ANALYSIS OF THE IMPACT OF SURFACE ROUGHNESS ON THE CAPACITY OF ADHESIVE JOINTS FROM ALUMINUM ALLOY 2024

Analiza wpływu chropowatości powierzchni na nośność połączeń klejowych stopu aluminium 2024

Łukasz BĄK
Ewelina GUŹLA ORCID 0000-0002-7359-6007
Michał ŁYKO

DOI: 10.15199/160.2020.2.5

A b s t r a c t: The purpose of the article was to deepen the state of knowledge regarding the impact of surface roughness on the capacity of single-lap adhesive joints from aluminum alloy 2024. The surfaces with a triangular outline and various height and longitudinal parameters have been deliberately shaped. The surface roughness of the samples was shaped by milling with four different table feed of 30, 50, 70 and 90 [mm/min]. Surface roughness was tested in a 2D system using a contact profilometer. The samples were connected using Loctite EA 3430 epoxy adhesive and then subjected to a static tensile test. As a result of the performed statistical analysis, it was shown that in the adopted variability area, along with the increase of the feed value, the value of roughness parameters and the capacity of joints increased. The highest capacity was obtained for the parameters Ra = 20,83 µm, Rz = 101,33 µm, Rv = 41,97 µm, Rku = 2,62 µm, RSm = 0,746 mm.

K e y w o r d s : surface roughness, lap adhesive joints, static tensile test

S t r e s z c z e n i e: Celem artykułu było pogłębienie stanu wiedzy dotyczącej wpływu chropowatości powierzchni na nośność jednozakładkowych połączeń klejowych stopu aluminium 2024. W sposób celowy ukonstytuowano powierzchnie o zarysie trójkątnym, różniące się wysokościowymi i wzdłużnymi parametrami chropowatości. Chropowatość powierzchni próbek kształtowano poprzez frezowanie z czterema różnymi prędkościami posuwu wynoszącymi 30, 50, 70 i 90 [mm/min]. Chropowatość powierzchni zbadano w układzie 2D przy pomocy profilometru stykowego. Próbki sklejono z wykorzystaniem kleju epoksydowego Loctite EA 3430, a następnie poddano statycznej próbie rozciągania. W wyniku przeprowadzonej analizy statystycznej wykazano, że w przyjętym obszarze zmienności wraz ze zwiększaniem wartości posuwu zwiększała się wartość parametrów chropowatości oraz nośność połączeń. Najwyższą nośność uzyskano dla parametrów Ra = 20,83 µm, Rz = 101,33 µm, Rv = 41,97 µm, Rku = 2,62 µm, RSm = 0,746 mm.

S ł o w a k l u c z o w e : chropowatość powierzchni, zakładkowe połączenia klejowe, statyczna próba rozciągania

Introduction

The phenomenon of adhesion is one of the factors conditioning the formation of adhesive joints. There are several theories that describe this phenomenon. One of them is mechanical theory of adhesion. According to this theory, due to the penetration of glue into the irregularities on the adhered surface, it is possible to create some kind of mechanical anchors between the surface and the glue. These anchors are capable of carrying significant loads. The topography of the surface determines the value of mechanical adhesion. Therefore, surface roughness can affect adhesive properties and, as a result, strength properties of the adhesive joint [4, 5].

There are several methods that allow modifying the geometric structure of the surface. One of them is mechanical treatment. The most commonly used methods of mechanical surface pre-treatment include: shot blasting, shot peening, grinding and abrasive blasting [7].

A lot of research has been carried out regarding the impact of various machining methods on the geometric structure of the surface and the capacity of the joints. For example, in paper [8] the author compared the effects of superfinishing, grinding and lapping on surface roughness and adhesive joint strength of steel. According to this paper, the highest values of joint strength were obtained for lapping, although the height parameters for these surfaces were relatively low.

In paper [6] the influence of sandblasting on surface properties for adhesion was examined. The research has shown that surface roughness and its adhesive properties depend more on the type of abrasive material than the applied pressure.

