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

Analiza wpływu chropowatości powierzchni na nośność zakładkowych połączeń klejowych stopu aluminium 2024

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Abstract: The article presents the analysis of the impact of surface roughness on the load capacity of lap adhesive joints from aluminum alloy 2024. The surfaces of the samples were prepared to bond using mechanical treatment methods, such as milling and abrasive blasting. The surface roughness of the samples for different pre-treatment variants, measured in the 2D system, was found in the range of: Rp=19,4÷60,6 [μm], Rv=16,5÷88,1 [μm], Rz=35,9÷147,0 [μm], Rc=32,2÷103,3 [μm], Rt=37,1÷174,7 [μm], Ra=8,91÷22,73 [μm], Rq=10,50÷27,33 [μm], Rsk=-0,2260÷0,6487, Rku=1,78÷5,85, RSm=0,1207÷0,7337 [mm], Rdq=23,4÷198,7 [°]. Strength tests showed an increase in the bearing capacity of joints the surfaces of which were subjected to both milling and abrasive blasting.

Keywords: surface roughness, milling, abrasive blasting, adhesive joints, bearing capacity

Streszczenie: W artykule przedstawiono analizę wpływu chropowatości powierzchni na nośność zakładkowych połączeń klejowych stopu aluminium 2024. Powierzchnie próbek zostały przygotowane do klejenia z zastosowaniem metod obróbki mechanicznej, takich jak frezowanie i piaskowanie. Chropowatość powierzchni próbek dla poszczególnych wariantów obróbki, zmierzona w układzie 2D, mieściła się w przedziale: Rp=19,4÷60,6 [μm], Rv=16,5÷88,1 [μm], Rz=35,9÷147,0 [μm], Rc=32,2÷103,3 [μm], Rt=37,1÷174,7 [μm], Ra=8,91÷22,73 [μm], Rq=10,50÷27,33 [μm], Rsk=-0,2260÷0,6487, Rku=1,78÷5,85, RSm=0,1207÷0,7337 [mm], Rdq=23,4÷198,7 [°]. Badania wytrzymałościowe wykazały wzrost nośności połączeń, których powierzchnie poddawane były zarówno frezowaniu, jaki i piaskowaniu.

Słowa kluczowe: chropowatość powierzchni, frezowanie, piaskowanie, połączenia klejowe, nośność

Introduction

The technological process of adhesive bonding is carried out in several stages in a strictly defined order. The first and one of the most important stages of adhesive bonding is the surface pre-treatment - without proper preparation of the adhered surface, it would be impossible to activate the necessary binding mechanisms (mechanical, physical and chemical) and to create a durable joint [3, 5]. Therefore, the surface should be prepared in a way that ensures:

- removal of all surface contaminants from the connected elements,
- appropriate surface activation,
- required surface wettability,
- good surface development [6, 8].

According to the mechanical theory of adhesion, the geometric structure of the surface affects the strength of adhesive joints. Due to irregularities on the adhered surface it is possible to form mechanical anchors between the surface and the adhesive. These anchors are capable of carrying significant loads [1, 8]. However, in some cases, surface irregularities decrease the ability for adhesive penetration (when there are too many pores and when they are too narrow) and may weaken the connection [7, 8]. Hence, it is reasonable to search for such values of roughness parameters and such surface treatment methods that would guarantee obtaining optimal joint strength.

Material and methods

The aim of the study was to analyze the impact of the geometric structure of the surface on the bearing capacity of single-lap adhesive joints from aluminum alloy 2024. Aluminum alloy 2024 is characterized by a high strength to weight ratio and good fatigue resistance. This alloy is non-weldable and difficult to process. It is also resistant to high temperatures and has a low corrosion resistance [2, 4]. The chemical composition of this alloy is shown in Table 1.

