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THE INFLUENCE OF SHOT PEENING ON THE STRESS STATE IN THE ADHESIVE LAYER AND THE LOAD CAPACITY OF ADHESIVE JOINTS

WPŁYW PNEUMOKULKOWANIA NA STAN NAPRĘŻEŃ W SPOINIE KLEJOWEJ I NOŚNOŚĆ POŁĄCZEŃ KLEJOWYCH

Abstract

The aim of the article was to determine the influence of shot peening of the outer surface of the overlap on the stress state in the adhesive layer and the load capacity of single lap adhesive joints made of EN AW-2024-T3 aluminum alloy. Experimental investigations and numerical simulations were carried out. According to the results of experimental analyses, shot peening with balls with a diameter of 1 mm for 120 s with a compressed air pressure of 0.5 MPa increased the load capacity of the adhesive joints by 33%. Numerical simulations have shown that shot peening, by deforming the joined elements, reduces the stress perpendicular to the surface of the adhesive layer which results in a reduction of equivalent (von Misses) stress and an increase in strength of adhesive joints.

Keywords: adhesive joints, shot peening, load capacity, finite element method

Streszczenie

Celem artykułu było określenie wpływu pneumokulkowania zewnętrznej powierzchni zakładki na stan naprężeń w spoinie klejowej oraz nośność połączeń klejowych jednozakładkowych wykonanych ze stopu aluminium EN AW-2024-T3. W ramach badań przeprowadzono doświadczenia eksperymentalne i obliczenia numeryczne. Zgodnie z wynikami doświadczeń eksperymentalnych, pneumokulkowanie połączeń klejowych kulkami o średnicy 1 mm w czasie 120 s z ciśnieniem sprężonego powietrza wynoszącym 0,5 MPa przyczyniło się do wzrostu nośności połączeń klejowych o 33%. Obliczenia numeryczne wykazały, że pneumokulkowanie, poprzez odkształcenie klejonych elementów, zmniejsza naprężenia prostopadłe do powierzchni spoiny klejowej, co skutkuje zmniejszeniem jej wytężenia (naprężenień zredukowanych) i wzrostem wytrzymałości połączeń klejowych.

Słowa kluczowe: połączenia klejowe, pneumokulkowanie, nośność, metoda elementów skończonych

1. Introduction

Adhesive joints are commonly used in different industries and in many cases they are a good alternative to traditional mechanical connections. The advantages of adhesive joints include, among others, the possibility of reducing the weight of the structure, good sealing and damping properties, no need to make holes and the ability to combine various materials and elements of different thickness [4, 21]. The most popular type of adhesive joints is lap joint [18].

The shear stress distribution in the adhesive layer in single lap adhesive joint loaded in tension is not uniform. One of the reasons for the uneven stress distribution is the change in dimensions at the ends of the lap (geometric notch). Another reason for this phenomenon is the difference in plastic properties of the adhesive and the adherend [1, 2, 16, 18]. The maximum stresses occur at the ends of the lap. Therefore, efforts should be made to reduce these maximum stresses in order to increase the strength of the adhesive joints [8]. There are many methods that allow reducing the maximum stresses in the edge zone of the overlap. These include for example:

- using of an adhesive with ductile behavior and low modulus [8],
- leaving a flash of adhesive [23],

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- rounding adherends corners [7, 29],
- tapering the adherends [13, 14],
- sandblasting of the lap zone [10],
- shot peening of the lap zone [18, 30-32].

Shot peening is a dynamic burnishing method. In this cold-working technology, the workpiece surface is bombarded by steel balls which are propelled by a compressed air [19, 27]. The basic parameters of the shot peening are: ball diameter, processing time, compressed air pressure, total number of balls and the distance of the nozzle from the workpiece surface [30]. Shot peening is widely used in different industries to improve the fatigue life [5, 26, 28], to enhance the surface hardness and roughness [26] and to strengthen welded joints [6]. Moreover, as already mentioned, shot peening strengthens the adhesive joints.

The positive effect of shot peening on the strength of adhesive joints has been proven in several studies. In the paper [30] the effect of shot peening on the shear strength of S235JR steel adhesive joints was investigated. The adhesive joints were made with Epidian 5 composition with PAC hardener (flexible joint) and Epidian 5 composition with Z1 hardener (rigid joint). The time of the shot peening treatment was 60 s, the pressure was 0.35-0.55 MPa and the ball diameter was 2 mm. As a result of the shot peening, the strength of the samples with a flexible joint increased by 17–27% and the strength of the samples with a rigid joints increased by 93–112%.

The authors of the work [31] studied the effect of shot peening on the strength of adhesive joints made of 2024 aluminum alloy. The treatment parameters were: ball diameter (2-2.5 mm), time (60-180 s) and pressure (0.2-0.3 MPa). It was shown that as a result of shot peening, the load capacity of the adhesive joints increased by 3.6-20.3%.

According to the results presented in the paper [32], shot peening treatment contributed to the increase in the strength of the adhesive joints of Ti6Al4V titanium alloy by 42-63%. The process was carried out with a constant pressure (0.6 MPa) and a constant ball diameter (1.5 mm). The time was varied in the range of 10-30 s. It was shown that the load capacity of the joints increases as the time increases.

