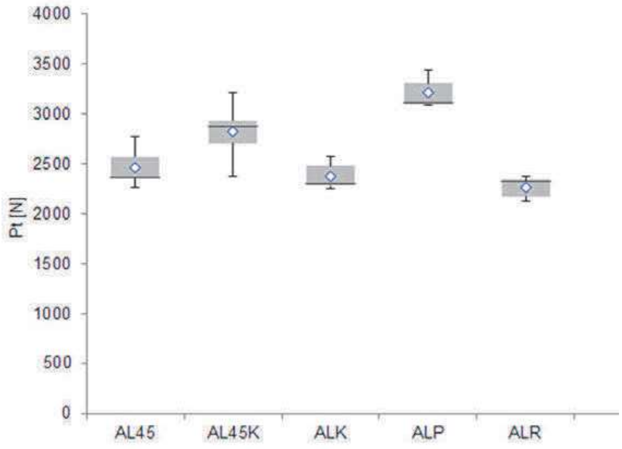


Fig. 3. Box plot - connections made of aluminum alloy 2024-T3

characterized by a much higher load capacity than the joints made of the aluminum alloy 2024-T3. Therefore, higher values of the roughness parameters Ra and Rz in the case of the aluminum alloy did not translate into a higher load capacity of the adhesive joint. In the case of steel connections, the STK45 variant has the highest load capacity (Pt = 4667.36 N) and, at the same time, the lowest value of the standard deviation. On the other hand, the STK variant had the lowest load capacity. In the case of aluminum alloy, the highest load capacity was observed for the ALP variant (Pt = 3210.46 N). The lowest load capacity and, at the same time, the lowest value of the standard deviation in the case of aluminum alloy connections were found for the ALR variant.

The normality of distribution of the data obtained from measurements of the load capacity was checked using the Shapiro–Wilk test. According to the test results, the data has a normal distribution.

Figures 2 and 3 show the box plots that were used to present the position and dispersion, as well as the shape of the distribution of the load capacity results.

Based on the box plots (Fig. 2 and Fig. 3), it can be concluded that in the case of steel adhesive joints, the STK variant is characterized by the greatest dispersion of the load capacity results. In the case of an aluminum alloy, the variant with the highest scattering of results is AL45K. Moreover, based on the diagrams, it can be assumed that the distribution of measurement results in the case of most variants is asymmetrical (for both steel and aluminum alloy adhesive joints). An example may be the STK variant, the graph of which may indicate right-hand asymmetry.

The next stage of the analyzes was performing the test-t, which made it possible analysis of significant differences between the load capacity of adhesive joints made of the 2024-T3 aluminum alloy and S235JR steel differing in the variants of the mutual arrangement of post-machining marks. Statistical significance α = 0.05 was assumed for the analyzes. The results of the significant difference test for steel connections are presented in Table 4, and for aluminum alloy connections in Table 5.

Based on Table 4 and Table 5, it can be concluded that the probability values pv are less than 5% in most

Table 4. Student's t-test results (S235JR steel)

Pv [%]	ST45	ST45K	STK	STP	STR
ST45	X				
ST45K	0.001	X			
STK	17.534	0.031	X		
STP	0.108	12.599	0.091	X	
STR	0.181	0.179	0.437	6.214	X

Table 5. Student's t-test results (aluminum alloy 2024)

Pv [%]	AL45	AL45K	ALK	ALP	ALR
AL45	X				
AL45K	3.469	X			
ALK	22.236	1.371	X		
ALP	0.015	2.359	0.001	X	
ALR	5.402	0.625	11.123	0.000	X

cases (probability values less than 5% are marked in red). This means that in most cases the results of the test-t show a statistically significant difference between the load capacity of the adhesive joints belonging to the compared variants (in the case of steel joints, the exceptions are the pairs STK and ST45, STP and ST45K, STR and STP, in the case of joints with of aluminum alloy, the pairs of ALK and AL45, ALR and AL45, ALR and ALK are an exception). Therefore, it can be concluded that in the adopted range of variability of the input factors, the influence of the directivity of the geometric structure of the adhesive surface on the load capacity of the joints is statistically significant.