The objective of work [13] was to investigate the effect of sandblasting and laser texturing on the roughness parameters and joint strength from 30CrMnSiA steel. The analyzes presented in the work showed that, as a result of sandblasting and laser texturing, roughness parameters such as Rz increased to 2,85 μm and 4,19 μm from 0,75 μm and Ra increased to 0,39 μm and 0,63 μm from 0,22 μm. Furthermore, the strength of the adhesive bond increased by 151% to 465.9% respectively after sandblasting and laser texturing.

The author of the work [10] pointed out that the shear strength of adhesive joints that were damaged as a result of breaking adhesive bonds should be associated with the roughness parameters such as lr, Δa and Δq. On the other hand, the strength of the connections in which cohesive bonds were broken depended (to a small extent) on the height parameters Ry, Rm, Rz and Ra.

The subject of the work [12] was to examine the influence of 3D geometric structure on the strength of adhesive joints. The work proved that the hybrid parameters such as Ssc, Sdr, Sdq can be used to control the correctness of surface preparation and forecast shear strength of lap adhesive joints glued with elastic adhesive compositions that are subjected to adhesive or adhesive-cohesive damage.

However, modifying the adhered surface roughness (by mechanical treatment, for example), does not always guarantee an increase in the strength of the connection. Excessive surface roughness and a large number of narrow pores may hinder the penetration of adhesive into the unevenness and, as a result, weaken the connection. In such cases it is very important to apply the right pressure during gluing [3, 5]. What is more, some research points out that in some cases mechanical surface pre-treatment may weaken the adhesive joint by forming excessive compressive stresses or structural micro-damage [1, 4, 11].

Therefore, it is reasonable to conduct further research on the impact of surface roughness on the capacity of adhesive joints and to search for surface treatment methods that guarantee the largest increase in joint strength.

Material and methods

The purpose of the work was to deepen the state of knowledge regarding the impact of surface roughness on the capacity of single-lap adhesive joint from aluminum alloy 2024. The chemical composition of this alloy is shown in table 1.

2024 aluminum alloy is characterized by a high strength and high temperature resistance. Its disadvantages include poor weldability and low corrosion resistance. It is mainly used in the automotive, aviation, machine and defense industries [2, 9].

The first stage of the study was to prepare the surface of the samples for adhesive bonding. The surfaces with a triangular outline and various height and longitudinal parameters have been deliberately shaped. For this purpose, the samples were milled using Jafo FWF 32J2 machine. The milling process was carried out at a constant spindle speed n. In order to obtain various values of surface roughness parameters, different values of table feed v_f were used (Table 2.).

Table 1. The chemical composition of aluminum alloy 2024 [2]

Component, weight %											
Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**	**Ti**	**V**	**Others***	**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%**											

Table 2. Milling parameters [own elaboration]

Variant	Spindle speed n [r/min]	Table feed v_f [mm/min]
1	140	30
2		50
3		70
4		90

Then, roughness measurements of the treated surface were carried out. The contact stylus profilometer Taylor Hobson Surtronic 25 and TalyProfile Lite software were used for the tests. The evaluation length was 12,5 mm.

The next step was to make a single-lap adhesive joint using Loctite EA 3430 adhesive. Loctite EA 3430 is a general purpose, two-component epoxy adhesive. It is characterized by a high rate of cure at room temperature. It has good gap filling properties. It is suitable for rough and poorly adherent surfaces [14]. The dimensions of the connection were 12.5 x 25 mm.

The final stage was to subject the joints to a static tensile test on a Zwick Roell Z030 testing machine. The test speed was 5 mm/min and the initial force was 30 N.

Results

The selected surface profilographs, showing the differences in the geometric surface for different values of table feed v_f, are placed below (Fig. 1).