The influence of various factors on the strength of adhesive joints can be analyzed not only experimentally, but also with the use of numerical analyzes. The usefulness of the finite element method (FEM) for calculating the strength of adhesive joints was checked in [12]. The authors of the study pointed out that numerical calculation of adhesive joints in the linear elastic range are not useful for predicting their strength because most adhesives exhibit non-linear properties. According to the authors' observations, the actual characteristics of stress-strain curve should be taken into account when forecasting the strength of adhesive joints.

The authors of the work [11] compared two methods of modeling the adhesive layer in adhesive joints in FEM calculations. The first method was based on modeling the joints with solid elements, and the second method - with cohesive elements. It was found that the use of cohesive elements simplifies the modeling of adhesive joints. Nevertheless, this method is more suitable for an analysis of adhesively bonded structures than for an analysis of adhesive layer strength

The finite element method was also used to analyze the effect of surface roughness on the stress state in the adhesive layer [35], the length of the overlap on the strength of adhesive joints [9], as well as the impact of shot-peening on the stress state in the adhesive joint [30, 33].

The papers [30, 33] explain the mechanism of strengthening adhesive joints using the shot peening method. As a result of the numerical simulations it was shown that under the influence of shot peening, compressive residual stresses are introduced into the outer layer of the lap surface. Under the influence of these stresses, the edge of the lap is deformed and pressed against the bonded material. As a result, the tensile, peel and principal normal stresses are reduced, which in turn translates into an increase in the strength of the adhesive joints (fig. 1).

The analysis of the available literature shows that shot peening can be successfully used as a method of strengthening lap adhesive joints. Therefore, it is justified to conduct further research focused on better understanding of the mechanism of this phenomenon, and thus its better use in industry. Therefore, the aim of the research presented in the article was to expand the current state of knowledge by carrying out experimental analyzes which allowed to determine the impact of shot peening on the load capacity of single lap adhesive joints made of sheets of EN AW-2024-T3 aluminum alloy. Moreover, a numerical simulation was carried out in order to assess the impact of shot peening of the lap zone on the stress state in the adhesive layer. The research presented in this article is a continuation of the research presented in [34].

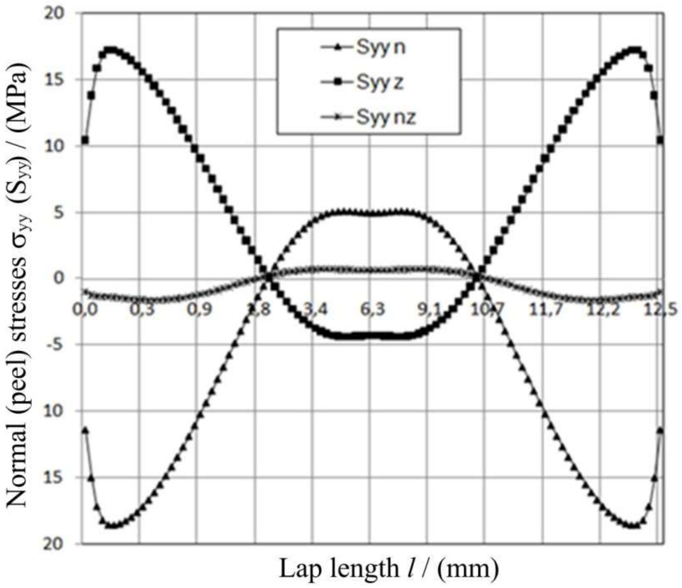

Fig. 1. The distribution of normal (peel) stresses σ_{yy} (S_{yy}) in the middle layer of the adhesive joints: n – shot peened joints, z – joints loaded with external force P = 2000 N, nz – joints shot peened and loaded with external force P = 2000 [30]

2. Material and methods

The first stage of the research involved carrying out experimental analyzes, aimed at determining the impact of shot peening on the load capacity of single lap adhesive joints made of EN AW-2024-T3 aluminum alloy sheets. The chemical composition of the EN AW-2024-T3 aluminum alloy is shown in Table 1.

Table 1. Chemical composition of EN AW-2024-T3 aluminum alloy in wt.% [3]

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	V	Inne*	Al
max 0,50	max 0,50	3,8 - 4,9	0,30 - 0,90	1,2 - 1,8	max 0,10	-	max 0,25	max 0,15	-	max 0,05	remaining
* Others, total ≤ 0,15%											

The bounding process started with the preparation of the adherend surface of the samples. In order to properly develop the geometric structure and increase the strength of adhesive joints, the surfaces were submitted to abrasive blasting with 95A electrocorundate (granulity of 0.27 mm) using a New-Tech sandblasting cabinet (New-Tech, Wrocław, Poland). The treatment was carried out for 30 s. The applied pressure was 0.7 MPa. The distance of the nozzle from the treated surface was about 0.07 m. The average values of the selected roughness parameters of the adherend surface after abrasive blasting were respectively: Ra = 4.53 µm, Rz = 25.95 µm, Rq = 5.67 µm, Rku = 2.99, RSm = 0.141 mm. The measurements were performed with a Taylor Hobson SURTRONIC 25 contact stylus profilometer and TalyProfile Lite software. The evaluation length was 12.5 mm. The measurements were performed in accordance with the PN-EN ISO 4287:1999 standard [31]. Fig. 2 shows a profilogram of the surface after abrasive blasting.