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. Variants of the applied pre-treatment methods [own elaboration]

No	Variant	Name	v_f [mm/min]
1.	Milling	F30	30
2.	Milling	F50	50
3.	Milling	F70	70
4.	Milling	F90	90
5.	Milling and abrasive blasting	FS30	30
6.	Milling and abrasive blasting	FS50	50
7.	Milling and abrasive blasting	FS70	70
8.	Milling and abrasive blasting	FS90	90

The first stage of the study was to prepare the surface of the samples for gluing. The adhered surface of the samples was subjected to different variants of mechanical pre-treatment, including milling and milling combined with abrasive blasting. The abrasive blasting was carried out using 95A corundum with a grain size of 0,27 mm. The duration of the treatment was 5 s. Milling was carried out at a spindle speed n = 140 r/min, depth of cut a_p = 0,4 mm and table feed vf of 30, 50 70 or 90 mm/min. All variants of the applied pre-treatment methods are presented in Table 2.

The next step was to examine the geometric structure of the surface. The tests were carried out in two-dimensional array. The contact stylus profilometer Taylor Hobson Surtronic 25 and TalyProfile Lite software were used for the tests. The evaluation length was 4 mm.

Then the samples were bonded. Adhesive joints were made using Loctite EA3430 two-component epoxy adhesive. A mixing tip was used to mix the adhesive components. The adhesive was applied to both surfaces, which were then joined. The dimensions of the adhesive joint were 25x12,5 mm. The samples were placed in a gluing appliance (Fig.1).

Fig. 1. The samples placed in a gluing appliance [own elaboration]

The samples were loaded with a constant force, using one-kilogram weights. The samples were kept in the appliance for 7 days at a temperature of 23±2 °C.

The last step was to examine the shear strength of adhesive joints. The samples were subjected to a static tensile test on a Zwick Roell Z030 testing machine. The initial force was 30 N and the test speed was 5 mm/min.

Results

The average values of roughness parameters and standard deviations for different variants of pre-treatment methods are presented in Table 3 and Table 4.

Average values were determined on the basis of three samples. Comparing the values of roughness parameters, it can be stated that the lowest values of Rp, Rv, Rz, Rt, Rq parameters occur for the F30 variant. The highest values of Rz, Rt, Ra, Rq parameters occur for the FS90 variant. Moreover, in most cases, the roughness parameter values are higher for variants with combined milling and abrasive blasting treatment than for the corresponding variants which were only milled. What is more, the surface roughness measurements for samples with combined milling and abrasive blasting are characterized by greater variability.

The selected surface profilograms, showing the differences in the geometric surface for various pre-treatment methods, are shown in Figure 2.

The results of the uniaxial static tensile test are shown in Table 5. Average values were determined on

Table 3. Average values of roughness parameters [own elaboration]

Variant	Rp [µm]	Rv [µm]	Rz [µm]	Rc [µm]	Rt [µm]	Ra [µm]	Rq [µm]	Rsk	Rku	RSm [mm]	Rdq [˚]
F30	19,4	16,5	35,9	34,7	37,1	8,91	10,50	0,1587	1,89	0,2293	24,5
F50	30,5	27,0	57,5	57,1	58,1	15,10	17,27	0,1280	1,78	0,3653	25,1
F70	40,4	36,1	76,5	76,5	77,9	18,17	21,37	0,0195	1,94	0,5187	23,4
F90	60,6	42,4	102,7	103,3	105,0	21,00	26,20	0,6487	2,69	0,7337	29,6
FS30	34,9	27,2	62,1	32,2	89,0	9,26	11,40	0,1258	3,36	0,1340	60,0
FS50	33,2	46,2	79,4	48,1	95,1	13,60	16,23	-0,0570	2,67	0,1923	73,4
FS70	53,7	62,6	116,3	69,5	145,7	19,43	22,63	-0,1367	2,32	0,1953	105,0
FS90	58,8	88,1	147,0	79,8	174,7	22,73	27,33	-0,2260	2,80	0,1207	198,7

Table 4. Standard deviation values of roughness parameters [own elaboration]

