THE INFLUENCE OF THERMAL SHOCK ON THE LOAD CAPACITY OF CYLINDRICAL ADHESIVE JOINTS MADE OF EN AC-ALSI7-MG0.3 ALUMINUM ALLOY AND GLASS-EPOXY COMPOSITE EP405-GE

Wpływ szoków termicznych na nośność połączeń klejowych czopowych walcowych wykonanych ze stopu aluminium EN AC-AlSi7-Mg0.3 i kompozytu szkło-epoksyd EP405-GE

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Abstract: The aim of the work was to investigate the effect of thermal shocks on the load capacity of cylindrical adhesive joints. The adhesive joints are made of ENAC-AlSi7Mg0.3 aluminum alloy (sleeve) and glass-epoxy compositeEP405-GE (pivot). The elements were joined together with the Araldite 2014 adhesive composition. The thicknesses of the adhesive layer were 0.025 mm, 0.075 mm or 0.125 mm. The adhesive joints were subjected to 0, 50, 100 or 150 cycles of temperature changes. The maximum temperature was 60˚C and the minimum temperature was -20˚C. The results of the strength tests show that in the accepted range of variability of input factors, subjecting the joints to thermal shocks had a positive effect on their load capacity. The highest values of load capacity were observed for joints with 0.125 mm or 0.075 mm thick adhesive layer, which were subjected to 150 cycles of temperature changes. According to the results of the regression and correlation analysis, within the adopted range of input factors variability, the number of cycles of temperature changes has a statistically significant influence on the load capacity. It has been shown that the load capacity of adhesive joints increases with an increase in the number of cycles of temperature changes. Student's t-test shows that statistically significant differences in the load capacity of adhesive joints subjected to a different number of thermal shocks cycles occur in the case of variants: G075L0 (adhesive layer thickness 0.075 mm, number of cycles 0) and G075L150 (adhesive layer thickness 0.075 mm, number of cycles 150) and variants: G125L0 adhesive layer thickness 0.125 mm, number of cycles 0) and G125L150 (adhesive layer thickness 0.125 mm, number of cycles 150).

Keywords: thermal shocks, cylindrical adhesive joints, aluminum alloy EN AC-AlSi7-Mg0.3, glass-epoxy composite EP405-GE

Streszczenie: Celem pracy była ocena wpływu szoków termicznych na nośność połączeń klejowych czopowych walcowych. Złącza klejowe wykonano ze stopu aluminium ENAC-AlSi7Mg0,3 (tuleja) oraz kompozytu szkło-epoksydowego EP405-GE (czop). Elementy połączono ze sobą za pomocą kompozycji klejowej Araldite 2014. Grubości utworzonych spoin klejowych wynosiły 0,025 mm, 0,075 mm i 0,125 mm. Połączenia klejowe poddano 0, 50, 100 lub 150 cyklom zmian temperatury. Temperatura maksymalna wynosiła 60˚C, a minimalna -20˚C. Wyniki badań wytrzymałościowych wskazują, że w przyjętym zakresie zmienności czynników wejściowych, poddawanie złączy szokom termicznym miało pozytywny wpływ na ich nośność. Najwyższe wartości nośności zaobserwowano w przypadku złączy ze spoiną o grubości 0,125 mm i 0,075 mm, które poddano 150 cyklom zmian temperatury. Zgodnie z wynikami analizy regresji i korelacji, w przyjętym zakresie zmienności czynników wejściowych, liczba cykli zmian temperatury ma istotny statystycznie wpływ na nośność połączeń. Wykazano, że nośność złączy klejowych rośnie wraz ze wzrostem liczby cykli zmian temperatury. Test t-Studenta wskazuje, że istotne statystycznie różnice w nośności połączeń poddawanych różnej liczbie cykli zmian temperatury występują w przypadku wariantów: G075L0 (grubość spoiny 0,075 mm, liczba cykli 0) i G075L150 (grubość spoiny 0,075 mm, liczba cykli 150) oraz wariantów: G125L0 (grubość spoiny 0,125 mm, liczba cykli 0) i G125L150 (grubość spoiny 0,125 mm, liczba cykli 150).

Słowa kluczowe: szoki termiczne, połączenie klejowe czopowe walcowe, stop aluminium EN AC-AlSi7-Mg0,3, kompozyt szkło-epoksydowy EP405-GE

Introduction

Adhesive technology is used in many different industries. The popularity of adhesive joints results from their numerous advantages, including the possibility of joining elements made of various materials, good damping and sealing properties, no need to make holes and possibility of reducing the weight of the structure [6, 14, 17]. Nevertheless, adhesive joints also have some disadvantages. One of such disadvantages is the limited temperature resistance of adhesives [7].

