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Original Research

# RELATIONSHIP BETWEEN 3D SURFACE ROUGHNESS PARAMETERS AND LOAD CAPACITY OF ADHESIVE JOINTS AFTER SHOT PEENING

# ZALEŻNOŚĆ POMIĘDZY PARAMETRAMI CHROPOWATOŚCI POWIERZCHNI 3D A NOŚNOŚCIĄ POŁĄCZEŃ KLEJOWYCH PO PNEUMOKULKOWANIU

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## Abstract

The aim of the article was to investigate whether roughness parameters in a 3D system can be used to assess the load capacity of adhesive lap joints strengthened in the shot peening process. The analyzes were carried out for single-lap adhesive joints made of EN AW-2024-T3 aluminum alloy, whose overlaps were shot peened for 60 to 180 s using balls with a diameter of 0.5 to 1.5 mm with a compressed air pressure of 0.3 to 0.5 MPa. As a result of the regression and correlation analysis, it was found that within the adopted range of input parameters variability, the load capacity of adhesive joints subjected to shot peening is most closely related to the roughness parameter *Sdr*. It has been shown that increasing the value of the *Sdr* parameter contributes to increasing the load capacity of adhesive joints. A mathematical model describing the impact of treatment time, balls diameter and compressed air pressure on the value of the *Sdr* parameter was also built. The model was built in accordance with the the Hartley's PS/DS-P:Ha$_3$ plan methodology. The obtained results allow to conclude that the *Sdr* parameter can be used to predict the load capacity of adhesive joints after shot peening and thus to assess the strengthening treatment (within the assumed range of input parameters variability). Additionaly, the simplicity and low cost of roughness measurements justify the use of this method in industrial purposes.

**Keywords:** shot peening, surface roughness, Hartley's PS/DS-P:Ha$_3$ plan

## Streszczenie

Celem artykułu było zbadanie, czy parametry chropowatości w układzie 3D mogą być stosowane do oceny nośności zakładkowych połączeń klejowych, umacnianych w procesie pneumokulkowania. Analizy przeprowadzono dla połączeń klejowych jednozakładkowych ze stopu aluminium EN AW-2024-T3, których zakadki pneumokulkowano w czasie od 60 do 180 s, kulkami o średnicy od 0,5 do 1,5 mm z ciśnieniem wynoszącym od 0,3 do 0,5 MPa. W wyniku przeprowadzonej analizy regresji i korelacji stwierdzono, że w przyjętym zakresie zmienności parametrów wejściowych, nośność połączeń klejowych poddanych pneumokulkowaniu jest najsilniej związana z parametrem chropowatości *Sdr*. Wykazano, że zwiększanie wartości parametru *Sdr*, przyczynia się do zwiększania nośności połączeń klejowych. Zbudowano również model matematyczny, opisujący wpływ czasu obróbki, średnicy kulek i ciśnienia sprężonowego powietrza na wartość parametru *Sdr*. Model zbudowano zgodnie z metodyką planu Hartleya PS/DS-P:Ha$_3$. Uzyskane wyniki pozwalają na stwierdzenie, że parameter *Sdr* może być wykorzystywany do przewidywania nośności połączeń klejowych po pneumokulkowaniu, a tym samym do oceny obróbki umacniającej (w przyjętym zakresie zmienności parametrów wejściowych), a prostota i niskie koszty pomiarów chropowatości przemawiają za słusznością użycia tej metody w celach przemysłowych.

**Słowa kluczowe:** pneumokulkowanie, chropowatość powierzchni, plan Hartleya PS/DS-P: Ha$_3$

## 1. Introduction

The stress state in the bond-line of single-lap adhesive joints is not uniform. The maximum stresses are recorded in the end part of the overlap. Failure of the adhesive bond begins at the point of stress concentration. Therefore, in order to increase the strength of adhesive joints, efforts should be made to reduce the value of maximum stresses [4, 7].