Conclusions

1. Machining with a 80x30x6 mm P40 flap disc constituted the geometrical structure of the surface with unidirectional directivity. The height parameters of the surface roughness of the samples made of the 2024-T3 aluminum alloy had the value of Ra = 2.27 ÷ 2.60 μm and Rz = 12.4 ÷ 14.4 μm, while the samples made of S235JR steel, due to the greater hardness of the steel, had lower values Ra = 1.16 ÷ 1.74 μm and Rz = 7.4 ÷ 10.1 μm.
2. The highest load capacity of the adhesive joints made of 2024-T3 aluminum alloy, amounting to 3210.46 N, had the samples with perpendicular arrangement of the post-machining marks in relation to the direction of the force loading the joint. The lowest load capacity, amounting to 2267.92 N, had the samples with parallel arrangement of the post-machining marks in relation to the direction of the force loading the joint. The difference between the values of the load capacity is 41.5%.
3. The highest load capacity of adhesive joints made of S235JR steel, amounting to 4667.36 N, had the samples with the arrangement of post-machining marks at an angle of 45° to the direction of the force loading the joint. The lowest load capacity, amounting to 3433.10 N, had the joints whose marks on one of the plates was perpendicular, and on the other, parallel to the direction of the force loading the adhesive joint. The difference between the values of the load capacity is 35.9%.
4. The analysis of significant differences between the load capacity of adhesive joints made of the 2024-T3 aluminum alloy and S235JR steel differing in the variants of the mutual arrangement of post-machining marks, performed with the t-test, showed statistically significant differences between the majority of variants, which proves a significant influence of the directivity of the geometric structure of the surface on load capacity of adhesive joints.

References

[1] Adamczak S. 2008. Pomiary geometryczne powierzchni. Zarysy kształtu, falistość i chropowatość. Warszawa: Wydawnictwo Naukowo-Techniczne.

[2] Dilger K., Burchardt B., Frauenhofer M. 2018. "Automotive Industry". In da Silva L. F. M., Öchsner A., Adams R. D. (ed.) Handbook of Adhesion Technology, 1332-1366 . Springer International Publishing AG.

[3] Etsion I. 2005. "State of Art in Laser Surface Texturing". Journal of Tribology 127: 248-253.

[4] Feng Z., Zhao H., Tan C., Zhu B., Xia F., Wang Q., Chen B., Song X. 2019. "Effect of laser texturing on the surface characteristics and bonding property of 30CrMnSiA steel adhesive joints". Journal of Manufacturing Processes 47: 219–228.

[5] Ghumatkar A., Budhe S., Sekhar R., Banea M. D., de Barros S. 2016. "Influence of Adherend Surface Roughness on the Adhesive Bond Strength". Latin American Journal of Solids and Structures 13: 2356-2370.

[6] Grzesik W. 2016. "Prediction of the Functional Performance of Machined Components Based on Surface Topography: State of Art". Journal of Materials Engineering and Performance 25: 4460-4468.

[7] Kłonica M., Kuczmaszewski J. 2018. Badania stanu energetycznego warstwy wierzchniej wybranych materiałów konstrukcyjnych po ozonowaniu. Lublin: Wydawnictwo Politechniki Lubelskiej.

[8] Komorek A., Godzimirski J. 2018. "The influence of selected adhesive properties and the manner of surface preparation upon impact strength of block adhesive joints". Journal of KONES Powertrain and Transport 25: 463-469.

[9] Kuczmaszewski J. 2006. Fundamentals of metal--metal adhesive joint design. Lublin: Lublin University of Technology Polish Academy of Sciences, Lublin Branch.

[10] Liu S., Jin S., Zhang X., Chen K., Wang L., Zhao H. 2018. "Optimization of 3D surface roughness induced by milling operation for adhesive-sealing". Procedia CIRP 71: 279-284.

[11] Loctite 3430 technical data, http://elektronika.mcc.pl/system/files/1545/loctite-ea-3430.pdf [access: April 2021].

[12] Loutas T. H., Kliafa P. M., Sotiriadis G., Kostopoulos V. 2019. "Investigation of the effect of green laser pre-treatment of aluminum alloys through a design-of-experiments approach". Surface & Coatings Technology 375: 370–382.

[13] Mandolfino C., Pizzorni M., Lertora E., Gambaro C. 2018. „Laser surface texturing of polypropylene to increase adhesive bonding". AIP Conference Proceedings 1960: 060004.