Variant	S^{2}Rp [µm]	S2Rv [µm]	S^{2}Rz [µm]	S^{2}Rc [µm]	S^{2}Rt [µm]	S^{2}Ra [µm]	S^{2}Rq [µm]	S^{2}Rsk	S^{2}Rku	S^{2}RSm [mm]	S^{2}Rdq [˚]
F30	0,2	0,2	0,2	0,0	0,4	0,03	0,08	0,0143	0,01	0,0005	1,9
F50	0,2	0,1	0,1	0,2	0,4	0,16	0,12	0,0078	0,01	0,0005	1,4
F70	0,3	0,1	0,2	0,2	0,4	0,19	0,05	0,0086	0,04	0,0005	2,2
F90	0,4	0,7	0,5	0,5	0,8	0,29	0,37	0,0057	0,02	0,0012	2,4
FS30	6,5	2,9	6,0	0,3	11,0	0,15	0,16	0,1873	0,64	0,0180	5,7
FS50	2,0	3,8	1,8	5,7	7,7	1,63	1,25	0,2720	0,60	0,0400	10,5
FS70	12,4	10,9	22,3	8,5	28,3	0,21	0,38	0,0460	0,40	0,0308	28,4
FS90	6,4	8,9	10,2	2,0	4,8	0,91	0,39	0,0781	0,53	0,0166	15,6

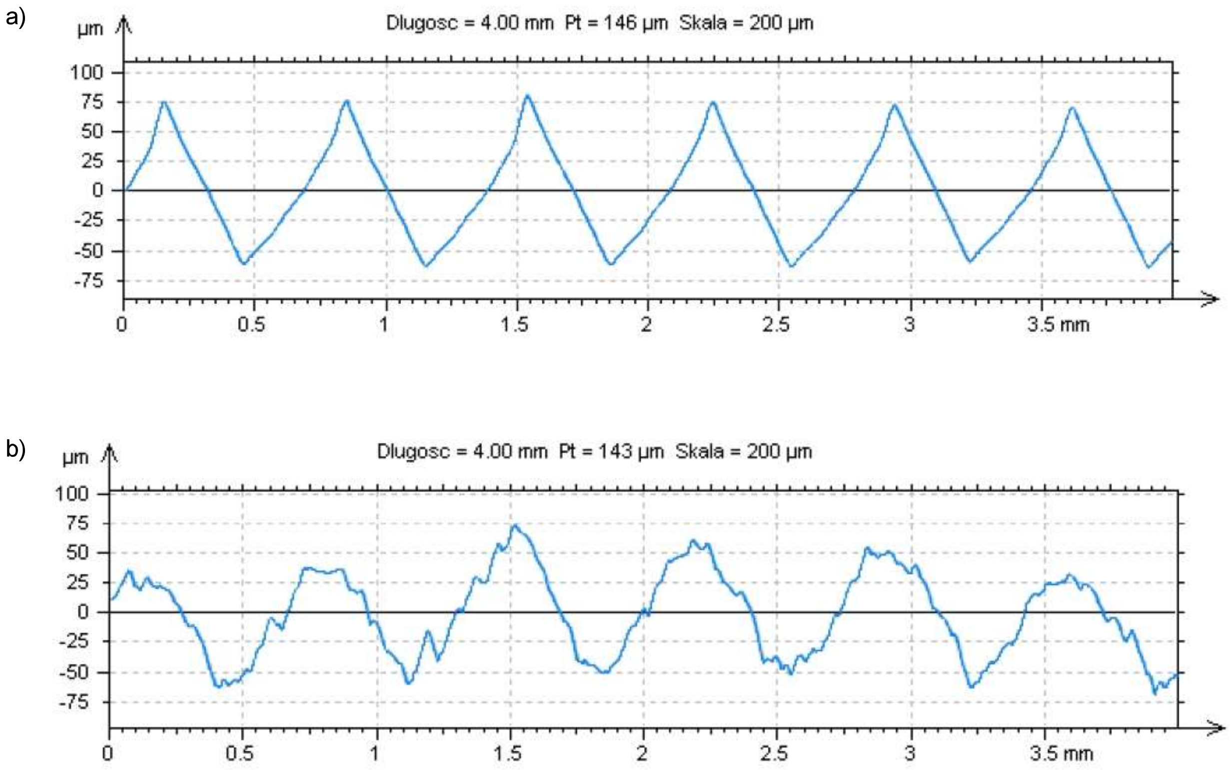

Fig. 2. Surface profilograms of the samples subjected to: a) milling – variant F90, b) milling and abrasive blasting - variant FS90 [own elaboration]

the basis of three samples. The highest values of shear strength were obtained for the samples subjected to milling and abrasive blasting. The samples which were only milled have lower shear strength values (the lower table feed, the lower shear strength). Interestingly, the bearing capacity for milled and abrasive blasted samples increased twofold (or even more) as compared to only milled samples.