The adhesives are of polymer nature. Therefore, the thermal properties of polymers influence the behavior of the adhesive joint at reduced, elevated or changing temperatures [4, 7]. Polymer materials (including adhesives) exposed to elevated temperatures are subject to the so-called thermal degradation. During degradation, macromolecules break down into smaller fragments. Increasing the cross-linking of the material structure in the initial stage of degradation may lead to an improvement in its strength properties. However, further degradation progress, resulting in a reduction of the molecular weight or excessive cross-linking of the structure, may contribute to the reduction of the material strength [18].

The phenomenon of increasing the strength of adhesive joints under the influence of elevated temperature was investigated in [20]. The analyzes were carried out on the joints formed with the use of the adhesive composition with the optimal curing agent content, the composition with the excess curing agent and the composition with the curing agent deficiency. The joints were subjected to additional heat treatment at the stage of forming the adhesive joints. It was shown that heat treatment contributed to an increase in the static strength of connections at ambient temperature, regardless of the curing agent content in the adhesive composition. It has also been proven that heat treatment of joints with an excess of curing agent resulted in a decrease in the static strength of joints operated at elevated temperatures. Therefore, the authors of the research concluded that heat treatment (reheating) cannot be treated as a universal method of increasing the strength of adhesive joints.

Not only high, but also low temperatures can significantly affect the properties of adhesives. It was proved in [19] that negative temperatures increase the brittleness of epoxy compounds. For this reason, adhesives that are used at low temperatures are generally more plastic than those intended for use at elevated temperatures [5]. It was shown in [12] that low temperatures increase the stiffness of adhesive joints, while high temperatures reduce it.

In practice, adhesive joints are most often exposed to cyclical temperature changes. The problem of thermal fatigue caused by thermal shocks has been the subject of various studies [8–11, 13].

The work [11] analyzes the effect of thermal loads on the shear strength of 316L steel single lap adhesive joints connected with Hysol 9484 and Hysol 3421 adhesives. The adhesive joints were subjected to 200 cycles of temperature changes. The minimum temperature was -40°C and the maximum 60°C. The conditioning time of the samples at each temperature was 15 minutes. According to the test results, subjecting the samples to thermal shocks reduced the mean value of the shear stress. The highest, 30% decrease in shear stress value was observed for joints connected with Hysol 9484 with mechanically processed adhesive surfaces.

Similar studies are presented in [9]. The adhesive joints of 316L steel, connected with Epidian 5 and Epidian 6 epoxy adhesives hardened with Z1 and PAC curing agents, were subjected to 200 cycles of temperature changes in the range from -40°C to 60°C. As a result of the research, it was found that the adhesive compositions with the PAC curing agent had the highest resistance to thermal shocks. In turn, the greatest decrease in the value of shear stresses in the aftermath of temperature changes was observed in the case of joints connected with the Epidian 5 + Z1 composition (about 50% decrease in shear stresses).

The subject of the work [8] was the analysis of the influence of cyclic temperature changes on the *Young's* modulus of adhesivecompositions based on Hysol 9466 and Hysol 3421 epoxy resin. The samples were subjected to 200 cycles of temperature changes. The minimum temperature was -40°C and the maximum 60°C. The author of the research showed that as a result of subjecting the samples to thermal shocks, the *Young's* modulus values decreased by 8% for Hysol 9466 and 20% for Hysol 3421.

The authors of the work [13] investigated the effect of thermal shocks on the interlayer adhesion of fiber-metal-laminate composites with a polymer-fiber layer used to make a glass fiber prepreg with a thermosetting epoxy matrix. The samples, depending on the variant, were subjected to 500 or 1000 cycles of temperature changes. The minimum temperature was -40°C and the maximum 60°C. It was observed that under the influence of thermal shocks the stiffness of the composite matrix and the strength of the interlayer adhesive joint decreased. It was found that differences in thermal expansion of composite components were the main reason for the reduction of the joint strength.