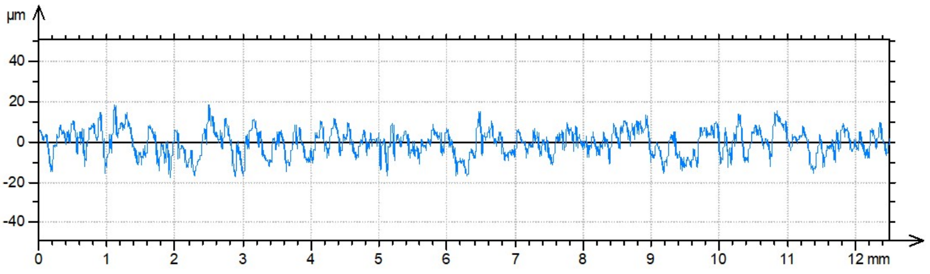

Fig. 2. Profilogram of the adherend's surface after abrasive blasting

After abrasive blasting, the adherents' surfaces were degreased in order to remove grease contamination and dust residues. Degreasing was performed with acetone.

The next step was to create single lap adhesive joints. The joints were made using the Loctite EA 3430 two-component epoxy adhesive (Loctite, Düsseldorf, Germany), which is suitable for joining poorly adhering or rough wooden, metal, ceramic or plastic surfaces [20]. After measuring the resin and hardener (in an amount not exceeding 20 g), the products were mixed together by hand for about 15 seconds. The ratio of epoxy resin to hardener was 1:1. The mixed adhesive was applied to both adherents' surfaces using a comb device. The air temperature during the preparation and crosslinking of the adhesive was 22 ±1°C, while the air humidity was 50%. The created adhesive joints were placed in the mechanical device and loaded with a constant force using one-kilogram weights. The adhesive connections were kept in the mechanical device (Fig. 3) for 3 days (62 hours). Figure 4 shows a scheme of the resulting adhesive connections.

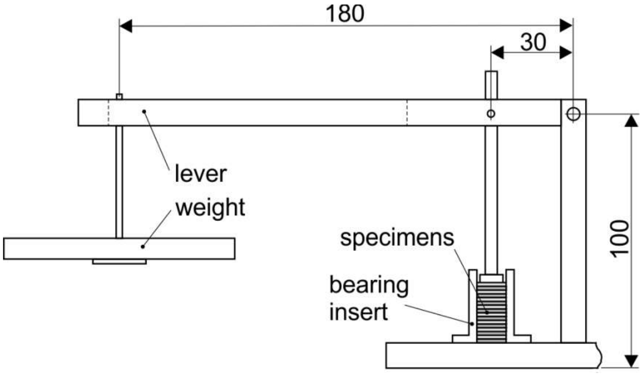

Fig. 3. The samples placed in a mechanical device (units in mm)

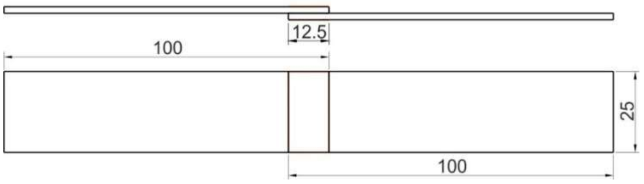

Fig. 4. The scheme of the adhesive joint

In total, 8 lap adhesive joints were made. The overlap lengths in the prepared adhesive connections were 12.5 + 0.1 mm.

The outer surface of the overlaps of the adhesive joints was then subjected to the shot peening. The device used for shot peening consisted of a working chamber closed with a lid. At the bottom of the working chamber, steel balls with a diameter of 1 mm were placed. The balls were propelled by a stream of compressed air supplied to the working chamber by a set of nozzles. The compressed air pressure was 0.5 MPa. The speeding balls hit the workpiece attached to the inside of the lid. The distance between the nozzle and the treated surface was 100 mm. Both sides of the adhesive joint overlap were shot peened. The processing time for one side of the overlap was 120 s. Only the overlap zone was shot peened. The remainder of the sample was protected using covers. The scheme of shot peening is shown in Fig. 5.