Figure 3 shows a bar chart with average values of bearing capacity and standard errors. On the basis of the chart, it can be observed that the samples subjected to milling and abrasive blasting are not only characterized

Table 5. The results of the static tensile test [own elaboration]

variant	bearing capacity P [kN] – sample no 1	bearing capacity P [kN] – sample no 2	bearing capacity P [kN] – sample no 3	average bearing capacity P [kN]	standard deviation of the bearing capacity S^2P [kN]	standard error [kN]	average shear strength Rt [MPa]	increase in shear strength [%]
F30	1,48	1,11	1,61	1,40	0,26	0,15	4,48	-
F50	2,18	1,96	2,37	2,17	0,21	0,12	6,94	-
F70	2,05	1,80	1,66	1,84	0,20	0,11	5,88	-
F90	3,06	2,09	2,78	2,64	0,50	0,29	8,46	-
FS30	4,67	4,12	4,91	4,57	0,41	0,23	14,61	226,19
FS50	6,45	5,61	5,64	5,90	0,48	0,28	18,88	171,89
FS70	6,12	3,95	5,10	5,06	1,09	0,63	16,18	175,32
FS90	4,92	6,93	6,73	6,19	1,11	0,64	19,82	134,30

by higher bearing capacity, but also higher values of standard errors compared to only milled samples.

The results of measurements of surface roughness and bearing capacity were statistically analyzed using Minitab and MS Excel. The statistical research included Student’s t-test, regression and correlation analysis.

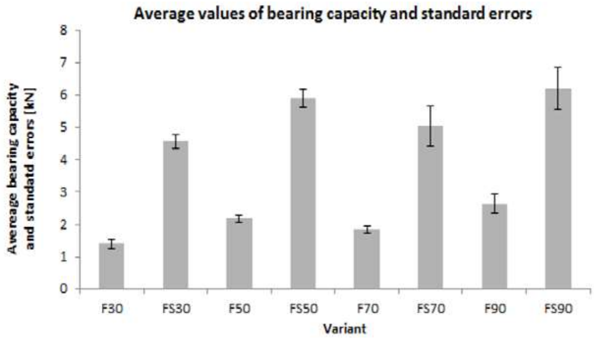

Fig. 3. Bar chart with average values of bearing capacity and standard errors [own elaboration]

The first stage of the statistical analysis was conducting Student’s t-test. The Student’s t-test was used to determine if the average values of bearing capacity of two different pre-treatment variants are significantly different from each other. Statistical significance α=0.05 was adopted. It means that a statistically significant difference between the obtained results occurs when the p-value < 5%.The results of Student’s t-test are shown in Table 6.

Student's t-test allowed to unequivocally determining a statistically significant difference between the obtained results. P-values in most cases are lower than 5%. Therefore, the results of the Student's t-test in most cases indicate a statistically significant difference in the bearing capacity of adhesive joints between samples subjected to milling and abrasive blasting, and samples which were only milled. The abrasive blasting of milled samples contributed to a significant increase in the bearing capacity of the joints. In the case of milled samples, the bearing capacity of adhesive joints does not show statistically significant differences between the F50 variant and variants F70 and F90, while in the case of abrasive blasted samples statistically significant differences occur only between the FS30 variant and the FS50 variant.

In the next step of the analysis, a box plot showing relationship between pre-treatment variant and bearing capacity was created (Fig. 4).

Based on the graph, it can be concluded that the largest spread of bearing capacity was obtained for variants FS70 and FS90. Samples that were exclusively milled are characterized by a smaller discrepancy in results compared to milled and abrasive blasted samples. Moreover, in the case of variants FS70 and FS90, the data distribution is the most asymmetrical.