To sum up, the problem of the influence of thermal shocks on the strength properties of adhesive joints seems to be a very important issue in the design and operation of adhesive structures. In the literature, there are some analyzes concerning the influence of thermal shocks on the strength of adhesive joints. However, the results of these analyzes are partial and inconclusive. Moreover, most of the research was carried out on lap joints in which the same materials were joined together. Therefore, it is justified to conduct further research that would allow for a better understanding of the problem, explaining the mechanism of the phenomena, and most importantly, predicting the strength properties of adhesive joints subjected to thermal shocks. Therefore, the aim of the research presented in the article is to assess the impact of thermal shocks on the load capacity of cylindrical adhesive joints made of ENAC-AlSi7Mg0.3 aluminum alloy and glass-epoxy compositeEP405-GE. The adhesive joints examined in the article reflect the actual joints in composite overhead insulators. A more detailed description of the overhead composite insulators can be found in the works [3, 21]. This article is a continuation of the research presented in [21], which included the analysis of the effect of natural seasoning on the load capacity of cylindricaladhesive joints.

Methodology

The analysis of the impact of thermal shocks on the load capacity of adhesive joints was carried out for cylindrical joints. The sleeves were made of ENAC-AlSi-7-Mg0.3 aluminum alloy (Table 1). The pivots were made

Table 1. Chemical composition of ENAC-AlSi7Mg0.3 aluminum alloy [1]

Fe	Si	Mn	Ti	Cu	Mg	Zn	Others	
max 0.19	6.5 - 7.5	max 0.1	max 0.25	max 0.05	0.25 - 0.45	max 0.07	each 0.03; total 0.1	Al - balance

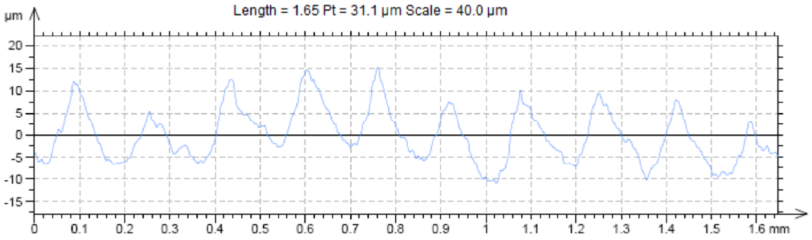
of EP405-GE glass-epoxy composite (manufacturer - KUVAG ISOLA Composites GmbH, Germany).

The two-component composition Araldite 2014 (manufacturer – Huntsman, Germany) was used to make the adhesive joints. Araldite 2014 is resistant to temperatures up to 120°C (248°F), exposure to different chemicals and water. It can be used for bonding ceramics, metals, GRP structures, electronic components and other elements exposed to an aggressive environment and elevated temperature. The curing of the Araldite 2014 composition takes place at room temperature [2].

The surfaces of pivots and sleeves were mechanically treated in order to develop the geometrical structure of the surface and, as a result, to increase the strength of adhesive joints between the adhesive and the adherends. The sleeve surfaces were turned on the LZ-360 universal lathe (manufacturer – Fabryka Maszyn Tarnów, Poland). The pivots surfaces were ground using a RUP-280 roller grinder (manufacturer – Fabryka Maszyn Tarnów, Poland) with an MVBE 45 grinding wheel with dimensions of 400x50x107 mm (manufacturer – Norton Saint-Gobain HPM Polska Sp. z o. o., Poland).

Then, the surface roughness of the adherends (sleeves and pivots) was measured. Measurements were carried out using an optical profilometerTalysurf CCI Lite (manufacturer –Taylor Hobson, England). The designations and the meaning of the surface roughness parameters were adopted in accordance with the PN-EN ISO 4287:1999standard [16].The results of the roughness measurements are presented in Table 2.