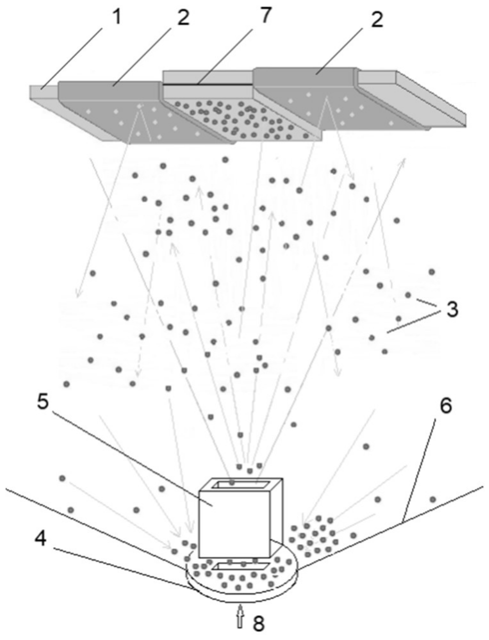

Fig. 5. Illustration of the shot peening process: 1 – specimen, 2 – cover, 3 – steel balls, 4 - compressed air nozzle, 5 – de Laval nozzle, 6 – bottom of the working chamber, 7 – adhesive, 8 – compressed air supply [17]

The adhesive joints subjected to and not subjected to shot peening were assessed in terms of their load capacity. For this purpose, a static tensile test was carried out in accordance with PN EN 1465:2009 [24]. The test was carried out using a ZWICK/ROELL Z100 testing machine (Zwick/Roell, Ulm, Germany). The samples were loaded with an axial force with a speed of 5 mm/min. The force at which the adhesive joint broke was considered as the load capacity of the adhesive joint Pt [N].

The second stage of the research was to carry out numerical simulations. The purpose of the simulations was to assess the impact of shot peening of the overlap zone on the stress state in the adhesive joint. Numerical calculations were performed in the Ansys 16.2 simulation software. The adopted model dimensions were as shown in Fig. 4. The information related to the data necessary to perform the numerical analysis was adopted on the basis of the authors' experience. The assumed thickness of the adhesive layer was 0.2 mm. As part of the numerical analysis, the stress state in the adhesive joints subjected to and not subjected to the shot peening process was compared.

As mentioned in the introduction to the article, shot peening of thin sheets introduces compressive stresses into their surface layer and causes plastic deformation of the sheets. This deformation can be described by the value of the deflection arrow f_A [mm]. In order to model the shot peening effect of adhesive joints in the Ansys program, the value of the deflection arrow for the shot peened EN AW-2024-T3 aluminum alloy sheet was determined. The sheet was subjected to shot peening with the following input parameters: ball diameter 1 mm, processing time 120 s, compressed air pressure 0.5 MPa. Only one side of the sheet was processed. The deflection arrow was measured with an Almen TSP TSP-3B plate deflection tester (Electronics Inc., Mishikawa, IN, USA). The measured value of the deflection arrow was 0.183 mm.

The next step was creating a numerical model of a single lap adhesive joint subjected to shot peening. It was assumed that the sheet in the model consisted of two layers with different thermal expansion. The thickness of the first layer (shot peened/with visible shot peeling effects) was 0.15 mm and its linear expansion coefficient was $7\ 10^{-5}$ 1/K. The second layer (non-shot peended/ without visible shot peening effects) was 1.85 mm thick and had a linear expansion coefficient of $5\ 10^{-5}$ 1/K. In order to model the effect of shot peening, the sheet was subjected to an elevated temperature of 325°C. As a result of the high temperature, the sheet was deformed. The deflection arrow of the deformed sheet was 0.183 mm (Fig. 6).

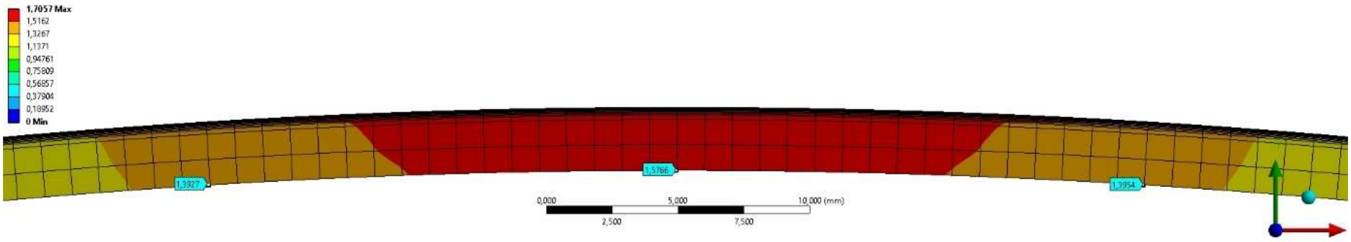

Fig. 6. Model of the sheet deformed in the results of shot peening

The thickness of the adhesive layer assumed in the model was 0.2 mm. In order to ignore the influence of temperature, it was assumed that the linear expansion coefficient of the adhesive was the same as that of the second layer ($5\ 10^{-5}$ 1/K). The adhesive's modulus of elasticity was 2000 MPa

With the aim of investigating the influence of shot peening on the stress state in adhesive joints, numerical analyzes were carried out:

- for the model of an adhesive joint loaded with a tensile force of 4000 N (adhesive joint not subjected to shot peening),
- for the model of an adhesive joint loaded with a tensile force of 4000 N and additionally subjected to elevated temperature (325°C) in order to model the effect of shot peening (adhesive joint subjected to shot peening).

3. Results

The results of experimental tests carried out in order to determine the effect of shot peening on the load capacity of single lap adhesive joints made of EN AW-2024-T3 aluminum alloy are presented in Table 2. The mean load capacity of the connections was determined on the basis of 8 samples and the confidence interval 1-α = 0.95 was calculated.

