TiAM kwartalnik naukowo-techniczny
TECHNOLOGIA I AUTOMATYZACJA MONTAŻU
ZESPOŁÓW • MASZYN • URZĄDZEŃ

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DOI: 10.7862/tiam.2022.4.4

RELATIONSHIP BETWEEN SURFACE ROUGHNESS AND LOAD CAPACITY OF ADHESIVE JOINTS MADE OF ALUMINUM ALLOY 2024-T3 AFTER SHOT PEENING

ZALEŻNOŚĆ MIĘDZY CHROPOWATOŚCIĄ POWIERZCHNI I NOŚNOŚCIĄ POŁĄCZEŃ KLEJOWYCH STOPU ALUMINIUM 2024-T3 PO PNEUMOKULKOWANIU

Abstract

The aim of the work was to investigate the influence of selected shot peening parameters on the load capacity of adhesive joints and on the surface roughness of samples made of aluminum alloy 2024-T3. The research was also aimed at verifying whether it is possible to assess the load capacity of adhesive joints on the basis of the surface roughness parameters after shot peening. The treatment variants were developed according to the matrix of the Hartley's PS/DS-P:Ha3 plan. Shot peening time varied from 60 to 180 s, ball diameter from 0.5 to 1.5 mm and compressed air pressure from 0.3 to 0.5 MPa. As a result of the analysis of the correlation between the load capacity of connections and the surface roughness, it can be concluded that the greatest relationship exists between the load capacity and the Rku parameter. The regression analysis shows that the load capacity of the connections should increase along with the increase of the Rku parameter. The study also showed that the Rku parameter is also most strongly associated with the deflection of the Almen strips. The Almen strip deflection increases with the increase of the Rku parameter. The regression equation describing the influence of shot peening parameters on the value of the Rku parameter indicates that the value of the Rku parameter increases with the increase of the treatment time and the decrease of the ball diameter and the compressed air pressure.

Keywords: shot peening, single-lap adhesive joint, load capacity, surface roughness, Hartley's PS/DS-P: Ha3 plan, Almen test

Streszczenie

Celem pracy było zbadanie wpływu wybranych parametrów pneumokulkowania na nośność połączeń klejowych oraz chropowatość powierzchni próbek ze stopu aluminium 2024-T3. Badania miały również na celu sprawdzenie, czy możliwa jest ocena nośności połączeń klejowych na podstawie parametrów chropowatości powierzchni po pneumokulkowaniu. Warianty pneumokulkowania opracowano zgodnie z matrycą planu Hartleya PS/DS-P:Ha3. Czas obróbki zmieniał się w zakresie od 60 do 180 s, średnica kulek od 0,5 do 1,5 mm i ciśnienie sprężonego powietrza od 0,3 do 0,5 MPa. W wyniku analizy korelacji miedzy nośnością połączeń i chropowatością powierzchni można stwierdzić, ze największa zależność występuje pomiędzy nośnością a parametrem Rku. Analiza regresji wskazuje, ze wraz ze zwiększaniem wartości parametru Rku nośność połączeń również powinna wzrastać. W ramach pracy wykazano również, że parametr Rku jest parametrem chropowatości najsilniej związanym ze strzałką ugięcia płytek Almena. Strzałka ugięcia płytek Almena wzrasta wraz ze wzrostem parametru Rku. Równanie regresji opisujące wpływ parametrów pneumokulkowania na wartość parametru Rku wskazuje, że wartość parametru Rku wzrasta wraz ze zwiększaniem czasu kulkowania i zmniejszaniem średnicy kulek i ciśnienia sprężonego powietrza.

Słowa kluczowe: pneumokulkowanie, jednozakładkowe połączenie klejowe, nośność, plan Hartleya PS/DS-P: Ha3, próba Almena

1. Introduction

Adhesives have been known and used for thousands of years. However, the most intensive development of adhesive technology has occurred in the last century. One of the precursors of bonding is the aviation industry. In addition, this technology is widely used in the railway, automotive, construction and electronics industries. It is also increasingly used in medicine and biology [5].

Adhesive connections have many advantages. One of the greatest is the excellent weight-to-strength ratio compared to alternative mechanical connections. Moreover, adhesive bounds are characterized by better

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stress distribution, good fatigue resistance, good corrosion resistance, possibility of connecting thin and fragile substrates, possibility of connecting different materials and aesthetic. Nevertheless, adhesive joints have drawbacks as well. The disadvantages of this technology are, above all, the toxicity and flammability of many adhesives, the need for an appropriate substrate surface preparation, duration of curing, limited strength in extreme or severe conditions (for example in elevated temperature) [4, 12].

The most commonly used type of adhesive connections is single lap joint. The shear stress distribution in the zone of the overlap is uneven. The maximum stresses are situated at the edges of the lap. By reducing these stresses, the strength of the connections can be increased [12, 15].

One of the methods that enable reducing such stress peaks is shot peening of the overlap zone. Shot peening is an example of dynamic stream burnishing. It is a cold working process which involves bombarding the treated surface by small spherical particles [21, 28]. If the tool is in the form of balls which are propelled by a stream of compressed air, then it is referred to pneumatic shot peening [16, 36]. The intensity of the pneumatic shot peening treatment can be controlled by changing the process parameters such as processing time, ball diameter, compressed air pressure, number of nozzles and the distance of nozzles from the workpiece [36]. The intensity of the shot peening process can be analyzed using the Almen test. The Almen test consists in one-sided shot peening of specially prepared, standardized strips (Almen control strips). There are three types of the strips: N, A and C. The types differ in thickness. The selection of the appropriate type of the Almen strip depends on the intensity of the process. N type strips are used for low, A for medium, C for high shot peening intensity. Shot peening processing causes the strips to bend. The measure of the shot peening intensity is the deflection value of the Almen control strips [38].