Table 2. Results of surface roughness measurements

<table>
<tr><th colspan="9">SLEEVE (turned)</th></tr>
<tr><td colspan="9">2Dparameters</td></tr>
<tr><td>Rp</td><td>Rv</td><td>Rz</td><td>Rc</td><td>Rt</td><td>Ra</td><td>Rq</td><td>Rsk</td><td>Rku</td></tr>
<tr><td>11.8 µm</td><td>7.51 µm</td><td>19.4 µm</td><td>17.7 µm</td><td>20.9 µm</td><td>4.64 µm</td><td>5.46 µm</td><td>0.579</td><td>2.00</td></tr>
<tr><td colspan="9">
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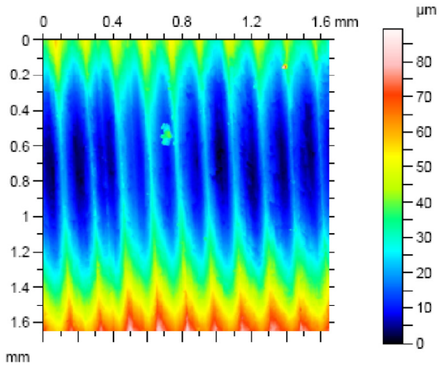
<tr><td colspan="9">3Dparameters</td></tr>
<tr><td colspan="2">Sq</td><td>Ssk</td><td>Sku</td><td>Sp</td><td>Sv</td><td>Sz</td><td colspan="2">Sa</td></tr>
<tr><td colspan="2">16.1 µm</td><td>0.853</td><td>3.10</td><td>63.1 µm</td><td>26.3 µm</td><td>89.5 µm</td><td colspan="2">13.0 µm</td></tr>
<tr><td colspan="9">
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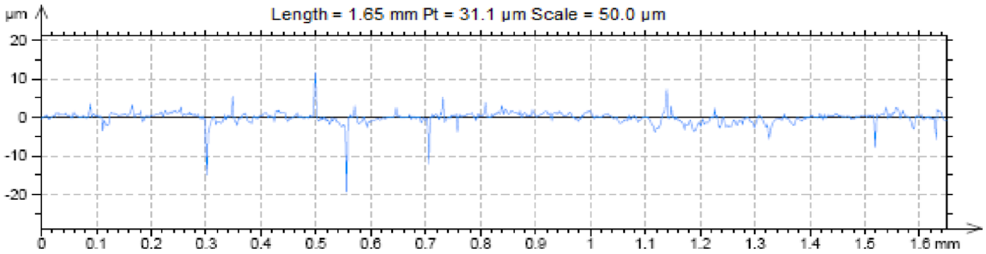
<table>
<tr><th colspan="9">PIVOT (ground)</th></tr>
<tr><td colspan="9">2Dparameters</td></tr>
<tr><td>Rp</td><td>Rv</td><td>Rz</td><td>Rc</td><td>Rt</td><td>Ra</td><td>Rq</td><td>Rsk</td><td>Rku</td></tr>
<tr><td>9.88 µm</td><td>8.75 µm</td><td>18.6 µm</td><td>4.16 µm</td><td>18.6 µm</td><td>0.599 µm</td><td>1.14 µm</td><td>0.635</td><td>29.4</td></tr>
<tr><td colspan="9">
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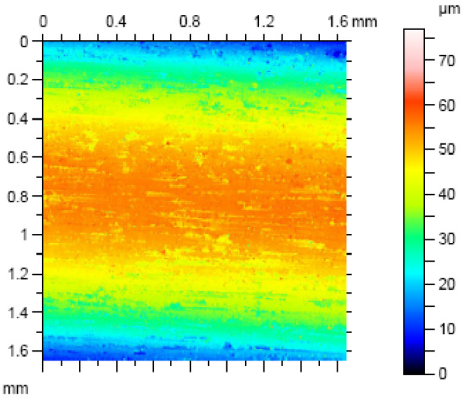
<tr><td colspan="9">3Dparameters</td></tr>
<tr><td colspan="2">Sq</td><td>Ssk</td><td>Sku</td><td>Sp</td><td>Sv</td><td>Sz</td><td colspan="2">Sa</td></tr>
<tr><td colspan="2">12.6 µm</td><td>-0.597</td><td>2.21</td><td>36.2 µm</td><td>40.8 µm</td><td>77.0 µm</td><td colspan="2">10.8 µm</td></tr>
<tr><td colspan="9">
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The next step was to degrease the surfaces of the adherends in order to remove grease contamination, dust and other machined residues that could weaken the connection. The pivots and sleeves were placed in an EMMI-40HC ultrasonic cleaner (manufacturer – EMAG, Poland) filled with acetone. After 5 minutes, the elements were removed from the washer and allowed to dry completely (the drying time was 5 to 10 minutes). The elements prepared in this way were bounded using the Araldite 2014 composition. A schematic drawing of the created cylindrical adhesive joints is shown in Figure 1.