Table 2. The results of experimental tests and the results of additional calculations for the adhesive joints subjected to and not subjected to shot peening

Variant	The results of measurements of the load capacity of adhesive joints P_t, N								Average value of the load capacity	Standard deviation
	P_{t_1}	P_{t_2}	P_{t_3}	P_{t_4}	P_{t_5}	P_{t_6}	P_{t_7}	P_{t_8}	$\overline{P_t}$, N	σ, N
With shot peening	9553	7483	9273	9653	9237	10507	10815	9024	9443±791	946
Without shot peening	8163	6164	6110	6535	7959	8396	7938	5372	7080±907	1084

On the basis of the results of experimental tests presented in Table 2, it can be concluded that the load capacity of shot peened adhesive joints is higher than the load capacity of untreated adhesive joints. Shot peening of the overlap zone allowed increasing the load capacity of adhesive joints by 33%.

The results of numerical calculations carried out in order to determine the stress distribution in the adhesive layer of the joints subjected to and not subjected to shot peening are shown in Figures 7-14. The maximum values of the analyzed stresses are summarized in Table 3.

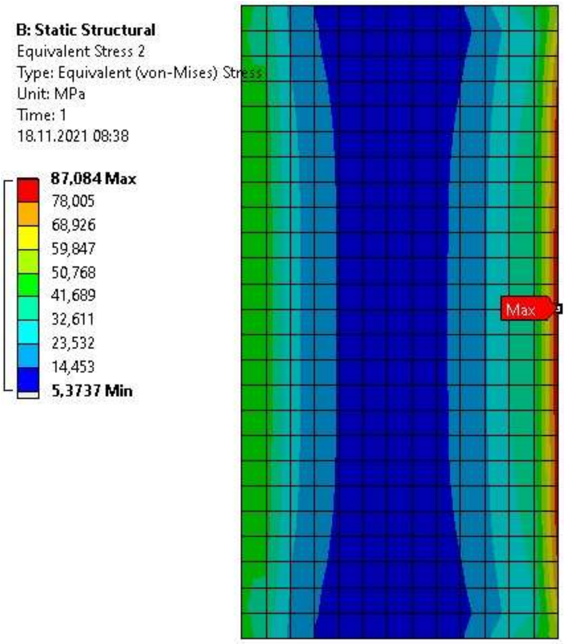

Fig. 7. Von Misses stress in the adhesive layer – without shot peening (load 4000 N)

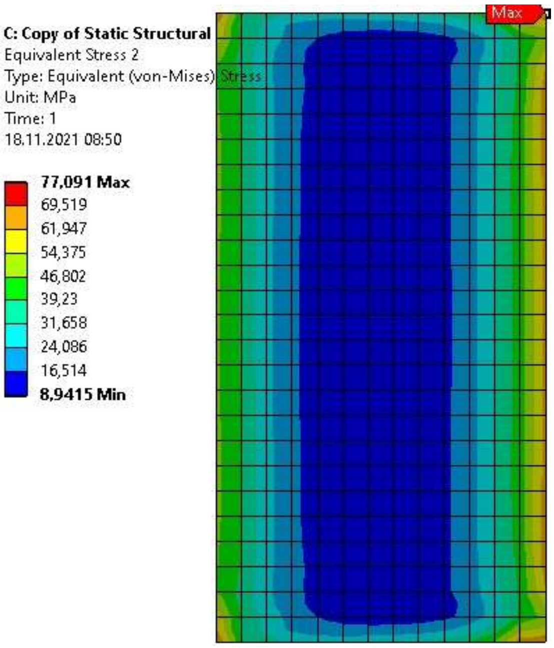

Fig. 8. Von Misses stress in the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

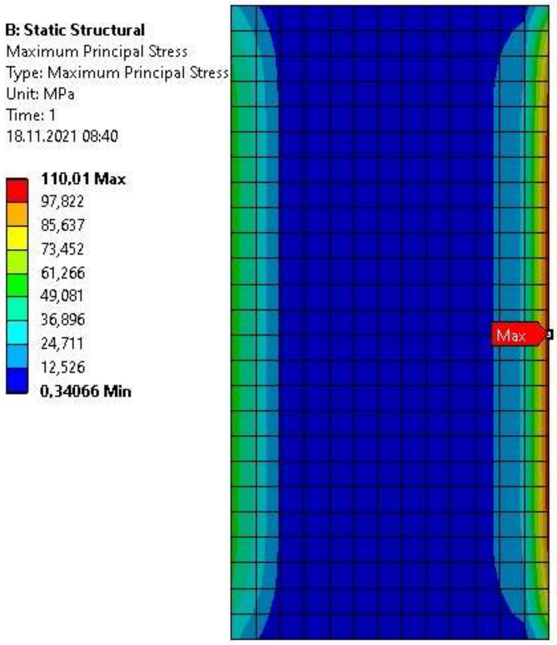

Fig. 9. Maximum principal stress in the adhesive layer – without shot peening (load 4000 N)