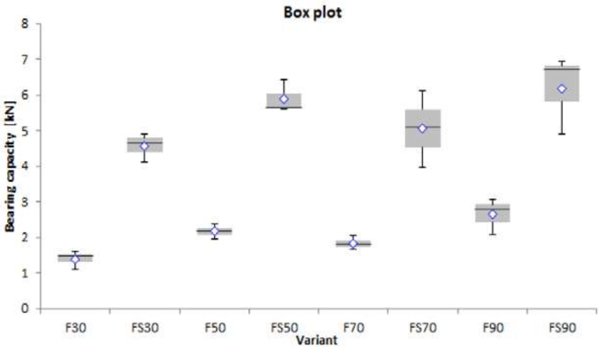

Fig. 4. Box plot showing relationship between pre-treatment variant and bearing capacity [own elaboration]

Table 6. Student's t-test results

Pv [%]	F30	F50	F70	F90	FS30	FS50	FS70	FS90
F30	x							
F50	0,870	x						
F70	4,292	5,635	x					
F90	1,564	11,868	4,624	x				
FS30	0,039	0,145	0,107	0,369	x			
FS50	0,031	0,089	0,076	0,062	1,097	x		
FS70	1,156	1,999	1,618	2,190	26,273	15,652	x	
FS90	0,682	1,067	0,915	0,891	5,647	35,225	13,654	x

As a result of regression analysis, regression equations showing the relationship between the bearing capacity of adhesive joints and roughness parameters were obtained. The calculated values of the Pearson correlation coefficients show the degree of linear relationship between the variables. The effects of regression and correlation analysis are shown in Table 7. and in Figure 5.

Based on Table 7, it can be concluded that in most cases the correlation between bearing capacity and surface roughness parameters is positive. It means that in the adopted area of variability, the bearing capacity of the connection increases with an increase of the surface roughness parameters (exceptions are Rsk and RSm parameters). The strongest correlation occurs between

Table 7. The results of correlation and regression analysis [own elaboration]

Roughness parameter	Linear regression equation	Pearson correlation coefficient r	p-value
Rp	$y_P = 1{,}83 + 0{,}0457\ xR_p$	0,364	0,080
Rv	$\mathbf{y_P = 1{,}06 + 0{,}0615\ x_{Rv}}$	**0,727**	**0,000**
Rz	$y_P = 0{,}870 + 0{,}0337\ x_{Rz}$	0,623	0,001
Rc	$y_P = 3{,}62 + 0{,}0016\ x_{Rc}$	0,020	0,928
Rt	$\mathbf{y_P = 0{,}518 + 0{,}0327\ x_{Rt}}$	**0,758**	**0,000**
Ra	$y_P = 2{,}06 + 0{,}104\ x_{Ra}$	0,273	0,197
Rq	$y_P = 2{,}07 + 0{,}0863\ x_{Rq}$	0,274	0,195
Rsk	$y_P = 4{,}02 - 3{,}62\ x_{Rsk}$	-0,537	0,007
Rku	$y_P = 0{,}19 + 1{,}45\ x_{Rku}$	0,500	0,013
RSm	$y_P = 5{,}39 - 5{,}38\ x_{RSm}$	-0,584	0,003
Rdq	$\mathbf{y_P = 2{,}03 + 0{,}0251\ x_{Rdq}}$	**0,779**	**0,000**