The milling process was carried out at a constant spindle speed of 140 r/min. The table feed was changed in the range from 30 to 90 mm/min. Based on the

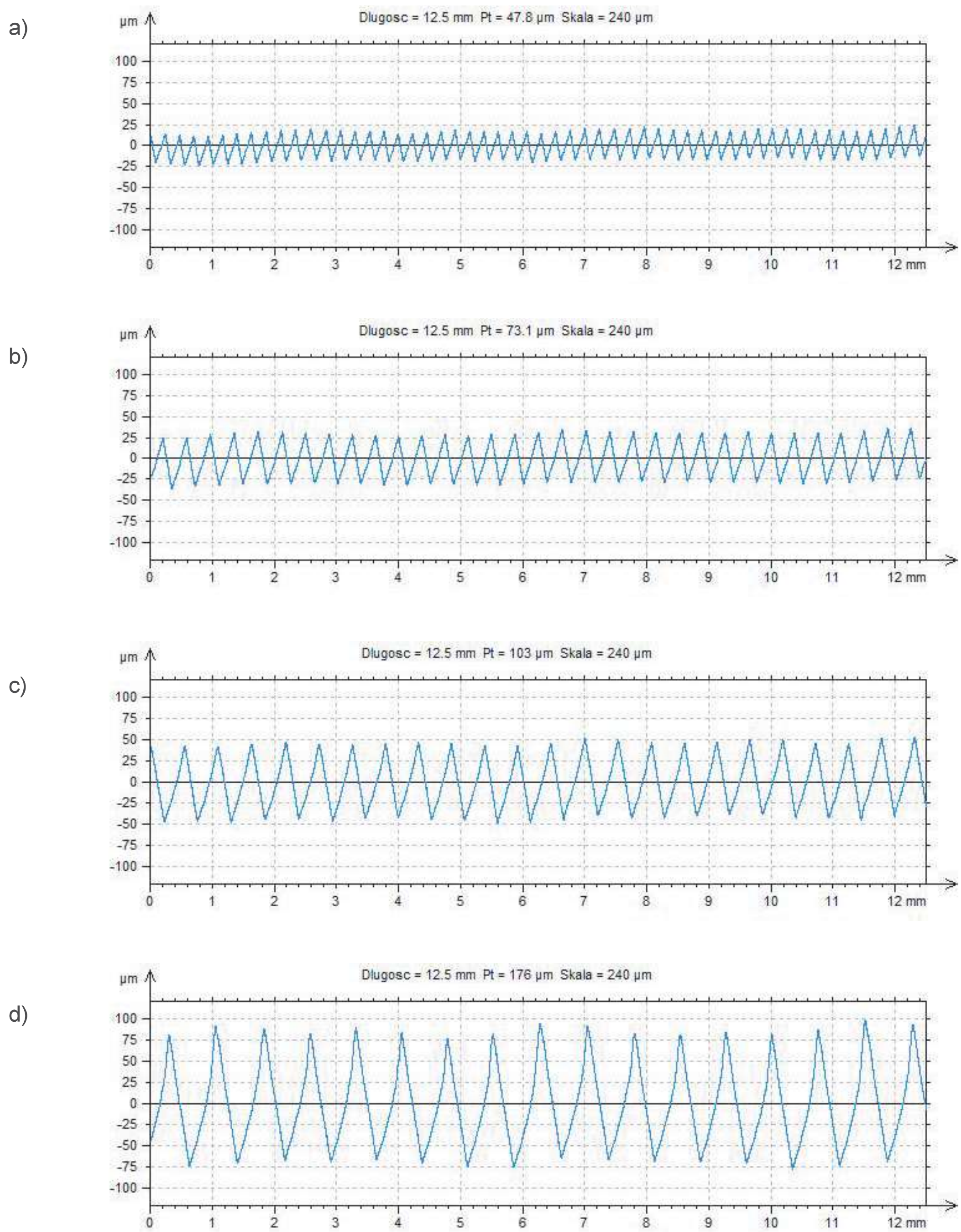

Fig. 1. Surface profilographs: a) table feed 30 mm/min, b) table feed 50 mm/min, c) table feed 50 mm/min, d) table feed 90 mm/min [own elaboration]

Table 3. The average values of the selected roughness parameters and the capacity [own elaboration]

No.	v_f [mm/min]	Ra [µm]	Rz [µm]	Rv [µm]	Rsk [µm]	Rku [µm]	RSm [mm]	capacity P [N]	standard deviation of capacity [N]
1	30	8,87	35,83	17,17	0,100	1,87	0,231	1403	259
2	50	15,87	58,40	28,30	0,09	1,80	0,377	2167	208
3	70	17,93	75,90	36,23	0,13	1,95	0,536	1836	201
4	90	20,83	101,33	41,97	0,63	2,62	0,746	2642	496

profilographs showed above, it can be seen that as the table feed increased, the surface roughness of the samples increased.