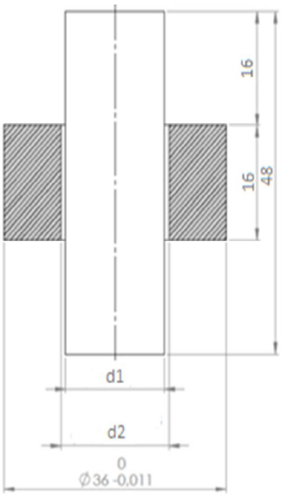

Fig. 1. Dimensions and shape of the cylindrical adhesive joints

The pivots diameter (d1) was 16-0.01 mm. The inner diameter of the sleeves (d2) was made in three dimensions: 16.05 mm, 16.15 mm, 16.25 mm so that it was possible to form joints with 0.025 mm, 0.075 mm or 0.125 mm adhesive layer thickness. The Araldite 2014 adhesive composition was applied to the inner surface of the sleeve and the central part of the pivot surface with a spatula. The sleeve was placed in the middle of the pivot. The sample prepared in this way was placed in a special device (jigging fixture).The device allowed to maintain the desired (coaxial) position of the joined elements and as a result the same thickness of the adhesive layer throughout the cross-section. The cross-linking process in the device was carried out for 48 hours at the temperature of 21 ± 1°C. The scheme of the device used is presented in Figure 2.

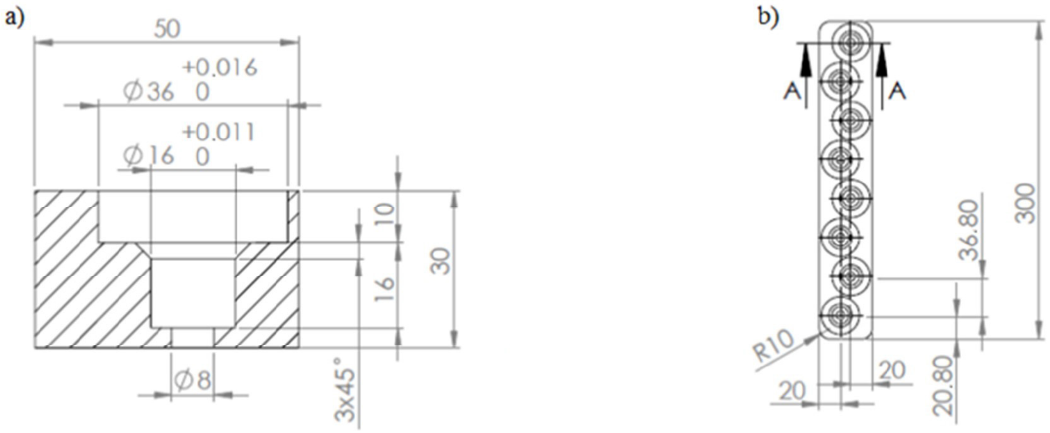

Fig. 2. Scheme of the device

The created adhesive joints were subjected to thermal shocks. For this purpose, the samples were alternately placed in a freezer (manufacturer – Electroline Equipment Inc, Canada) at a temperature of -20°C and in a vacuum dryer (model DZ-2BC II, manufacturer – Huanghua Faithful Instrument Co., LTD, China) at a temperature of 60°C. The samples were conditioned at each temperature for 30 min. Figure 3 shows the conditions of the conducted thermal shocks.

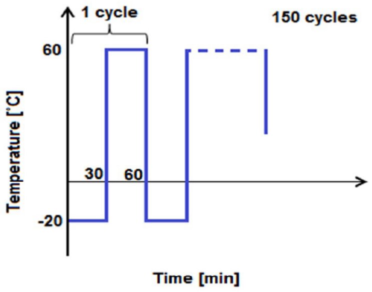

Fig. 3. Thermal shock conditions

After the samples were subjected to thermal shocks, 12 variants of adhesive joints were obtained. The variants differed in the number of cycles of temperature changes and the thickness of the adhesive layer. All variants are presented in Table 3.

The last step of the research was testing the strength of the cylindrical adhesive joints. The samples were subjected to an axial shear test on a Zwick/RoellZ100 testing machine (manufacturer: ZwickRoell GmbH & Co. KG, Germany). Figure 4 shows a sample placed in the handle of the machine.

Strength tests were carried out in accordance with the PN-EN ISO 10123: 2019-07 standard (Adhesives – Determination of shear strength of anaerobic adhesives using pin-and-collar specimens) [15]. During the tests, a test speed of 5 mm/min, initial force of 50 N and a maximum deformation of 15 mm were assumed

Table 3. Variants of the created cylindrical adhesive joints

Serial No	Adhesive layer thickness [mm]	Number of cycles of temperature changes	Variant
1.	0.025	0	G025L0
2.		50	G025L50
3.		100	G025L100
4.		150	G025L150
5.	0.075	0	G075L0
6.		50	G075L50
7.		100	G075L100
8.		150	G075L150
9.	1.125	0	G125L0
10.		50	G125L50
11.		100	G125L100
12.		150	G125L150