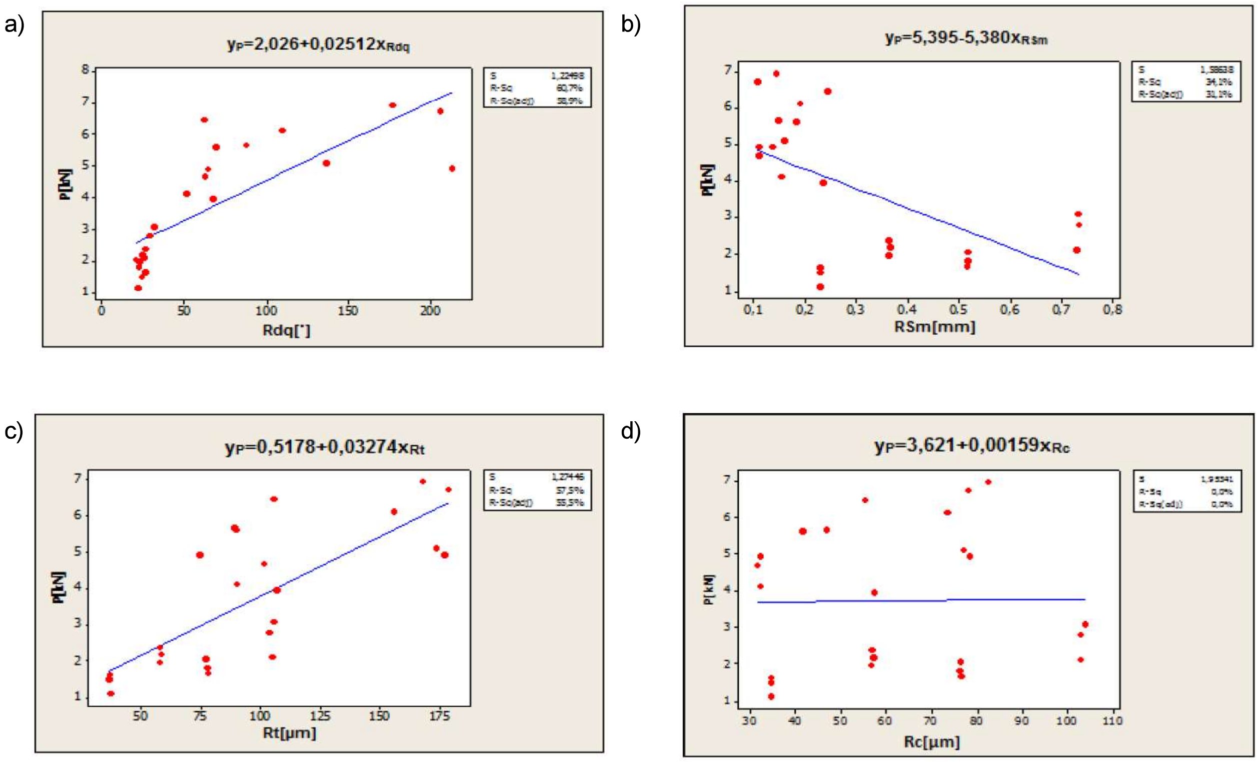

Fig. 5. Graphs of regression equations showing the relationship between the bearing capacity P and selected roughness parameters: a) Rdq, b) RSm c) Rt, d) Rc. [own elaboration]

the variables P and Rv (r = 0,727), P and Rt (r = 0, 758), as well as P and Rdq (r = 0, 779).

Conclusions

The analysis allowed determining the effect the surface roughness, obtained as a result of milling and milling combined with abrasive blasting, on the bearing capacity of lap adhesive joints from aluminum alloy 2024.

Based on the results of surface roughness tests, it can be stated that subjecting milled samples to abrasive blasting contributes to an increase in the values of most of the tested roughness parameters. What is more, the samples subjected to milling and abrasive blasting have a higher bearing capacity than samples whose surfaces were only milled. The highest bearing capacity of the connection was obtained for variant which was milled with the highest adopted table feed (v_f=90 mm/min) and abrasive blasted. The lowest bearing capacity was obtained for variant milled with the lowest assumed table feed (v_f=30 mm/min). It means that in the adopted area of variation, increasing the table feed contributes to increasing the bearing capacity of the connections. Apart from that, regression and correlation analysis showed that the bearing capacity of joints increases with the increase in the value of surface roughness parameters, apart from RSk and RSm (in the adopted area of variation).

The largest correlation occurs between the bearing capacity P of adhesive joints and the roughness parameters Rv, Rt, Rdq (r=0.727÷0.779). These roughness parameters could be used to predict the bearing capacity of the adhesive joints.

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