The table above presents the average values of selected roughness parameters and capacity of connections (Table 3.)

The highest capacity of the adhesive connection was obtained for samples whose surface was treated at a table feed of 90 mm/min, whereas the lowest capacity was obtained for samples milled with a table feed of 30 mm/min. Based on table 3, it can be concluded that as the table feed increased, the surface roughness increased. However, this did not quite translate into increasing the load capacity of the connection, as evidenced by variant 3. The highest standard deviation value was observed for variant 4. This variant is therefore characterized by the greatest variability.

The test results were subjected to statistical analysis. In the first step of the analysis, box plots were created. Selected box plots are presented in figure 2.

a)

b)

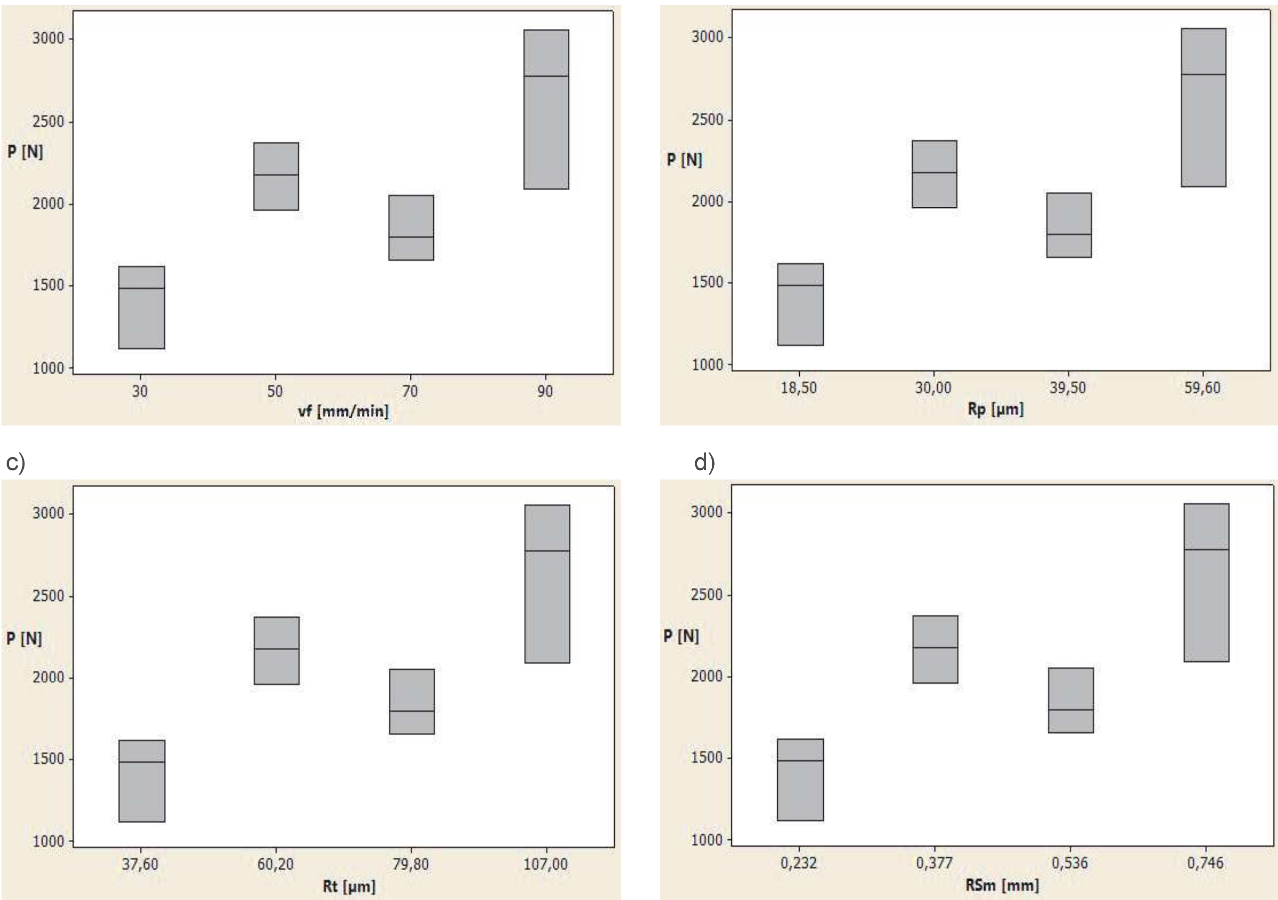

Fig. 2. Box plots: a) dependence of P on v_f, b) dependence of P on Rp, c) dependence of P on Rt, d) dependence of P on RSm [own elaboration]

Based on the graphs, it can be concluded that the largest spread of capacity values was obtained for the fourth variant. Moreover, in most cases the data distribution is asymmetrical.

The next stage of statistical analysis was the one-way analysis of variance (ANOVA) which allowed studying the influence of the input variables (table feed and roughness parameters) on the output variable (capacity of the connection). Statistical significance α=0.05 was adopted. The results of the ANOVA and regression equation analysis are shown in table 4.

Table 4. Results of the one-way analysis of variance (ANOVA), regression equation analysis and Pearson's correlation coefficients [own elaboration]