There are various methods of reducing the stress concentration in the end part of the overlap. One of them is shot peening of the outer surface of the overlap [3, 4, 10]. Shot peening of the outer surface of the overlap leads to the reduction of stresses in the bond-line of joints subjected to stretching [9, 11]. It has been proven that the greatest stress reduction occurs in the case of normal stresses perpendicular to the bond-line surface. Figure 1 shows a comparison of normal stresses perpendicular to the surface of the bond-line in connections not subjected to and subjected to shot-peening. In the case of joints not subjected to shot peening, the maximum values of these stresses are about 78 MPa. On the other hand, in the case of connections subjected to shot peeningg, the maximum stress values are only about 28 MPa [11].

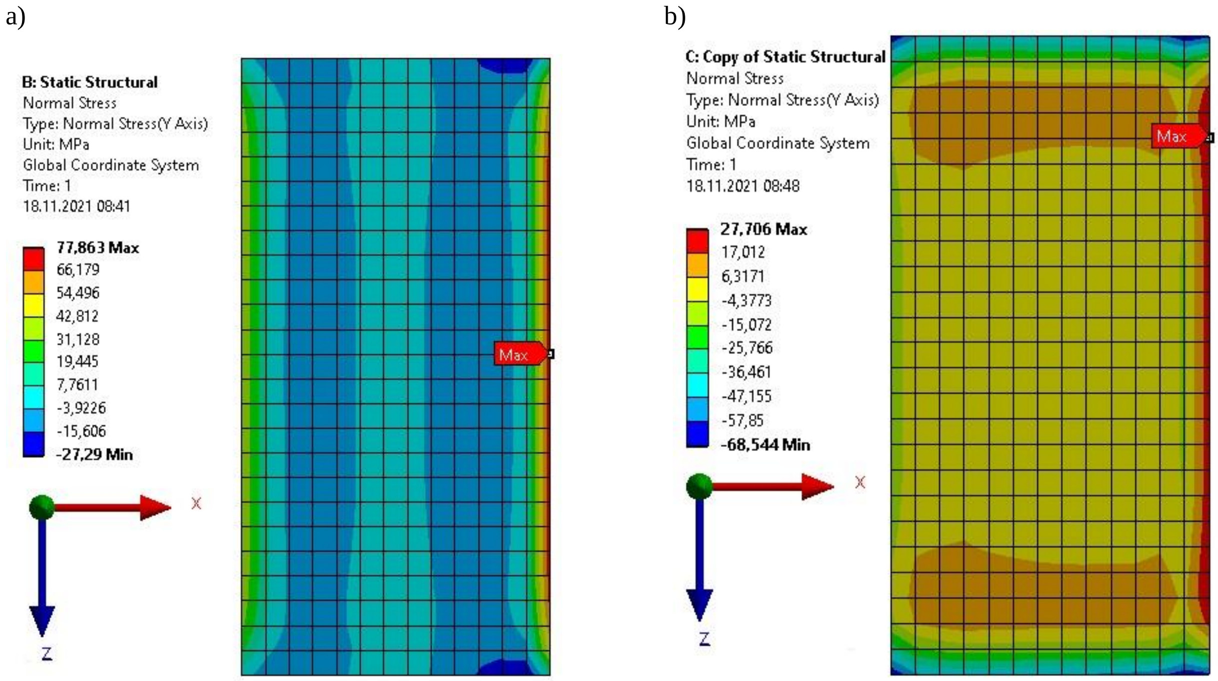

**Fig. 1.** Comparison of the values of normal stresses perpendicular to the surface of the bond-line in the adhesive connections: a) not subjected to shot peening, b) subjected to shot peening [11]

As a result of reducing the maximum values of normal stresses perpendicular to the surface of the bond-line, the capacity ratio of the bond-line decreases, which in turn translates into an increase in the strength of the adhesive joint [11].

Shot peening, which is one of the types of dynamic burnishing, has great potential for strengthening adhesive bonds. Therefore, it would be useful to identify ways to assess the correctness of this type of strengthening treatment in order to facilitate its implementation in industrial applications.