Fig. 10. Maximum principal stress in the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

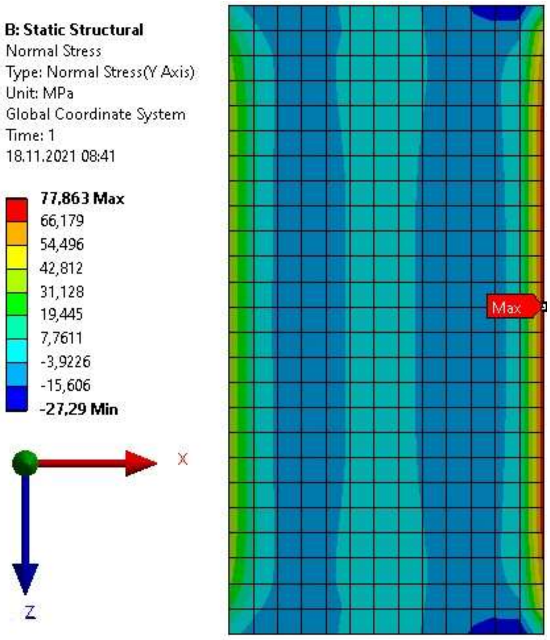

Fig. 11. Normal stress perpendicular to the adhesive layer – without shot peening (load 4000 N)

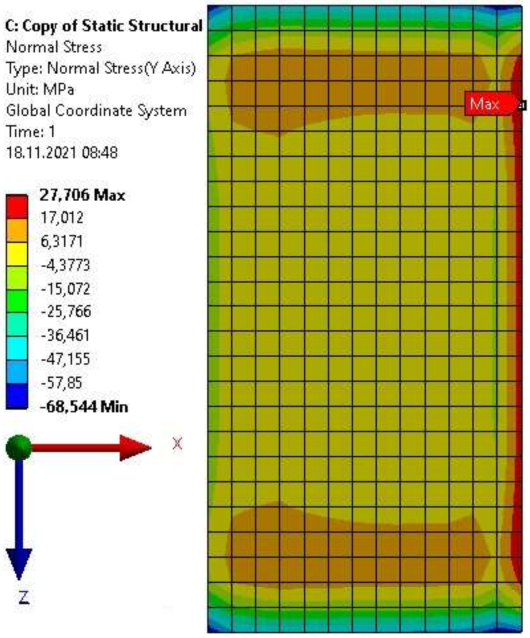

Fig. 12. Normal stress perpendicular to the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

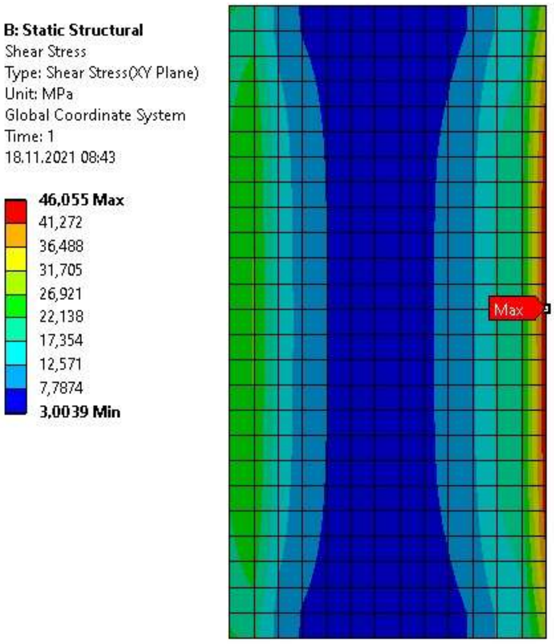

Fig. 13. Shear stress in the adhesive layer – without shot peening (load 4000 N)

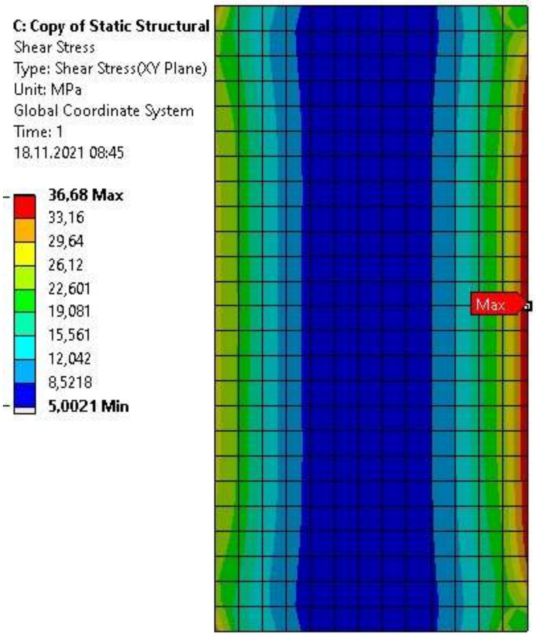

Fig. 14. Shear stress in the adhesive layer – with shot peening (load 4000 N, temperature 325°C)