As already mentioned, pneumatic shot peening of the outer surfaces of the laps is one of the methods of strengthening the adhesive joints. Pneumatic shot peening leads to the constitution of compressive residual stresses in the outer layer of the treated surface. The edges of the overlap are deformed and pressed against the joined material. The introduced compressive stresses reduce the concentration of stresses resulting from the external load and effectively increase the strength of the joints [35, 36].

The effect of pneumatic shot peening treatment on adhesive joints strength has been analyzed in several studies. Zielecki [36] analyzed adhesive joints made of S235JR steel. One group of the connections was characterized by a rigid adhesive joint (Epidian 5 (CIECH Sarzyna S.A, Nowa Sarzyna, Poland) composition with Z1 hardener), and the other by a flexible adhesive joint (Epidian 5 composition with PAC hardener). The joints were shot peened for 60 s with 2 mm diameter balls and pressure ranging from 0.35 to 0.55 MPa. As a result of pneumatic shot peening, the strength of the samples with a flexible joint increased by 17-27%. Moreover, the increase in strength was proportional to the increase in compressed air pressure. In the case of samples with a rigid joint, the increase in strength was 93-112%.

Zielecki and Korzyńska [31] used pneumatic shot peening process to strengthen the adhesive bonds made of titanium alloy Ti6Al4V. The treatment was carried out for 10 to 30 seconds. The diameter of the balls was 4.5 mm and the pressure was 0.6 MPa. The strength of the connections increased by 42-63%. It was also found that increasing the treatment time led to an increase in the adhesive joint strength.

In another work Korzyńska et al. [16] managed to increase the strength of connections made of titanium alloy Ti6Al4V by 18-57%. Moreover, it has been shown that there is a relationship between the strength of the joints and the state of stress after shot peening.

The possibility of strengthening the adhesive joints made of aluminum alloy 2024 with the method of pneumatic shot peening was investigated in [30]. The treatment time was 60-180 s, balls diameter 2-2.5 mm and compressed air pressure 0.2-0.3 MPa. The maximum increase in load capacity was 20.3% (treatment time 120 s, ball diameter 2 mm, pressure 0.2 MPa).

Shot peening affects not only the adhesive joints strength, but also the geometric structure of the treated surface. As a result of the treatment, numerous indentations of spherical shape, small depth and radius many times greater than the depth are formed [36]. According to the research results presented in [14], as the treatment time is lengthened, the surface roughness initially increases and then begins to decrease.

Moreover, shot peening increases the hardness of the treated surface. The increase of microhardness results from grain refinement and work hardening [3]. The authors of the work [23] point out that the pressure of compressed air has a greater influence on the hardness and the number of defects than the processing time. With increasing pressure, the number of defects decreases and the hardness increases. However, when a certain pressure limit is exceeded, the treated surface deteriorates again. According to [24] surface hardening induced by shot peening improve the wear behavior of treated elements.

Another analyzes show that shot peening have a beneficial effect on fatigue strength. In the work [18] 51CrV4 steel was tested. It has been shown that the fatigue strength of the samples shot peened for 10 minutes with 2 mm diameter balls and at 0,6 MPa compressed air pressure increased by 1.5%. The positive effect of shot peening on fatigue strength was also observed in [2]. It has been shown that the shot penning treatment of X80 steel samples increases their resistance to crack initiation, which in turn leads to an increase in fatigue strength and an increase in resistance to hydrogen embrittlement. Moreover, shot peening also has a beneficial effect on the fatigue strength of elements with chrome coatings [7].

Laber [20] compared the influence of the surface layer condition after burnishing or grinding on the tribological properties of ductile iron. As a result of the conducted analyzes, it was shown that a more favorable condition of the surface layer is obtained in the burnishing. Such layer is characterized by a lower surface roughness according to the Ra parameter, greater strengthening and higher values of compressive residual stresses, which favorably influences the tribological properties.

In many cases, the functional properties are very closely related to certain properties of the surface layer – surface roughness, hardness or residual stresses. Grzesik [8, 9, 10, 11] in several works presented considerations on the influence of individual surface roughness parameters on the functional properties of machine parts. On the basis of the observations presented by him, it can be concluded that reducing the roughness causes an increase in fatigue strength. However, when the Ra (arithmetical mean height) takes values from 2.5 to 5 µm, then the material microstructure and the residual stress have a greater influence. If there is no residual stress, then the value of the parameter Ra less than 0.1 µm strongly affects the fatigue strength [8, 11]. Grzesik [9] also draws attention to the fact that the sensitivity of fatigue strength to surface roughness values increases with increasing material strength (e.g. for precipitation hardening aluminum alloys or for hardened steels). It also explains that the propagation and nucleation of fatigue cracks is largely dependent on the surface roughness.

In the works [8, 11] it was noted that high values of Sq (root mean square height) and Sds (summit density) are associated with high unevenness and high density of peaks per unit area, and thus with a high friction coefficient. Moreover, the static friction coefficient may largely depend on the effects of skewness (Rsk) and kurtosis (Rku). Positive skewness (Rsk>0) reduces the friction coefficient. If the skewness is negative (Rsk<0) then the friction is more intense than in the Gaussian distribution (Rku = 3, Rsk = 0).

According to the observations presented in [8], the real contact area of the element increases with the increase of surface roughness, and thus the corrosion resistance decreases. Therefore, height parameters (mainly Sz – maximum height) and the arithmetic mean summit curvature (Ssc) have the greatest influence on the corrosion properties. Surfaces dominated by deep valleys are more prone to corrosion than anisotropic surfaces.