In general, in order to ensure repeatability of the dynamic burnishing process and maintain the required quality of machined parts, the following methods are used:

- assessment of the degree of surface coverage with imprints resulting from the impact of burnishing elements,
- assessment of the intensity of dynamic burnishing (Almen strip test),
- analysis of the geometric structure of the surface after treatment,
- analysis of the physical properties of the surface layer,
- analysis of the functional properties of the machined elements [8].

It was decided to check whether one of the mentioned methods (analysis of the geometrical structure of the surface after treatment) can be used to assess the strengthening treatment and to predict the load capacity of lap adhesive joints subjected to shot peening. For this purpose, the relationship between the surface roughness parameters of EN AW-2024-T3 aluminum alloy samples subjected to shot peening and the load capacity of adhesive joints made of EN AW-

2024-T3 aluminum alloy after shot peening was analyzed.

## 2. Experimental details

The subject of the analyzes were adhesive bonds made of aluminum alloy EN AW-2024-T3, bonded with the use of two-component epoxy adhesive Loctite EA 3430 and plates of aluminum alloy EN AW-2024-T3. The dimensions of the adhesive bond and the plate are shown in Figure 2.

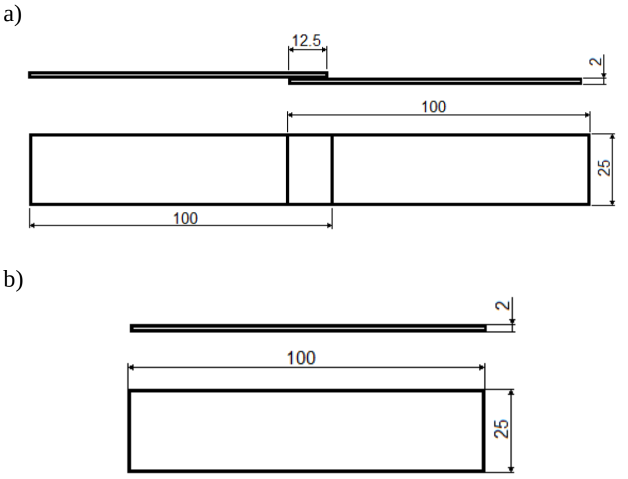

**Fig. 2.** Scheme of: a) adhesive bond, b) plates for measuring surface roughness

In order to obtain the appropriate degree of development, ensuring greater adhesive strength, the bonding surfaces were subjected to abrasive blasting. The processing was carried out on a New-Tech machine (New-Tech, Wrocław, Poland) with the use of ekeltrocorundum with a grain size of 0.27 mm. Then, the bonding surfaces were cleaned of dust and grease residues with acetone.

The next step was to create adhesive bonds. Bonds were made using two-component epoxy adhesive Loctite EA 3430 (Loctite, Düsseldorf, Germany). The adhesive components were mixed by hand and applied to both bonded surfaces. The bonds were placed in a fixing device ensuring constant pressure. Crosslinking in the device lasted 3 days. The cross-linking temperature was 22 ± 1˚C.

The adhesive bonds and plates made of aluminum alloy EN AW-2024-T3 were subjected to shot peening. The tests were carried out for 11 variants of the shot peening process. Individual variants differed in processing parameters. Treatment parameters were selected in accordance with the Hartley plan matrix for three levels of variability of input factors: shot peening time *t*, diameter of steel balls *d* and compressed air pressure *p* (Table 1).