Table 3. The values of maximum stresses in the adhesive joints

Stress, MPa	Adhesive joint not subjected to shot peening (load 4000 N)	Adhesive joints subjected to shot peening (load 4000 N, temperature 325°C)	Stress value decrease, %
von Misses	87.08	77.09	11
maximum principal	110.01	61.96	44
normal perpendicular to the adhesive layer	77.86	27.71	64
shear	46.05	36.68	20

According to the results of numerical calculations, shot peening of the adhesive joint overlap causes deformation of the joined elements and leads to a reduction in the value of the analyzed stresses. The biggest decrease in the stress value, amounting to 64%, occurred in the case of normal stresses perpendicular to the adhesive layer. Reducing the value of normal perpendicular stresses results in a reduction of equivalent (von Misses) stress and an increase in strength. The results of the performed numerical analyzes are of qualitative and not quantitative importance. Linear properties of the adhesive and adherents were assumed.

4. Conclusions

1. The results of the research show that shot peening can be successfully used to strengthen the adhesive joints (in the adopted range of variability of input factors). The load capacity of the adhesive joints shot peened with the following input parameters: ball diameter 1 mm, processing time 120 s and compressed air pressure 0.5 MPa is higher than the load capacity of the non-processed adhesive joints. Shot peening of the overlap zone allowed increasing the load capacity of adhesive joints by 33%.

2. The results of numerical simulations show that shot peening of the outer surface of the lap leads to a reduction of stresses in the adhesive layer. The biggest decrease in the stress value, amounting to 64%, occurred in the case of normal stresses perpendicular to the adhesive layer. The maximum principal stresses decreased by 44%, the shear stresses by 20%, and the von Misses stresses by 11%.

3. Due to shot peening of the outer surface of the adhesive joint overlaps, the joined elements deform plastically (the overlap edge is pressed against the adherend). The resulting deformation generates compressive stresses in the adhesive layer. Adding up the stresses resulting from deformation and external load causes that the stresses in the adhesive layer in adhesive joints subjected to shot peening are up to 64% lower than the stresses in the adhesive layer of joints not subjected to the treatment.

Bibliography

[1] Aimmanee S., Preeda H. 2017. “Stress analysis of adhesive-bonded tubular-coupler joints with optimum variable-stiffness-composite adherend under torsion”. Composite Structures 164: 76–89. https://doi.org/10.1016/j.compstruct.2016.12.043

[2] Ashcroft I.A., Mubashar A. 2018. Numerical approach: Finite element analysis. In da Silva L.F.M., Öchsner A., Adams R. (eds.) Handbook of Adhesion Technology, 701–740. Springer-Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-319-55411-2_25

[3] ASTM B209-96. Standard specification for aluminium and aluminium-alloy sheet and plate. ASTM International, West Conshohocken, PA, USA, 1996.

[4] Bretuj W., Wieczorek K. 2016. „Zachowanie się układu hybrydowego izolatorów kompozytowego i ceramicznego w warunkach eksploatacyjnych”. Przegląd elektrotechniczny 10: 171-174.

[5] Bucior M., Gałda L., Stachowicz F., Zielecki W. 2016. “The effect of technological parameters on intensity of shot peening proces of 51CrV4 steel”. Acta Mechanica et Automatica 10(3): 213-217.

[6] Bucior M., Zielecki W., Kubit A. 2017. “Construction of heads for strengthening of plate and butt-welded joints with pneumatic shot peeing methods”. Technologia i Automatyzacja Montażu 4: 32-36.

[7] Calik A. 2016. “Effect of adherend shape on stress concentration reduction of adhesively bonded single lap joint”. Engineering Review 36: 29–34.

[8] da Silva L.F.M., Marques E.A.S., Campilho R.D.S.G. 2018. Design rules and methods to improve joint strength. In da Silva L.F.M., Öchsner A., Adams R. (eds.) Handbook of Adhesion Technology, 773–810. Springer-Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-319-55411-2_27

[9] Domińczuk J. 2013. „Model numeryczny pozwalający na ocenę wpływu długości zakładki na wytrzymałość połączeń klejowych”. Technologia i Automatyzacja Montażu 3: 50-54.

[10] Godzimirski J., Jagiełło A. 2018. “Effect of surface treatment cold-work hardening after adhesive curing on strength of adhesive lap joints”. Technologia i Automatyzacja Montażu 4: 43-49.

[11] Godzimirski J., Pietras A. 2013. „Modelowanie spoin połączeń klejowych w obliczeniach MES”. Technologia i Automatyzacja Montażu 4: 40-44.

[12] Godzimirski J., Tkaczuk S. 2001. „Możliwość wykorzystania MES do obliczania wytrzymałości połączeń klejowych”. Technologia i Automatyzacja Montażu 2: 43-46.