The surface roughness has a significant influence on adhesion and bonding. For more developed surfaces, coating is more effective and adhesive joints are stronger. In the case of adhesive joints, the geometric structure of the surface should be adapted to the type of adhesive. In the work [37] the influence of roughness parameters of surface treated in the milling process on the strength of adhesive joints was investigated. It has been proved that in the case of joints connected with elastic adhesives, the parameters lr (profile length ratio), Δa (average absolute slope) and Δq (root mean square slope) have a large impact on the strength of the joints. In turn, according to the results presented in [32], the shear strength of joints connected with an elastic adhesive is proportional to the following parameters: Sq Spd (Spd – density of peaks), Spc (arithmetic mean peak curvature), Sdr (developed interfacial ratio), Sdq (root mean square gradient). The strongest correlation occurs between the strength of connections and the product of Sq Spd parameters. Similar studies were carried out in the work [34]. In this case, the surface roughness parameters in the 2D system were analyzed. According to the results of the analysis, the parameters most strongly correlated with the strength of adhesive joints are Rlr, Rda, Rdq. Rlr is the profile length factor equal to the ratio of the actual (developed) profile length to the length of the sampling or evaluation length, on which it was determined, Rda is the arithmetical mean slope and Rdq is the root mean square slope [33].

In summary, shot peening process can be used to strengthen adhesive joints and has a beneficial effect on many technological and functional properties of the workpieces. Additionally, it has numerous advantages, such as low energy consumption, low cost and simplicity [22]. Nevertheless, research on the impact of pneumatic shot peening on the strength of adhesive joints is uncommon, partial and concerns mainly joints made of steel and titanium alloys. Therefore, it is justified to conduct more profound analyzes of the effect of the pneumatic shot peening on the strength of adhesive joints made of other frequently used alloys. Moreover, the conducted analysis of the literature shows that surface roughness has a significant influence on many functional properties. Surface roughness measurements, especially in the 2D system, are characterized by simplicity and low costs. Accordingly, it is reasonable to investigate the relationship between the surface roughness parameters after shot peening and the load capacity of adhesive joints after shot peening.

The aim of the work was to investigate the influence of the pneumatic shot peening treatment on the load capacity of adhesive joints and surface roughness of samples made of aluminum alloy 2024-T3. The research also included an analysis of the effect of pneumatic shot peening on the deflection of the Almen strips. The tests were carried out according to Hartley's PS/DS-P:Ha3 plan, described in [17]. As part of the work, the analyzes of regression and correlation between the load capacity and surface roughness parameters, between the Almen strip deflection and surface roughness parameters and between the load capacity and the Almen strip deflection were carried out. The performed research allowed for selection the roughness parameters that would enable the evaluation of the correctness of the strengthening treatment.

2. Experimental details

The adhesive connections were made of plates cut from a sheet of EN AW-2024-T3 aluminium alloy. This alloy is mainly used in the aerospace, engineering, defence and automotive industries. One of the biggest advantages of this alloy is high strength to weight ratio. Apart from that it distinguishes itself through high temperature resistance and good fatigue strength [6, 19]. The chemical composition of aluminium alloy 2024-T3 is summarized in Table 1.

Table 1. Chemical composition of EN AW-2024-T3 aluminium alloy [6]

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%											

The adherend surfaces were prepared for bonding. For this purpose the surfaces were subjected to abrasive blasting with 95A electrocorundate. The parameters of the treatment were: time 30 s, grain size 27 mm and air pressure 0.7 MPa. The average values of selected roughness parameters after abrasive blasting were respectively: Rz = 25.95 μm, Ra = 4.53 μm, Rv = 13.8 μm, Rq = 5.67 μm, Rku = 2.99, RSm = = 0.141 mm. The surfaces were also degreased using acetone.

The next step was bonding the samples with the use of two-component epoxy adhesive – Loctite EA3430. Information about the adhesive can be found in the product description [13]. The samples were cross linked in a mechanical press, which allowed the proper pressing of the adherent surfaces. The cross--linking time was 3 days and the temperature was 24°C. The dimensions of the aluminium alloy plates were 100x25x2 mm. The length of the joint lap was 12.5 mm.

Subsequently, the overlap zones of the joints were subjected to the pneumatic shot peening process with different treatment time t [s], ball diameter d [mm] and compressed air pressure p [MPa] (Fig. 3).

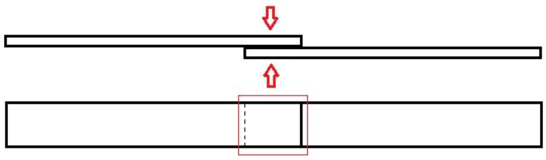

Fig. 1. Scheme of the adhesive joint with marked zones of shot peening

The treatment variants were developed according to the matrix of the Hartley's PS/DS-P:Ha3 plan. The main values of the parameters (input factors), change intervals and coded values are listed in Table 2 and the scheme of the adhesive joint with marked zones of shot peening is shown in Figure 1.

The strength of the adhesive joints after shot peening was measured in a static tensile test. The connections were loaded until they were broken. The breaking force was adopted as the load capacity Pt [N] of the adhesive joint. The static tensile test was carried out in accordance with PN EN 1465:2009 [25].

The tests also included measuring the surface roughness parameters of the plates cut from a sheet of EN AW-2024-T3 aluminum alloy and subjected to shot peening with the processing parameters listed in Table 2. The test was carried in a 2D system. 2D roughness measurements are more often used in industry than 3D measurements because they are easier and cheaper. 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 [26].