**Table 1.** Shot peening parameters

| **Variant** | **Shot peening parameters** | | |
|---|---|---|---|
| | **Time** *t***, s** | **Balls diameter** *d***, mm** | **Comperssed air pure** *p***, MPa** |
| 1 | 60 | 0.5 | 0.5 |
| 2 | 180 | 0.5 | 0.3 |
| 3 | 60 | 1.5 | 0.3 |
| 4 | 180 | 1.5 | 0.5 |
| 5 | 60 | 1.0 | 0.4 |
| 6 | 180 | 1.0 | 0.4 |
| 7 | 120 | 0.5 | 0.4 |
| 8 | 120 | 1.5 | 0.4 |
| 9 | 120 | 1.0 | 0.3 |
| 10 | 120 | 1.0 | 0.5 |
| 11 | 120 | 1.0 | 0.4 |

Shot peening was carried out in a device consisting of a working chamber closed with a cover to which the samples (adhesive joints and plates made of aluminum alloy EN AW-2024-T3) were attached. In the case of adhesive joints, only the overlap zone was treated. The remaining part was protected against the impact of the burnishing elements by caps.

The tests were also carried out for variant 12, meaning samples not subjected to shot peening treatment.

More details on the methodology of preparing adhesive joints and the shot peening process can be found in [12].

In order to determine the impact of shot peening on the load capacity of adhesive bonds, the bonds were subjected to a static uniaxial tensile test. The test was carried out on a ZWICK/ROELL Z100 machine (Zwick/Roell, Ulm, Germany) in accordance with the PN EN 1465:2009 standard [6].

3D surface roughness measurements were carried out for EN AW-2024-T3 aluminum alloy plates. Measurements were performed using a Taylor Hobson Talysurf CCI Lite optical profilometer (Taylor Hobson Ltd, Leicester, England). Table 2 presents the measured 3D surface roughness parameters.

**Table 2.** Measured 3D surface roughness parameters [2]

| **3D surface roughness parameters** | |
|---|---|
| *Sq* | Root mean square height, μm |
| *Ssk* | Skewness |
| *Sku* | Kurtosis |
| *Sp* | Maximum peak height, μm |
| *Sv* | Maximum pit height, μm |
| *Sz* | Maximum height, μm |
| *Sa* | Aritmetic mean height, μm |
| *Sal* | Auto-correlation lenght, mm |
| *Str* | Texture-aspect ratio |
| *Sdq* | Root mean square gradient |
| *Sdr* | Developed interfacial area ratio, %, |
| *Spd* | Plateau root mean square rouhgness, 1/mm$^2$ |
| *S10z* | Ten point height, μm |

Measurements of 3D surface roughness parameters were made in accordance with the ISO 25178-2:2021 standard [2]. The obtained results were subjected to statistical analyses.

## 3. Results and discussion

Tables 3-5 show the average values of the load capacity ($P_t$) of untreated adhesive joints, the average values of the load capacity of adhesive joints subjected to 11 variants of shot peening, and the corresponding average values of 3D surface roughness parameters. The average values of the load capacity of adhesive joints were determined on the basis of load capacity measurements performed for 8 samples. The average values of the roughness parameters were determined based on the results of three surface roughness measurements.

**Table 3.** The average values of load capacity of adhesive joints and the average values of surface roughness parameters – part 1

| Variant | $P_t$, N | *Sq*, µm | *Ssk* | *Sku* | *Sp*, µm |
|---|---|---|---|---|---|
| 1 | 8166 | 2.56 | 0.0262 | 3.62 | 12.35 |
| 2 | 7168 | 1.58 | -0.0699 | 3.69 | 8.91 |
| 3 | 8226 | 2.09 | -1.0420 | 3.77 | 6.53 |
| 4 | 4819 | 3.91 | 0.0849 | 3.11 | 14.75 |
| 5 | 8781 | 3.35 | -0.5400 | 3.97 | 13.68 |
| 6 | 9410 | 3.42 | -0.1653 | 4.07 | 14.15 |
| 7 | 7005 | 1.90 | -0.0966 | 3.61 | 9.67 |
| 8 | 7097 | 3.21 | -0.0329 | 2.64 | 10.46 |
| 9 | 8688 | 2.93 | -0.4494 | 4.06 | 10.72 |
| 10 | 9443 | 3.67 | -0.0460 | 3.57 | 15.36 |
| 11 | 8633 | 3.43 | -0.2201 | 3.93 | 16.09 |
| non-peened | 7080 | 0.41 | -0.14107 | 4.39 | 3.97 |