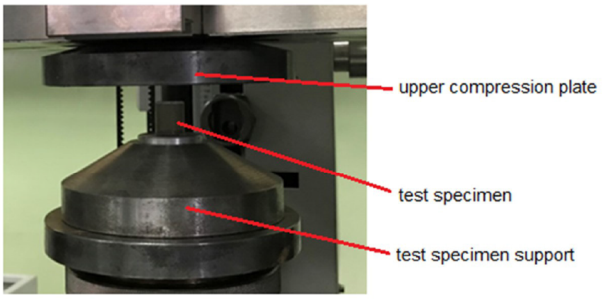

Fig. 4. The sample placed in the handle of the machine

Results and discussion

Table 4 and Figure 5 show the results of strength tests carried out for 12 variants of adhesive joints.

Table 4. Strength test results

Wariant	Loadcapacity – sample no 1	Loadcapacity – sample no 2	Loadcapacity – sample no 3	Loadcapacity – sample no 4	Loadcapacity – sample no 5	Loadcapacity – sample no 6	Loadcapacity – sample no 7	Loadcapacity – sample no 8	Loadcapacity – sample no 9	Loadcapacity – sample no 10	Loadcapacity – average	Range R=Pmax-Pmin	Standard deviation
	P_1 [N]	P_2[N]	P_3[N]	P_4[N]	P_5[N]	P_6[N]	P_7[N]	P_8[N]	P_9[N]	P_{10}[N]	$P_{śr}$[N]	R [N]	σ [N]
G025L0	25112.71	28023.37	22261.08	20604.80	21862.16	20862.19	23167.45	26328.75	27845.20	22107.59	23817.53	7418.57	2799.67
G025L50	27333.71	21565.68	22055.58	25590.38	25708.87	26043.79	26261.69	27695.24	18858.11	29161.20	25027.43	10303.09	3192.66
G025L100	20752.99	28458.72	23907.96	24486.44	25619.28	27828.39	27247.12	26070.27	23514.06	26041.39	25392.66	7705.73	2304.23
G025L150	23589.24	21148.52	26880.74	26886.57	23588.71	23527.38	23314.81	22106.06	21882.15	26352.29	23927.65	5738.05	2090.88
G075L0	26208.53	24758.36	26444.87	13230.16	25911.43	19236.50	24745.84	25439.84	21089.39	24998.15	23206.31	13214.72	4210.60
G075L50	23903.23	29265.31	24718.64	29869.88	27519.99	18522.98	22706.30	24040.49	24446.96	21657.13	24665.09	11346.90	3464.64
G075L100	19799.32	19745.32	28628.21	24614.85	26061.77	29102.76	23783.63	26340.85	30129.65	26223.56	25442.99	10384.33	3575.48
G075L150	26191.64	25277.76	31584.72	31247.82	25219.04	26907.70	27265.66	22708.88	21483.75	24512.64	26239.96	10100.98	3252.13
G125L0	23956.96	24619.43	26665.20	19890.89	26199.82	20003.17	24916.84	22182.02	26355.67	25792.23	24058.22	6774.31	2539.92
G125L50	27476.50	27998.86	27112.49	25474.86	26347.16	25012.62	21656.53	23330.69	25026.18	25993.08	25542.90	6342.33	1933.17
G125L100	27659.24	24712.40	24113.39	23554.22	27813.81	29879.01	26365.35	23702.57	21413.58	23194.78	25240.83	8465.43	2600.04
G125L150	29733.20	27063.86	23856.34	26531.96	28482.58	24581.49	26540.47	25965.29	25084.13	27225.79	26506.51	5876.87	1769.85

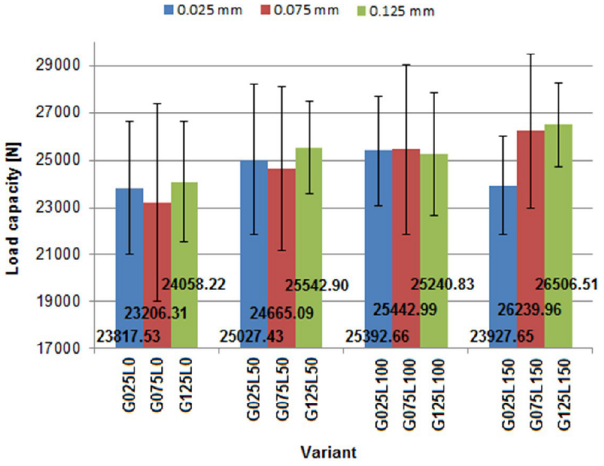

Fig. 5. Strength test results

Table 5. The results of the analysis of significant differences between the load capacity of adhesive joints with different adhesive layer thickness