The final stage of the tests was to assess the intensity of shot peening using the Almen test according to SAE J443 standard [27]. Almen control strips of A2 type (hardness 44-50 HRC, thickness 1.32 mm, flatness ± 0.038 mm) were used for the research. Shot peening parameters are shown in Table 2. One side of the strips was processed. As a result of pneumatic shot peening, compressive residual stresses were constituted in the surface layer of the samples. This stresses caused the strips to bend. The deflection of the Almen control strips was measured with a TSP-3B measuring device.

Table 2. Treatment variants, main values of the parameters, change intervals and coded values

Factor's name	Value at the top and bottom level		Central values of input factors	Variation units	Method of encoding factor
Processing time t [s]	+ –	180 60	$x_{10} = \frac{180+60}{2} = 120$	$\Delta x_1 = \frac{180-60}{2} = 60$	$x_1 = \frac{t-120}{60}$
Ball diameter d [mm]	+ –	1.5 0.5	$x_{10} = \frac{1.5+0.5}{2} = 1$	$\Delta x_2 = \frac{1.5-0.5}{2} = 0.5$	$x_2 = \frac{d-1}{0.5}$
Pressure p [MPa]	+ –	0.5 0.3	$x_{10} = \frac{0.5+0.3}{2} = 0.4$	$\Delta x_3 = \frac{0.5-0.3}{2} = 0.1$	$x_3 = \frac{p-0.4}{0.1}$

Treatment variants

No.	x_1	x_2	x_3
1	–	–	+
2	+	–	–
3	–	+	–
4	+	+	+
5	–	0	0
6	+	0	0
7	0	–	0
8	0	+	0
9	0	0	–
10	0	0	+
11	0	0	0
12	Non-peened		

3. Discussion and results

Table 3 presents the average values of surface roughness parameters, the average values of the deflection of the Almen strips and the average values of load capacity of adhesive joints after pneumatic shot peening.

Based on the results of measurements presented in Table 3, it can be concluded that shot peening treatment can be used to strengthen adhesive joints made of aluminum alloy 2024-T3. The highest load capacity was obtained for the shot peening variant no. 10 (processing time 120 s, ball diameter 1 mm, pressure 0.5 MPa) and for variant no. 6 (processing time 180 s, ball diameter 1 mm, pressure 0.4 MPa). The load capacity of the joints in variant no. 10 is 33.4% greater than the load capacity of non-peened joints. On the other hand, the lowest load capacity was obtained for the variant no. 4, which is characterized by the highest shot peening parameters (processing time 180 s, ball diameter 1.5 mm, pressure 0.5 MPa).

Table 3. The average values of surface roughness parameters, the average values Almen strip deflection and the average values of load capacity of adhesive joints after pneumatic shot peening

No	Pt, N	f_A, mm	Rp, µm	Rv, µm	Rz, µm	Rc, µm	Rt, µm	Ra, µm	Rq, µm	Rsk	Rku	RSm, mm	Rdq, °	Rda, °
1	8166	0.071	5.67	5.49	11.16	6.06	18.88	1.90	2.37	0.0823	3.04	0.171	8.662	5.444
2	7168	0.051	3.47	3.61	7.08	3.40	12.00	1.13	1.43	-0.0371	3.07	0.129	7.228	4.454
3	8226	0.043	2.59	3.16	5.75	3.94	9.49	1.15	1.42	-0.3792	2.82	0.335	4.236	2.154
4	4819	0.242	5.92	4.91	10.82	7.36	19.46	2.22	2.72	0.1356	2.50	0.310	5.952	3.546
5	8781	0.049	5.10	5.84	10.94	6.49	18.74	1.96	2.45	-0.2156	3.03	0.234	7.350	4.466
6	9410	0.08	5.75	5.90	11.64	6.54	19.48	2.09	2.61	0.0043	2.95	0.206	8.086	5.140
7	7005	0.035	4.02	3.82	7.83	4.07	12.92	1.33	1.65	0.1009	2.90	0.144	7.152	4.480
8	7097	0.152	5.19	4.48	9.68	6.81	16.16	2.03	2.45	0.1688	2.50	0.311	5.432	3.260
9	8688	0.027	5.04	5.90	10.94	6.28	19.48	1.94	2.40	-0.1862	2.99	0.211	8.034	4.838
10	9443	0.054	6.45	6.55	12.98	7.29	26.20	2.27	2.87	0.0294	2.89	0.222	8.564	5.414
11	8633	0.067	5.67	6.50	12.16	7.16	21.02	2.11	2.65	-0.1134	3.11	0.215	8.628	5.306
12	7079	-	-	-	-	-	-	-	-	-	-	-	-	-

* Pt – load capacity, f_A – Almen strip deflection.