**Table 4.** The average values of surface roughness parameters – part 2

| Variant | *Sv*, µm | *Sz*, µm | *Sa*, µm | *Sal*, mm | *Str* |
|---|---|---|---|---|---|
| 1 | 14.58 | 26.9 | 2.00 | 0.0629 | 0.920 |
| 2 | 10.00 | 18.9 | 1.23 | 0.0519 | 0.905 |
| 3 | 11.34 | 17.9 | 1.68 | 0.0957 | 0.926 |
| 4 | 15.70 | 30.5 | 3.10 | 0.1426 | 0.856 |
| 5 | 23.70 | 37.4 | 2.68 | 0.0871 | 0.927 |
| 6 | 21.63 | 35.8 | 2.65 | 0.0959 | 0.906 |
| 7 | 11.50 | 21.2 | 1.49 | 0.0626 | 0.889 |
| 8 | 14.14 | 24.6 | 2.61 | 0.1144 | 0.910 |
| 9 | 21.20 | 31.9 | 2.32 | 0.0755 | 0.907 |
| 10 | 22.21 | 37.5 | 2.88 | 0.0965 | 0.899 |
| 11 | 22.68 | 38.8 | 2.68 | 0.0856 | 0.925 |
| non-peened | 6.14 | 8.1 | 0.33 | 0.02667 | 0.025 |

**Table 5.** The average values of surface roughness parameters – part 3

| Variant | *Sdq* | *Sdr*, % | *Spd*, 1/mm$^2$ | *S10z*, µm |
|---|---|---|---|---|
| 1 | 0.213 | 2.180 | 79.3 | 20.3 |
| 2 | 0.169 | 1.401 | 114.8 | 14.1 |
| 3 | 0.107 | 0.566 | 28.2 | 13.3 |
| 4 | 0.138 | 0.938 | 15.6 | 19.5 |
| 5 | 0.200 | 1.928 | 21.8 | 25.6 |
| 6 | 0.202 | 1.972 | 31.7 | 26.4 |
| 7 | 0.176 | 1.517 | 93.1 | 15.3 |
| 8 | 0.132 | 0.860 | 19.4 | 16.3 |
| 9 | 0.209 | 2.085 | 33.7 | 24.6 |
| 10 | 0.215 | 2.214 | 30.5 | 27.1 |
| 11 | 0.207 | 2.062 | 25.6 | 26.3 |
| non-peened | 0.082 | 0.334 | 428.1 | 4.4 |

According to the results presented in Table 3, the load capacity of shot peened adhesive bonds is in most cases higher than the load capacity of non-penned bonds. The increase in the load capacity of adhesive joints subjected to shot peening was possible due to the deformation of the adherends (the edge of the overlap was pressed against the adherend). The deformation resulted in constituting compressive stresses in the bond-line. Summing up the stresses from the deformation and from the external load resulted in a reduction of stresses in the bond-line of the joints subjected to shot-peening in comparison to untreated bonds. The mechanism of strengthening of adhesive bonds due to shot peening was investigated and described in more detail in [11].

Figures 3-5 show selected isometric images of the surface after shot peening.