[13] Günther N., Griese M., Stammen E., Dilger K. 2020. “Loading capacity of adhesive joints regarding their manufacturing proces”. Journal of Advanced Joining Processes 1: 100020. https://doi.org/10.1016/j.jajp.2020.100020

[14] Hart-Smith L.J. 2018. Adhesively bonded joints in aircraft structures. In da Silva L.F.M., Öchsner A., Adams R. (eds.) Handbook of Adhesion, 1235–1284. . Springer-Verlag, Berlin Heidelberg. https://doi.org/10.1007/978-3-642-01169-6_44

[15] Her S.C., Chan C.F. 2019. “Interfacial Stress Analysis of Adhesively Bonded Lap Joint”. Materials 12: 2403. https://doi.org/10.3390/2Fma12152403

[16] Kavdir E.Ç., Aydin M.D. 2020. “The experimental and numerical study on the mechanical behaviors of adhesively bonded joints“. Compos Part B 184: 107725. https://doi.org/10.1016/j.compositesb.2019.107725

[17] Korzyńska K. 2019. „Badania wpływu procesu pneumokulowania na wytrzymałość zakładkowych połączeń klejowych". Rozprawa doktorska, Politechnika Lubelska, Lublin.

[18] Korzyńska K., Zielecki W., Korzyński M. 2018. “Relationship between residual stress and strength of single lap joints made of Ti6Al4V alloy, adhesively bonded and treated using pneumatic ball peening”. Journal of Adhesion Science and Technology 32(17): 1849–1860. https://doi.org/10.1080/01694243.2018.1450108

[19] Lin Q., Liu H., Zhu C., Chen D., Zhou S. 2020. “Effects of different shot peening parameters on residual stress, surface roughness and cell size”. Surf Coat Technol 398:126054. https://doi.org/10.1016/j.surfcoat.2020.126054

[20] Loctite EA 3430 technical data, [access November 2021], http://tds.henkel.com/tds5/Studio/ShowPDF/243%20NEW-EN?pid=EA%203430&format=MTR&subformat=HYS&language=PL&plant=WERCS

[21] Mirski Z., Wróblewski R., Gołembiewski A. 2015. „Resistance of adhesive joints to impact high temperature”. Przegląd spawalnictwa 10: 108-114.

[22] Omari M.A., Mousa H.M., AL-Oqla F.M. et al. 2019. “Enhancing the surface hardness and roughness of engine blades using the shot peening proces”. International Journal of Minerals, Metallurgy, and Materials 26: 999–1004. https://doi.org/10.1007/s12613-019-1818-5

[23] Petrie E.M. 2008. “The fundamentals of adhesive joint design and construction: Function-specific construction is the key to proper adhesion and load-bearing capabilities”. Metal Finishing 106(11): 55–57. https://doi.org/10.1016/S0026-0576(08)80314-5

[24] PN EN 1465:2009 Adhesives – Determination of tensile lap-shear strength of bonded assemblies. Warsaw: Polish Committee for Standardization.

[25] PN-EN ISO 4287:1999. Specifications of product geometry – Geometric structure of the surface: profile method – Terms, definitions and parameters of the geometric structure of the surface. Warsaw: Polish Committee for Standardization.

[26] Rodopoulos C.A., Curtis S.A., de los Rios E.R., Solis Romero J. 2004. “Optimisation of the fatigue resistance of 2024-T351 aluminium alloys by controlled shot peening–methodology, results and analysis”. International Journal of Fatigue 26: 849–856.

[27] Tan L., Yao C., Zhang D., Ren J., Shen X., Zhou Z. (2020). Effects of different mechanical surface treatments on surface integrity of TC17 alloys. Surface and Coatings Technology 398: 126073. https://doi.org/10.1016/j.surfcoat.2020.126073

[28] Zaleski K. 2009. “The effect of shot peening on the fatigue life of parts made of titanium alloy ti-6Al-4V”. Maintenance and Reliability 4: 65-71.

[29] Zhao X., Adams R.D., da Silva L.F.M. 2011. “Single lap joints with rounded adherend corners: Experimental results and strength prediction”. Journal of Adhesion Science and Technology 25: 837–856.

[30] Zielecki W. 2008. “Determinants determining the strength properties of adhesive joint. Habilitation Thesis, Technical University of Košice, Košice, 2008.

[31] Zielecki W., Bąk Ł., Guźla E., Bucior M. 2019. „Analiza statystyczna wpływu parametrów pneumokulowania na nośność połączeń klejowych stopu aluminium 2024”. Technologia i Automatyzacja Montażu 1: 30-34.

[32] Zielecki W., Korzyńska K. 2016. „Umacnianie zakładkowych połączeń klejowych stopu tytanu Ti6Al4V metodą pneumokulowania”. Technologia i Automatyzacja montażu 1: 44-47.

[33] Zielecki W., Perłowski R., Trzepieciński T. 2007. „Analiza stanu naprężeń w spoinie połączenia klejowego umocnionego metodą pneumokulkowania”. Technologia i Automatyzacja Montażu 1: 31-33.

[34] Zielecki W., Trzepieciński T., Bąk Ł., Ozga E. 2022. "Load capacity of single-lap adhesive joints made of 2024-T3 aluminium alloy sheets after shot peening". The International Journal of Advanced Manufacturing Technology 119: 3013-3028.

[35] Zielecki W., Zielecki K. 2010. „Analiza MES wpływu struktury geometrycznej powierzchni na stan naprężeń w spoinie klejowej”. Technologia i Automatyzacja Montażu 4: 49-51.