Parameter	Independent variable	Pv1	Correlation coefficient	Pv2	Regression equation
P	v_f	0,008	0,726	0,007	y_P=995,8+16,94x_{vf}
P	Rp	0,008	0,761	0,004	y_P=1035+26,40x_{Rp}
P	Rv	0,008	0,726	0,007	y_P=753,5+40,70x_{Rv}
P	Rz	0,008	0,756	0,004	y_P=896,5+16,44x_{Rz}
P	Rc	0,008	0,757	0,004	y_P=925,8+16,07x_{Rc}
P	Rt	0,008	0,752	0,005	y_P=920,8+15,34x_{Rt}
P	Ra	0,008	0,757	0,004	y_P=610,0+88,30x_{Ra}
P	Rq	0,008	0,755	0,005	y_P=731,2+68,70x_{Rq}
P	Rsk	0,008	0,666	0,018	y_P=1649+1527x_{Rsk}
P	Rku	0,008	0,638	0,025	y_P=-70,3+1012x_{Rku}
P	RSm	0,008	0,732	0,007	y_P=1069+1994x_{RSm}

P – capacity, Pv1 – probability level in the one-way analysis of variance (ANOVA), Pv2 – probability level in the analysis of the linear correlation coefficient

Based on the Pv1 value, it can be stated that in the adopted area of input parameter variability, values of table feed and selected roughness parameters have a significant impact on the capacity of the samples. What is more, Pearson's correlation coefficients indicate quite strong positive linear correlations between capacity and roughness parameters or table feed. The strongest linear correlations occur between strength and Rc, Rz and Rq parameters. This is confirmed by Pv2 values, which are lower than 5% for all independent variables. Based on regression equations, which are a kind of mathematical model of the phenomenon, it can be stated that in the adopted area of variability, increasing the table feed and thus increasing the roughness parameters of the glued surface, contributes to increasing the capacity of the tested adhesive joints. The results of the regression equation analysis for the selected roughness parameters are presented below (Fig. 3.).