Number of cycles	Compared variants		p [%]
0	G025L0	G075L0	35.370
	G025L0	G125L0	42.135
	G075L0	G125L0	29.598
50	G025L50	G075L50	40.531
	G025L50	G125L50	33.430
	G075L50	G125L50	24.776
100	G025L100	G075L100	48.532
	G025L100	G125L100	44.582
	G075L100	G125L100	44.339
150	G025L150	G075L150	**3.880**
	G025L150	G125L150	**0.413**
	G075L150	G125L150	41.161

Table 6. The results of the analysis of significant differences between the load capacity of joints with 0.025 mm thick adhesive layer, which were subjected to 0, 50, 100 and 150 cycles of temperature changes

p [%]	G025L0	G025L50	G025L100	G025L150
G025L0	X	18.984	9.351	46.090
G025L50		X	38.647	18.804
G025L100			X	7.699
G025L150				X

Table 7. The results of the analysis of significant differences between the load capacity of joints with 0.075 mm thick adhesive layer, which were subjected to 0, 50, 100 and 150 cycles of temperature changes

p [%]	G075L0	G075L50	G075L100	G075L150
G075L0	X	20.453	10.853	**4.460**
G075L50		X	31.361	15.427
G075L100			X	30.424
G075L150				X

Based on Table 4 and Figure 5, it can be concluded that the adhesive joints that have not been subjected to thermal shocks have the lowest load capacity. Adhesive joints with the same adhesive layer thickness, which were subjected to cyclical temperature changes, have a higher load capacity. Therefore, within the accepted range of variability of input factors, subjecting the adhesive joints to thermal shocks had a positive effect on their load capacity. The highest values of load capacity were observed for joints with 0.125 mm and 0.075 mm thick adhesive layer, which were subjected to 150 cycles of temperature changes. In the case of joints with 0.075 mm thick adhesive layer, it was noticed that the load capacity increases with an increase in the number of cycles. The increase in the load capacity of joints subjected to thermal shocks can be explained by the fact that high temperature could increase the cross-linking of the adhesive structure and stiffness of joints.

The results of the research on the influence of thermal shocks on the load capacity of cylindrical adhesive joints were statistically analyzed using the Student's t-test. Statistical significance α = 0.05 was assumed for the analyzes. Student's t-test was used to analyze significant differences between the load capacity of adhesive joints subjected to the same number of cycles of temperature changes, differing in the thickness of the adhesive layer. The results of the Student's t-test are presented in Table 5.

Based on Table 5, it can be seen that the probability values p are in most cases greater than 5%. Therefore, within the accepted range of variability of input factors, the compared variants of adhesive joints do not show statistically significant differences in terms of load capacity. Statistically significant differences in load capacity are revealed only between the pair G025L150 (adhesive layer thickness 0.025 mm, number of cycles 150) and G075L150 (adhesive layer thickness0.075 mm, number of cycles 150) and the pair G025L150 (adhesive layer thickness0.025 mm, number of cycles 150) and G125L150 (adhesive layer thickness 0.125 mm, number of cycles 150). This means that only in the case of these two pairs, the thickness of the adhesive joint has a significant influence on the load capacity of the adhesive joints.

Student's t-test was also used to analyze significant differences between the load capacity of adhesive joints with the same thickness of the adhesive layer, but with a different number of cycles of temperature changes. The analyzes were performed for joints with 0.025 mm (Table 6), 0.075 mm (Table 7) and 0.125 mm (Table 8) thick adhesive layer.

Table 8. The results of the analysis of significant differences between the load capacity of joints with 0.125 mm thick adhesive layer, which were subjected to 0, 50, 100 and 150 cycles of temperature changes

p [%]	G125L0	G125L50	G125L100	G125L150
G125L0	X	7.990	15.858	**1.179**
G125L50		X	38.589	13.014
G125L100			X	11.076
G125L150				X

On the basis of Table 6, it can be concluded that all p values are greater than 5%. Therefore, within the accepted range of variability of input factors, in the case of adhesive joints with 0.025 mm thick adhesive layer, the number of cycles of temperature changes does not have a significant effect on their load capacity. According to the results presented in Table 7, only when comparing the variants G075L0 and G075L150 the p value is less than 5%. This means that within the accepted range of variability of input factors, a statistically significant difference in load capacity occurs in the case of joints with 0.075 mm thick adhesive layer, which were not subjected to cyclic temperature changes or were subjected to 150 cycles of thermal shocks. A similar situation is observed in Table 8. According to the presented results, within the accepted range of variability of the input factors, a statistically significant difference in load capacity occurs only between joints with 0.125 mm thick adhesive layer, which were not subjected to thermal shocks or were subjected to 150 cycles of temperature changes.