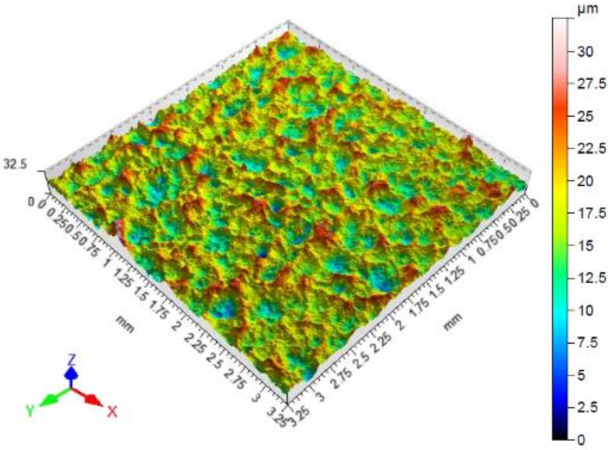

**Fig. 3.** Isometric image of the surface after shot peening - variant no 10 ($t$ = 120 s, $d$ = 1.0 mm, $p$ = 0.5 MPa)

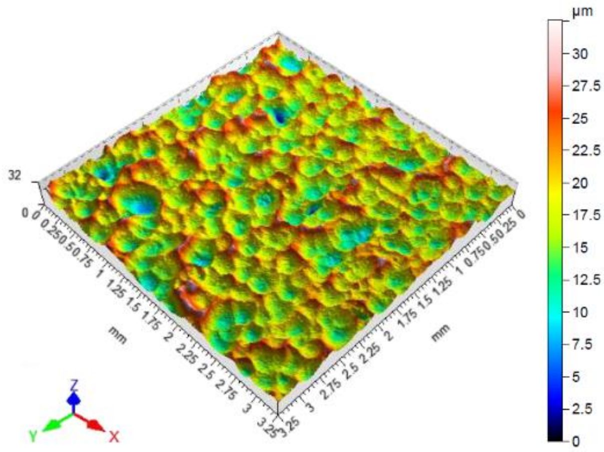

**Fig. 4.** Isometric image of the surface after shot peening - variant no 4 ($t$ = 180 s, $d$ = 1.5 mm, $p$ = 0.5 MPa)

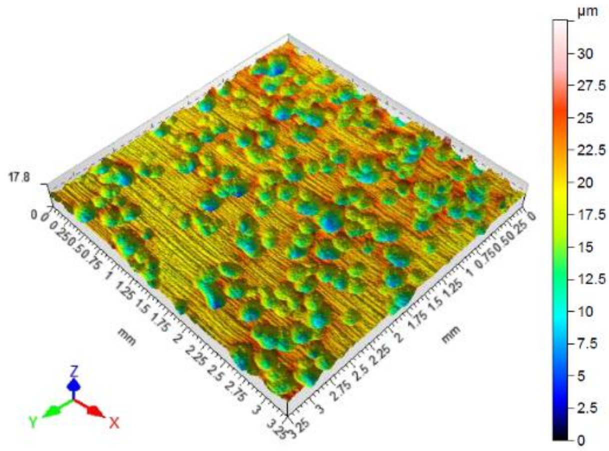

**Fig. 5.** Isometric image of the surface after shot peening - variant no 3 (t = 60 s, d = 1.5 mm, p = 0.3 MPa)

On the basis of Figures 3-5, it can be concluded that numerous spherical recesses appeard on the surface of the samples subjected to phot peening. Depending on the adopted processing parameters, these surfaces differ in the density of visible imprints resulting from the impact of burnishing elements. Variant no. 10 and 4 is characterized by full coverage with the imprints after shot peening. However, in the case of variant no. 3, incomplete coverage with the imprints can be observed.

The first stage of the analysis was to determine the relationship between the load capacity of adhesive joints after shot peening and 3D surface roughness parameters. For this purpose, one-way ANOVA, regression and correlation analysis were performed. It was assumed that the results of the analysis are statistically significant when the probability values (p-value) are lower than the significance level ($\alpha$) of 0.05. Probability values determined for one-way ANOVA are presented in Table 6.

**Table 6.** One-way analysis of variance (ANOVA) results

| **Parameter** | **Independent variable** | ***Pv1**** |
|---|---|---|
| $P_t$ | *Sq* | 0.160 |
| $P_t$ | *Ssk* | 0.001 |
| $P_t$ | *Sku* | 0.036 |
| $P_t$ | *Sp* | 0.296 |
| $P_t$ | *Sv* | 0.000 |
| $P_t$ | *Sz* | 0.143 |
| $P_t$ | *Sa* | 0.261 |
| $P_t$ | *Sal* | 0.403 |
| $P_t$ | *Str* | 0.042 |
| $P_t$ | *Sdq* | 0.019 |
| $P_t$ | *Sdr* | 0.087 |
| $P_t$ | *Spd* | 0.001 |
| $P_t$ | *S10z* | 0.077 |

* *Pv1* – probability level determined in one-way analysis of variance (ANOVA).