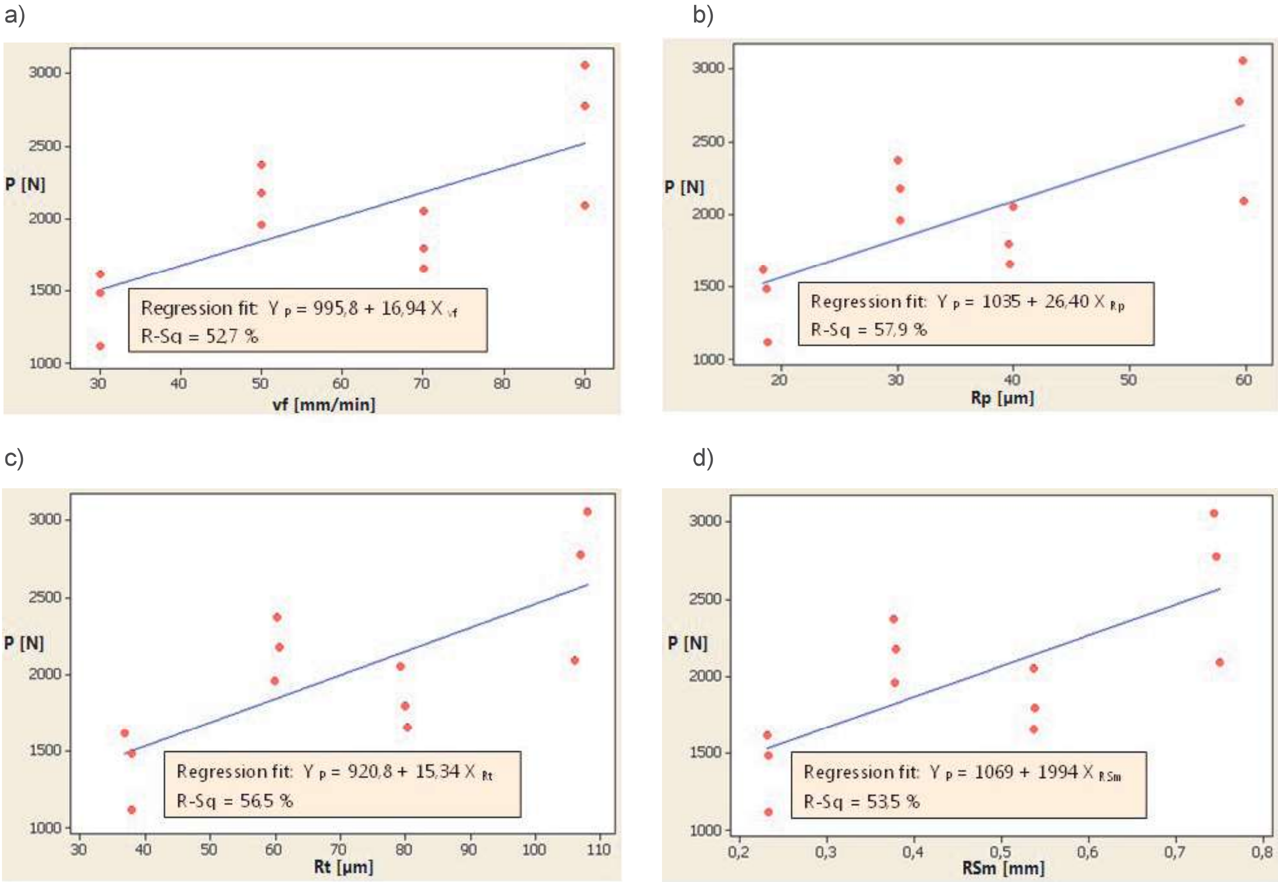

Fig. 3. Graphs and regression equations: a) dependence of P on v_f, b) dependence of P on Rp, c) dependence of P on Rt, d) dependence of P on RSm [own elaboration]

The last step of the analysis was conducting Student's t-test, in which the average capacity values for four different surface treatment variants were compared (Table 5).

The results of the Student's t-test prove that the use of different table feed and thus achieving different values of roughness parameters causes a significant difference between the capacity of most compared samples (in the adopted variation area). This difference is most evident in the samples milled at a table feed of 30 mm/min and 50 mm/min.