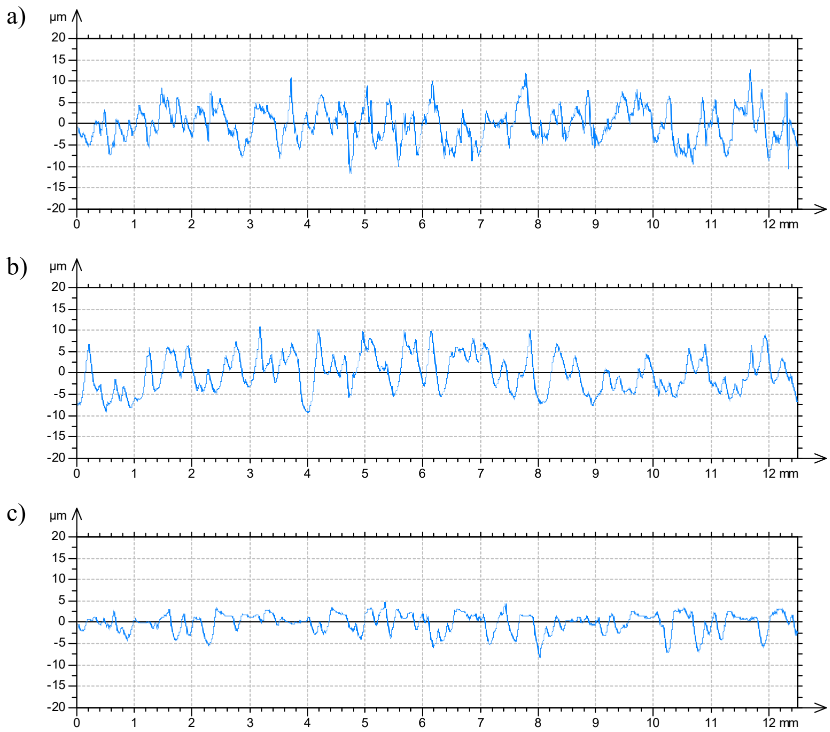

Fig. 2. Selected surface profiles: a) surface profile for treatment variant no. 10 (highest load capacity of adhesive joints), b) surface profile for variant no. 4 (lowest load capacity of adhesive joints), c) surface profile for variant no. 3

In the case of variant no. 4, the low load capacity of the adhesive joint could be caused by assuming too high values of the shot peening parameters. Too intensive treatment could damage the cohesive or adhesive bonds and weaken the joints. Figure 2 shows selected surface profiles after shot peening.

As a result of shot peening, numerous spherical-shaped indentations were formed on the treated surface. The Figure 2 shows that the geometrical structure of the surface may differ significantly depending on the values of the processing parameters. Compared to Fig. 2a and Fig 2b, Fig. 2c show a much smaller (incomplete) surface coverage with traces of shot peening.

The first step in the analysis of the test results was to determine the relationship between the surface roughness parameters and the load capacity of adhesive joints (after shot peening). Table 4 and Figure 3 show the results of the correlation analysis, the regression equations, and the results of assessing the significance of the coefficients.

Table 4. Regression equations, coefficients of linear correlation between the surface roughness parameters and the load capacity of adhesive joints (after pneumatic shot peening), results of assessing the significance of the coefficients

Parameter	Independent variable	Pv1	Regression equation	Pv2	Linear correlation coefficient R	Pv3
Pt	Rp	0.179	$y_{Pt}=7070+176x_{Rp}$	0.656	0.152	0.656
Pt	Rv	0.274	$y_{Pt}=4852+606x_{Rv}$	0.091	0.533	0.091
Pt	Rz	**0.036**	$y_{Pt}=5804+213x_{Rz}$	0.281	0.357	0.281
Pt	Rc	0.240	$y_{Pt}=7243+119x_{Rc}$	0.710	0.127	0.710
Pt	Rt	0.274	$y_{Pt}=6148+102x_{Rt}$	0.284	0.355	0.284
Pt	Ra	0.394	$y_{Pt}=7046+494x_{Ra}$	0.652	0.154	0.652
Pt	Rq	0.594	$y_{Pt}=6810+501x_{Rq}$	0.568	0.194	0.568
Pt	Rsk	0.566	$y_{Pt}=7811-3694x_{Rsk}$	0.150	-0.465	0.150
Pt	Rku	0.485	$y_{Pt}=-4016+4139x_{Rku}$	**0.031**	**0.647**	0.031
Pt	RSm	**0.036**	$y_{Pt}=8983-4574x_{RSm}$	0.496	-0.230	0.496
Pt	Rdq	0.306	$y_{Pt}=4523+475x_{Rdq}$	0.109	0.510	0.109
Pt	Rda	0.306	$y_{Pt}=5194+625x_{Rda}$	0.135	0.480	0.135

Pt – load capacity, Pv1 – probability level in the one-way analysis of variance (ANOVA), Pv2 – probability level for independent variable in the regression analysis, Pv3 – probability level in the analysis of the linear correlation coefficient

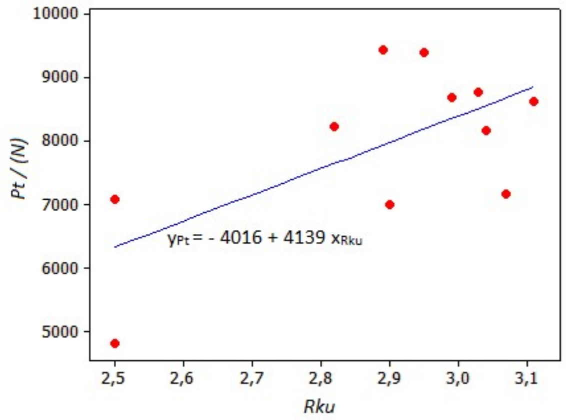

Fig. 3. The load capacity of joints Pt versus surface roughness parameter Rku

According to the results of the one-way analysis of variance ANOVA (Table 4), in the adopted range of variability of the input parameters, only the independent variable Rz and RSm influences the Pt parameter in a statistically significant way. This is confirmed by the Pv1 values, which only in these two cases are lower than 5%.

Based on the regression equations (Table 4), it can be concluded that increasing the values of the roughness parameters contributes to increasing the load capacity of the adhesive joints (the exceptions are the parameters Rsk and RSm). The assessment of the significance of the regression equation coefficients shows that only in the case of the parameter Rku, the influence of the independent variable on the equation result is statistically significant (Pv2<0,05). However, the coefficient of determination shows that in the case of the parameter Rku, only 41.9% of the results of the load capacity of adhesive joints can be described by the obtained regression equation.