[14] Pereira A.M., Ferreira J.M., Antunes F.V., Bártolo P.J. 2010. "Analysis of manufacturing parameters on the shear strength of aluminium adhesive single-lap joints". Journal of Materials Processing Technology 210: 610–617.

[15] PN-EN 10025-1:2007. Wyroby walcowane na gorąco ze stali konstrukcyjnych - Część 1: Ogólne warunki techniczne dostawy. Warszawa: Polski Komitet Normalizacyjny.

[16] PN-EN 1465:2009. Kleje - Oznaczanie wytrzymałości na ścinanie przy rozciąganiu połączeń na zakładkę. Warszawa: Polski Komitet Normalizacyjny.
[17] PN-EN 3997:2016-02. Lotnictwo i kosmonautyka - Stop aluminium AL-P2024- AlCu4Mg1 - T3 - Blachy i taśmy - 0,4 mm ≤ a ≤ 6 mm. Warszawa: Polski Komitet Normalizacyjny.
[18] Rudawska A. 2013. Wybrane zagadnienia konstytuowania połączeń adhezyjnych jednorodnych i hybrydowych. Lublin: Wydawnictwo Politechniki Lubelskiej.
[19] Rudawska A., Zaleski K., Miturska I., Skoczylas A. 2019. "Effect of the Application of Different Surface Treatment Methods on the Strength of Titanium Alloy Sheet Adhesive Lap Joints". Materials 12: 4173.
[20] Sorrentino L., Marfia S., Parodo G., Sacco E. 2020. "Laser treatment surface: An innovative method to increase the adhesive bonding of ENF joints in CFRP". Composite Structures 233: 111638.
[21] Spadro C., Sunseri C., Dispenza C. 2007. "Laser surface treatments for adhesion improvement of aluminium alloys structural joints". Radiation Physics and Chemistry 76: 1441–1446.
[22] Zaleski K., Matuszak J., Zaleski R. 2018. Metrologia warstwy wierzchniej. Lublin: Wydawnictwo Politechniki Lubelskiej.
[23] Zheng R., Lin J., Wang PC, Wu Y. 2016. "Correlation between surface characteristics and static strength of adhesive-bonded magnesium AZ31B". The International Journal of Advanced Manufacturing Technology 84: 1661–1670.
[24] Zielecki W. 2007. „Wpływ rozwinięcia struktury powierzchni na wytrzymałość zakładkowych połączeń klejowych". Technologia i Automatyzacja Montażu 2 i 3: 108: 111.
[25] Zielecki W., Pawlus P., Perłowski R., Dzierwa A. 2011. „Analiza wpływu struktury geometrycznej powierzchni w układzie 3D na wytrzymałość połączeń klejowych". Technologia i Automatyzacja Montażu 1: 33-37.
[26] Zielecki W., Pawlus P., Perłowski R., Dzierwa A. 2013. „Surface topography effect on strength of lap adhesive joints after mechanical pre-treatment". Archives of Civil and Mechanical Engineering 13: 175-185.
[27] Zielecki W., Zielecki K. 2010. „Analiza MES wpływu struktury geometrycznej powierzchni na stan naprężeń w spoinie klejowej". Technologia i Automatyzacja Montażu 4: 49-51.

dr hab. inż. Władysław Zielecki, prof. PRz
Wydział Budowy Maszyn i Lotnictwa Politechniki Rzeszowskiej , Katedra Technologii Maszyn i Inżynierii Produkcji
al. Powstańców Warszawy 8, 35-959 Rzeszów, Polska
e-mail: wzktmiop@prz.edu.pl

dr inż. Łukasz Bąk
Wydział Budowy Maszyn i Lotnictwa Politechniki Rzeszowskiej, Katedra Przeróbki Plastycznej
al. Powstańców Warszawy 8, 35-959 Rzeszów, Polska
e-mail: lbak@prz.edu.pl

mgr inż. Ewelina Guźla
Wydział Budowy Maszyn i Lotnictwa Politechniki Rzeszowskiej, Katedra Technologii Maszyn i Inżynierii Produkcji
al. Powstańców Warszawy 8, 35-959 Rzeszów, Polska
e-mail: e.guzla@prz.edu.pl