The results of the one-way analysis of variance ANOVA (Table 6) indicate that within the adopted range of variability of the input factors, the independent variables *Ssk*, *Sku*, *Sv*, *Str*, *Sdq* and *Spd* have a significant impact on the dependent variable $P_t$. This is indicated by the probability values *Pv1*, which in these cases are less than 0.05.

Table 7 shows the results of the regression analysis.

**Table 7.** Regression analysis results

| **Parameter** | **Independent variable** | **Regression equation** | ***Pv2**** |
|---|---|---|---|
| $P_t$ | *Sq* | $y_{P_t} = 7500 + 154x_{Sq}$ | 0.623 |
| $P_t$ | *Ssk* | $y_{P_t} = 7623 - 1405x_{Ssk}$ | 0.044 |
| $P_t$ | *Sku* | $y_{P_t} = 1905 + 1660x_{Sku}$ | 0.000 |
| $P_t$ | *Sp* | $y_{P_t} = 7157 + 65,6x_{Sp}$ | 0.370 |
| $P_t$ | *Sv* | $y_{P_t} = 5766 + 127x_{Sv}$ | 0.001 |
| $P_t$ | *Sz* | $y_{P_t} = 5885 + 70,6x_{Sz}$ | 0.011 |
| $P_t$ | *Sa* | $y_{P_t} = 7615 + 145x_{Sa}$ | 0.715 |
| $P_t$ | *Sal* | $y_{P_t} = 9652 - 19286x_{Sal}$ | 0.032 |
| $P_t$ | *Str* | $y_{P_t} = -15553 + 25920x_{Str}$ | 0.001 |
| $P_t$ | *Sdq* | $y_{P_t} = 4174 + 21089x_{Sdq}$ | 0.000 |
| $P_t$ | *Sdr* | $y_{P_t} = 5666 + 1415x_{Sdr}$ | 0.000 |
| $P_t$ | *Spd* | $y_{P_t} = 8190 - 5,37x_{Spd}$ | 0.441 |
| $P_t$ | *S10z* | $y_{P_t} = 5221 + 131x_{S10z}$ | 0.001 |

* *Pv2* –probability level determined for the independent variable in the regression analysis.

The linear regression equations presented in Table 7 show the influence of 3D surface roughness parameters on the load capacity of adhesive joints. According to the regression equations, within the adopted range of input factors variability, the load capacity of the adhesive joints increases with the increase in the surface roughness parameters. The exceptions are the parameters *Ssk*, *Sal* and *Spd*. Based on *Pv2* values, it can be concluded that the parameters *Ssk, Sku, Sv, Sz, Sal, Str, Sdq, Sdr* and *S10z* have a statistically significant impact on the load capacity of the adhesive joints ($Pv2<0.05$). Therefore, the equations describing the influence of the parameters *Ssk, Sku, Sv, Sz, Sal, Str, Sdq, Sdr* and *S10z* on the load capacity of adhesive joints could be used to predict the load capacity of adhesive joints after shot peening.

Table 8 shows the results of the linear correlation analysis.

**Table 8.** Results of the linear correlation analysis

| Parameter | Independent variable | Linear correlation coefficient R | Pv3* |
|---|---|---|---|
| $P_t$ | *Sq* | 0.089 | 0.623 |
| $P_t$ | *Ssk* | -0.353 | 0.044 |
| $P_t$ | *Sku* | 0.593 | 0.000 |
| $P_t$ | *Sp* | 0.161 | 0.370 |
| $P_t$ | *Sv* | 0.542 | 0.001 |
| $P_t$ | *Sz* | 0.437 | 0.011 |
| $P_t$ | *Sa* | 0.066 | 0.715 |
| $P_t$ | *Sal* | -0.375 | 0.032 |
| $P_t$ | *Str* | 0.534 | 0.001 |
| $P_t$ | *Sdq* | 0.603 | 0.000 |
| $P_t$ | *Sdr* | 0.635 | 0.000 |
| $P_t$ | *Spd* | -0.139 | 0.441 |
| $P_t$ | *S10z* | 0.564 | 0.001 |

* *Pv3* – probability level in linear correlation coefficient analysis.