It was assumed in the research that a strong correlation between the variables occurs when the absolute values of the linear correlation coefficients are greater than 0.7. According to the results of the correlation analysis (Table 4), in the adopted range of variability of the input parameters, the strongest relationship occurs between the load capacity of the adhesive joints and the roughness parameter Rku. The linear correlation coefficient in this case is 0.647. Therefore, it is not a strong correlation. Slightly lower values of the correlation coefficient were obtained for the parameters Rv and Rdq (for Rv R=0.53, for Rdq R=0.51). The weakest correlation occurs for the parameters Ra, Rp and Rc (R=0.15÷0.13).

In the next step, it was checked which roughness parameter is most strongly correlated with the deflection of the Almen strips. Table 5 and Figure 4 show the results of the correlation analysis, the regression equations, and the results of assessing the significance of the coefficients.

Table 5. Regression equations, coefficients of linear correlation between the surface roughness parameters and the deflection of the Almen strips, results of assessing the significance of the coefficients

Parameter	Independent variable	Pv1	Regression equation	Pv2	Linear correlation coefficient R	Pv3
f_A	Rp	0.112	y_{fA}=-0.0247+0.0208x_{Rp}	0.246	0.382	0.246
f_A	Rv	0.417	y_{fA}=0.0892-0.0020x_{Rv}	0.915	-0.037	0.915
f_A	Rz	0.179	y_{fA}=0.0290+0.00497x_{Rz}	0.602	0.177	0.602
f_A	Rc	0.251	y_{fA}=-0.0457+0.0210x_{Rc}	0.138	0.477	0.138
f_A	Rt	0.417	y_{fA}=0.0427+0.00207x_{Rt}	0.653	0.153	0.653
f_A	Ra	0.066	y_{fA}=-0.0450+0.0679x_{Ra}	0.166	0.449	0.166
f_A	Rq	0.727	y_{fA}=-0.0340+0.0498x_{Rq}	0.212	0.409	0.212
f_A	Rsk	0.824	y_{fA}=0.0871+0.211x_{Rsk}	0.071	0.564	0.071
f_A	Rku	0.362	y_{fA}=0.781-0.243x_{Rku}	**0.003**	**-0.807**	0.003
f_A	RSm	0.179	y_{fA}=-0.0359+0.509x_{RSm}	0.083	0.544	0.083
f_A	Rdq	0.106	y_{fA}=0.194-0.0159x_{Rdq}	0.272	-0.363	0.272
f_A	Rda	0.033	y_{fA}=0.167-0.0200x_{Rda}	0.327	-0.327	0.327

f_A – Almen strip deflection, Pv1 – probability level in the one-way analysis of variance (ANOVA), Pv2 – probability level for independent variable in the regression analysis, Pv3 – probability level in the analysis of the linear correlation coefficient

The results of the one-way analysis of variance ANOVA (Table 5) indicate that, in the adopted range of variability of the input parameters, almost all of the independent variables do not significantly affect the dependent variable (Almen strip deflection). Only the independent variable Rda influences the f_A parameter in a statistically significant way (Pv1<0,05).

According to the regression equations (Table 5), it can be concluded that with the increase of the roughness parameters Rv, Rku, Rdq and Rda, the deflection of the Almen strips decreases. In other cases, increasing the roughness parameters leads to an increase in the deflection of the Almen strips. The evaluation of the significance of the regression equation coefficients indicates that only the independent variable Rku significantly influences the result of the regression equation (Pv2<0.05). The Pv2 probability values for the remaining variables are greater than 0.05.

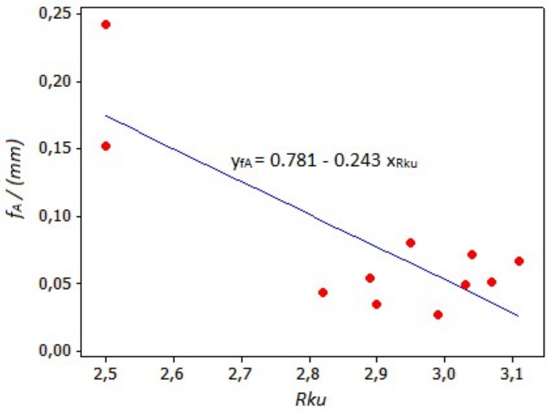

Fig. 4. The Almen strip deflection f_A versus surface roughness parameter Rku

In addition, there is a strong correlation between the independent variable Rku and the deflection of the Almen strips. The value of the linear correlation coefficient in this case is -0.806. The weakest correlation was observed between the Almen strip deflection and the roughness parameter Rv.

As part of the research, the relationship between the load capacity of adhesive joints and the deflection of the Almen strips was also analyzed. It was shown that the linear correlation coefficient is -0.733. Therefore, there is a strong correlation between the load capacity and the Almen strip deflection. According to the regression equation (Figure 5), the load capacity of the connections decreases as the Almen strip deflection increases.

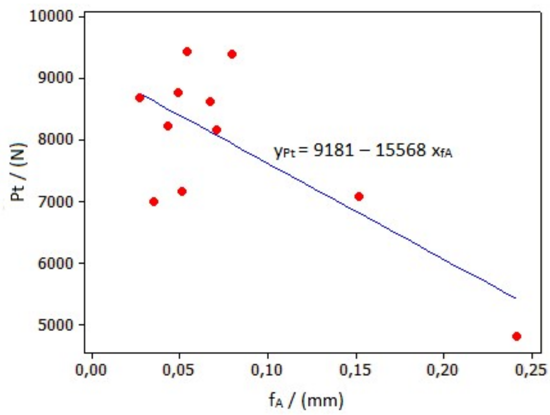

Fig. 5. The load capacity of joints Pt versus the Almen strip deflection f_A

The conducted analyzes show that the roughness parameter most strongly correlated with both the load capacity of the joints and the Almen strip deflection is the parameter Rku. Therefore, the Rku parameter can be used to evaluate the deflection of the Almen strips and the load capacity of adhesive joints after shot peening.