Table 9. Results of the one-way analysis of varianceANOVA

Input variable	Output variable	p
Adhesive layer thickness (ALT)	Load capacity (P)	0.480
Number of thermal shock cycles (CN)	Loadcapacity (P)	0.057

The results of the strength tests were also subjected to the one-way analysis of varianceANOVA. This analysis was used to determine the extent to which the dependent variable (adhesive layer thickness or the number of cycles) affects the independent variable (load capacity). The results of the analysis are presented in Table 9.

The p values listed in Table 9. are greater than 0.05. This means that, according to ANOVA, both the thickness of the adhesive layer and the number of thermal shock cycles do not have a significant effect on the load capacity of the adhesive joints.

Subsequently, regression and correlation analysis was performed. The input factor was the thickness of the adhesive layer (ALT) or the number of thermal shock cycles (CN). The output factor was the load capacity of the adhesive joints. As a result of the conducted analyzes, regression equations were obtained. The equations show the relations between the load capacity and the adhesive layer thickness and between the load capacity and the number of thermal shock cycles. The calculated values of the Pearson's linear correlation coefficient (R) indicate the degree of linear dependence between the analyzed variables. The values of the determination coefficient R2 specify the percentage of changes in the output variable resulting from changes in the input variable. The results of the regression and correlation analysis are presented in Table 10.

Table 10. Results of regression and correlation analysis

Input variable	Output variable	Linearregressione quation	Pearson's correlation coefficient R	Coefficient of determination R^2	p_1	p_2	p_3
ALT	P	yP = 24325 +7958xALT	0.111	0.012	0.000	0.226	0.226
CN	P	yP = 24041 + 11.7 xCN	0.225	0.051	0.000	0.013	0.013

p_1 - probability value for the constant, p_2 - probability value for the coefficient for the adhesive layer thickness / number of cycles, p_3 - probability value for the regression equation

According to the results of the analysis presented in Table 10, the regression equation describing the relationship between the load capacity and the number of thermal shock cycles can be considered statistically significant ($p3<0.05$). Moreover, both the constant value and the value of the coefficient at the number of cycles have a significant influence on the result of the regression equation. The value of the Pearson linear coefficient indicates that the load capacity of adhesive joints increases with an increase in the number of thermal shock cycles. The regression equation describing the relationship between the load capacity of the joints and the adhesive layer thickness is not statistically significant ($p3> 0.05$). Therefore, the thickness of the adhesive layer does not significantly affect the load capacity of the adhesive joints.

Conclusions

1. In the adopted variability of input factors, subjecting the samples to thermal shocks contributed to the increase of the load capacity of the adhesive joints. The highest increase in load capacity, amounting to 13%, was observed in the case of joints with 0.075 mm thick adhesive layer, which were subjected to 150 cycles of temperature changes. The increase in the load capacity of joints subjected to thermal shocks can be explained by the fact that high temperature could increase the cross-linking of the adhesive structure and stiffness of joints.
2. The analysis of significant differences between the load capacity of adhesive joints with different adhesive layer thicknesses showed that within the adopted range of variability of the input factors, only joints with adhesive layer thickness of 0.025 mm and 0.075 mm, as well as, 0.025 and 0.125 mm, which were subjected to 150 cycles of temperature changes, differ significantly in terms of load capacity. Therefore, only in these two cases the thickness of the adhesive joint had a significant influence on the load capacity of the joints.
3. The analysis of significant differences between the load capacity of joints subjected to a different number of cycles of thermal shock showed that within the adopted range of variability of the input factors, statistically significant differences in load capacity occur only in the case of joints with 0.075 mm or 0,125 mm thick adhesive layer, which were not subjected to thermal shocks or were subjected to 150 cycles of thermal shock. Therefore, only in these cases the number of cycles of temperature changes had a significant impact on the load capacity of the adhesive joints.
4. According to the results of the regression and correlation analysis, the relationship between the load capacity of the adhesive joints and the number of cycles is statistically significant. The value of Pearson's linear correlation coefficient indicates that the load capacity of a connection increases with an increase in the number of cycles of temperature changes.

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