Table 5. Student's t-test results

Pv [%]	vf =30 mm/min	v_f =50 mm/min	v_f =70 mm/min	v_f =90 mm/min
v_f = 30 mm/min	-			
v_f =50 mm/min	0,890	-		
v_f =70 mm/min	4,407	5,931	-	
v_f =90 mm/min	1,552	11,684	4,548	-

Conclusions

The use of machining treatment such as milling enables a deliberate constitution of surface roughness. Based on the analysis of the impact of selected roughness parameters on the capacity of 2024 aluminum alloy adhesive joints, it can be concluded that in the adopted area of input parameters variability, increasing table feed contributes to increasing the surface roughness, which in turn translates into increased joint load capacity.

The statistical analysis shows that the values of the considered roughness parameters significantly affect the capacity of the connections. Furthermore, the analysis of regression equations and linear correlation coefficients indicates a fairly strong linear correlation between the capacity and roughness parameters of the samples.

References

[1] da Silva L.F.M., das Neves P.J.C., Adams R.D., Wang A., Spelt J.K. 2009. "Analytical models of adhesively bonded joints Part II: Comparative study". International Journal of Adhesion and Adhesives 29: 331-341.

[2] Dobrzański L. (red.). 2010. Leksykon Materiałoznawstwa. Praktyczne zestawienie norm polskich, zagranicznych i międzynarodowych. Cz. 4, rozdział 1: Metale nieżelazne i ich stopy. Warszawa: Wydawnictwo Verlag Dashofer.

[3] Godzimirski J. 1994. „Czynniki kształtujące wytrzymałość połączeń klejowych". Technologia i Automatyzacja Montażu 4: 61-64.

[4] Godzimirski J., Kozakiewicz J., Łunarski J., Zielecki W. 1997. Konstrukcyjne połączenia klejowe elementów metalowych w budowie maszyn. Rzeszów: Oficyna Wydawnicza Politechniki Rzeszowskiej.

[5] Kuczmaszewski J. 2006. „Fundamentals of metal-metal adhesive joint design". Lublin: Politechnika Lubelska, Oddział PAN w Lublinie.

[6] Rudawska A., Danczak I., Müller M., Valasek P. 2016. „The effect of sandblasting on surface properties for adhesion". International Journal of Adhesion & Adhesives 70: 176–190.

[7] Rudawska A. 2013. Wybrane zagadnienia konstytuowania połączeń adhezyjnych jednorodnych i hybrydowych. Lublin: Politechnika Lubelska.

[8] Rudawska A. 2014. „Selected aspects of the effect of mechanical treatment on surface roughness and adhesive joint strength of steel sheets". International Journal of Adhesion & Adhesives 50: 235–243.

[9] Sieniawski J. 2009. „Stopy aluminium stosowane w technice lotniczej". Mechanik 7: 649-654.

[10] Zielecki W. 2007. „Wpływ rozwinięcia struktury powierzchni na wytrzymałość zakładkowych połaczeń klejowych".Technologia i Automatyzacja Montażu 1,2: 108-111.

[11] 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.

[12] 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: 33-36.

[13] Ziwei Feng, Hongyun Zhao, Caiwang Tan, Jun Chen, Yong Wang, Bo Chen and Xiaoguo Song. 2019. "Modification of surface treatment on the strength of 30CrMnSiA steel adhesively bonded joints". Materials Research Express 6: 116521.

[14] https://www.woronko-kleje.pl/sg_obrazki_/00029403_zalac_001.pdf [access: 10.05.2019].

---

dr inż. Łukasz Bąk
Wydział Budowy Maszyn i Lotnictwa, 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, Katedra Technologii Maszyn i Inżynierii Produkcji
al. Powstańców Warszawy 8, 35-959 Rzeszów, Polska
e-mail: e.guzla@prz.edu.pl

mgr inż. Michał Łyko
Wydział Budowy Maszyn i Lotnictwa, Katedra Technologii Maszyn i Inżynierii Produkcji
al. Powstańców Warszawy 8, 35-959 Rzeszów, Polska