The value of the Rku (kurtosis) parameter is calculated from the formula (1):

$$Rku = \frac{1}{Rq^4}\left[\frac{1}{lr}\int_0^{lr}\left|Z^4(x)\right|dx\right] \qquad (1)$$

where: Rq – root mean square height, lr – evaluation length, $Z(x)$ – roughness profile equation, Z_i – height distribution of the 1- point of the surface roughness, n – number of points on the x-axis for which the Z_i value is determined.

In the Rku formula, the value of the root mean square is in the fourth power. Therefore, the values of the Rku parameter largely depend on the depth of the indentations and the height of the peaks of the profile. In the case of a profile with very slender peaks, the value of the Rku parameter may exceed 20. If the height distribution is normal, then the Rku=3. The values of the Rku parameter can be used to infer about surface defects [1, 29].

Due to the fact that the Rku parameter can be used to assess the load capacity of adhesive joints after shot peening, the next stage of was to develop a regression equation describing the influence of shot peening on the value of the Rku parameter. The equation was developed according to the methodology of Hartley's plan PS/DS-P:Ha3 described in [17]. The equations determined according to the methodology of the Hartley's plan PS/DS-P:Ha3 take the shape of a second-order polynomial (2):

$$\begin{aligned} y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \\ + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + \\ + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \end{aligned} \qquad (2)$$

where: x_1 – coded value for the treatment time t [s], x_2 – coded value for the ball diameter d [mm], x_3 – coded value for the pressure p [MPa] and $b_0,\dots,b_{23}$ – regression equation coefficients.

Table 6 and Figure 6 show the detailed results of Rku roughness measurements together with the results of mathematical model.

Table 6. Results of tests and calculations for the roughness parameter Rku

Variant				Results of the test of Rku parameter					Results of the calculations			
No.	x_1	x_2	x_3	y_1	y_2	y_3	y_4	y_5	$\overline{y}_i$	$S^2(y)_i$	$\hat{y}_i$	$(\overline{y}-\hat{y}_i)^2$
1	-	-	+	3.06	2.88	3.24	3.31	2.70	3.04	0.06	3.14	0.01
2	+	-	-	3.32	3.06	3.05	2.95	2.97	3.07	0.02	3.14	0.00
3	-	+	-	2.50	3.55	2.70	2.83	2.50	2.82	0.19	2.34	0.22
4	+	+	+	2.50	2.41	2.68	2.45	2.47	2.50	0.01	2.34	0.02
5	-	0	0	3.26	2.63	3.03	2.92	3.32	3.03	0.08	2.96	0.01
6	+	0	0	2.66	2.88	2.69	2.97	3.57	2.95	0.14	2.96	0.00
7	0	-	0	2.85	3.18	2.83	2.86	2.77	2.90	0.03	2.94	0.00
8	0	+	0	2.25	2.40	2.68	2.54	2.62	2.50	0.03	2.54	0.00
9	0	0	-	3.15	3.11	3.09	2.57	3.04	2.99	0.06	2.96	0.00
10	0	0	+	2.97	2.70	2.99	3.19	2.59	2.89	0.06	2.96	0.00
11	0	0	0	2.63	2.88	2.90	3.28	3.86	3.11	0.23	2.96	0.02
Σ	-	-	-	-	-	-	-	-	31.80	0.90	-	0.30

* $\overline{y}_i$ – average value of Rku parameter, $S^2(y)_i$ – variance of experimental results, $\hat{y}_i$ – value of Rku parameter determined using regression equation (3), $(\overline{y}-\hat{y}_i)^2$ – variance determined using regression equation (3).

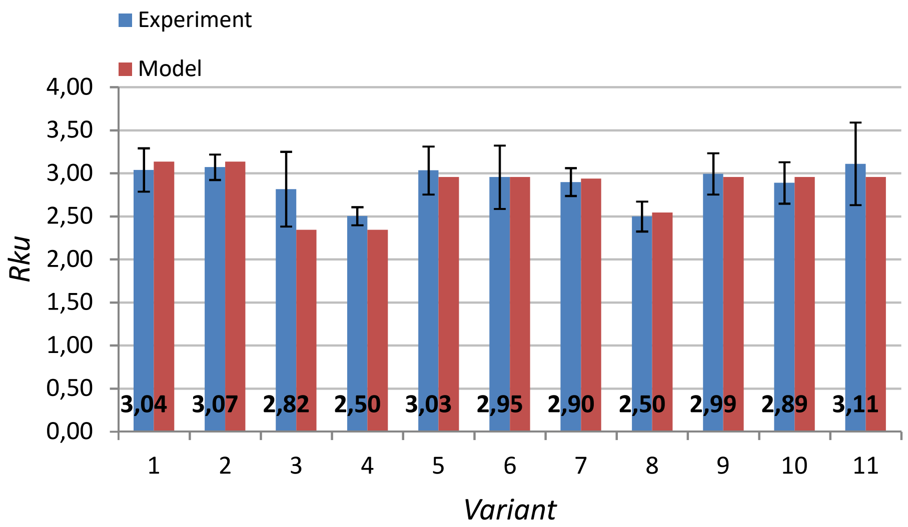

Fig. 6. Results of the tests (with values and standard deviation) and the calculations for the roughness parameter Rku

The obtained results of the surface roughness parameter Rku were evaluated for repeatability with the use of the Cochran criterion. The calculated G value is 0.26 and is less than the critical value ($G_{0,05;11;4} = 0.3096$). Therefore, the repeatability of the experimental conditions can be considered as satisfactory.

In the next steps, the values of the coefficients of the regression equation were determined and then their significance was assessed. The results of the calculations and the results of the significance assessment are presented in Table 7.

After elimination of the irrelevant coefficients, decoding the equation using appropriate values from Table 2 and re-arranging, the following regression equation was obtained (3):

$$y_{Rku} = 0{,}9042 + 0{,}01316\,x_t + 1{,}345\,x_d + 3{,}948\,x_p - 0{,}8708\,x_d^2 - 0{,}0329\,x_t x_p \quad (3)$$

where y_{Rku} is the surface roughness parameter Rku, x_t is the processing time variable, x_d is the ball diameter variable and is the x_p compressed air pressure variable. The regression equation (3) describes the effects of peening time, ball diameter and compressed air pressure on the surface roughness parameter Rku. The obtained model is nonlinear. The values of the parameter Rku calculated from the model (3) are presented in the penultimate column in Table 6. The model and experimental values are similar. The linear correlation coefficient is 0.83. Figure 7 shows graphs developed from the regression equation (3).

Table 7. Critical values, calculated values and significance assessment

Coefficient	Critical value	Calculated value	Significance of coefficient	
b_0	0.1422	2.9576	$\lvert b_0 \rvert > b_{0kr}$	Relevant
b_1	0.1052	-0.0600	$\lvert b_1 \rvert < b_{kkr}$	Irrelevant
b_2	0.1052	-0.1983	$\lvert b_2 \rvert > b_{kkr}$	Relevant
b_3	0.1052	-0.0750	$\lvert b_3 \rvert < b_{kkr}$	Irrelevant
b_{11}	0.1657	0.0773	$\lvert b_{11} \rvert < b_{kkkr}$	Irrelevant
b_{22}	0.1657	-0.2177	$\lvert b_{22} \rvert > b_{kkkr}$	Relevant
b_{33}	0.1657	0.0243	$\lvert b_{33} \rvert < b_{kkkr}$	Irrelevant
b_{12}	0.1289	-0.0865	$\lvert b_{12} \rvert < b_{kjkr}$	Irrelevant
b_{13}	0.1289	-0.1975	$\lvert b_{13} \rvert > b_{kjkr}$	Relevant
b_{23}	0.1289	-0.0705	$\lvert b_{23} \rvert < b_{kjkr}$	Irrelevant

b)

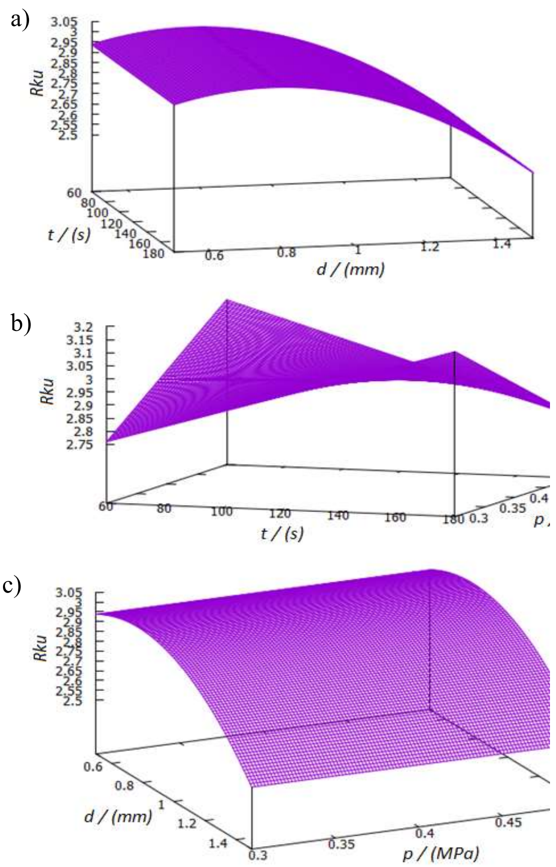

Fig. 7. Graphs showing: a) the effect of the time and ball diameter on Rku (p=0.4 [MPa]), b) the effect of the time and the pressure on Rku (dk =1 [mm]), c) the effect of the ball diameter and the pressure on Rku (t=60 [s]).

Based on the regression equation (3) and the obtained graphs (Fig. 7), it can be concluded that for the assumed area of variability of the input factors, increasing the shot peening time contributes to increasing the value of the Rku parameter. On the other hand, increasing the diameter of the balls and the pressure of compressed air decreases the value of the Rku parameter.

4. Conclusion

On the basis of the conducted analyzes, it was shown that in the adopted range of variability of the input factors:

- the roughness parameter, which is most strongly correlated with both the deflection of the Almen strips and the load capacity of adhesive joints after shot peening is the Rku parameter (the values of the linear correlation coefficient are respectively 0.647 and -0.807),
- there is a strong correlation between the load capacity of the adhesive joints and the deflection of the Almen strips (the value of the linear correlation coefficient is -0.733),
- the load capacity of the adhesive joints after shot peening increases with decreasing the value of the Rku parameter and the Almen strip deflection,
- the value of the Almen strip deflection increases with the increase of the Rku parameter,
- the value of the Rku parameter increases with the increase of the treatment time and the decrease of the ball diameter and the compressed air pressure.

Summarizing, the Rku roughness parameter can be used to predict the load capacity of adhesive joints after shot peening. The Almen test can be applied at the start of a batch of parts to check and document the shot peening process. Then, the correctness of the shot peening process can be assessed on the basis of the surface roughness. The Almen test is quite expensive. Moreover, mounting of the Almen strips to the workpiece means that such a part often has to be additionally reinforced locally in the place where the control strip was fixed. Therefore, the assessment of the load capacity of the adhesive joints after shot peening on the basis of the surface roughness allows for a significant reduction in costs and simplification of the process. As a result, it can be successfully used by enterprises that use shot peening for strengthen adhesive joints.

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