The linear correlation coefficients presented in Table 8 are less than 0.7. Therefore, within the adopted range of input factors variability, there is no strong linear correlation between the surface roughness parameters and the load capacity of the adhesive joints. The highest value of the linear correlation occurs in the case of the *Sdr* parameter and amounts to 0.635. This is a positive correlation, which means that the load capacity of the adhesive joints increases with the increase in the value of the *Sdr* parameter. According to the probability value *Pv3*, the influence of the *Sdr* parameter on the load capacity of adhesive joints is statistically significant ($Pv3<0.05$).

The obtained results of the regression and correlation analysis allow to conclude that the *Sdr* roughness parameter can be used to evaluate the strengthening treatment (within the adopted range of input parameters variability).

The *Sdr* parameter (developed interfacial area ratio) is calculated as the ratio of the increase of the surface area of a limited scale inside the defined area to the defined area [2]. The *Sdr* parameter for a perfectly flat surface takes the value of 0. The value of the *Sdr* parameter is particularly important in the case of adhesion and bonding, because a surface with a larger area of development enables a stronger connection with another surface or coating [1].

After showing that within the adopted range of variability, the *Sdr* roughness parameter is most closely related to the load capacity of the adhesive joints, a mathematical model describing the impact of selected parameters of the shot peening on the value of the *Sdr* parameter was build. The mathematical model (1), taking the form of a second degree polynomial, was built in accordance with the methodology proposed in the Hartley PS/DS-P:Ha$_3$ plan:

$$\begin{aligned} y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 \\ + b_{11}{x_1}^2 + b_{22}{x_2}^2 \\ + b_{33}{x_3}^2 + b_{12}x_1x_2 \\ + b_{13}x_1x_3 + b_{23}x_2x_3, \end{aligned} \tag{1}$$

where : $y$ – output factor, $x_k$ – input factors, $k = 1, 2, 3$, $b_0, \dots, b_k$ – regression coefficients, $b_{kk}, \dots, b_{kj}$ – regression coefficients showing the effects of interaction of input factors, $j = 1, 2, 3$. The methodology of the Hartley PS/DS-P:Ha$_3$ plan is described in detail in [5].

The input factors were the parameters of the shot peening process: peening time *t*, diameter of the balls *d* and compressed air pressure *p*. The method of coding the input factors is presented in Table 9. The output factor was the value of the *Sdr* parameter.

**Table 9.** Ranges of volatility and the method of coding input factors

| Input factor | Variation units | Method of encoding factor |
|---|---|---|
| Processing time $t$, s | $\Delta x_1 = \frac{180-60}{2}$ | $x_1 = \frac{t-120}{60}$ |
| Ball diameter $d$, mm | $\Delta x_2 = \frac{1.5-0.5}{2}$ | $x_2 = \frac{d-1}{0.5}$ |
| Pressure $p$, MPa | $\Delta x_3 = \frac{0.5-0.3}{2}$ | $x_3 = \frac{p-0.4}{0.1}$ |

The first stage of the mathematical model building was to calculate the values of the the regression equation coefficients and to determine the critical values for the the regression equation coefficients in accordance with the methodology of the Hartley PS/DS-P:Ha$_3$ plan [5].

The calculated values of the equation coefficients were evaluated for statistical significance. The purpose of the assessment was to check whether the calculated coefficients have a significant impact on the result of the equation and whether the equation is useful for estimating the output value (*Sdr* value). The evaluation of the significance of the equation coefficients consisted in comparing the calculated absolute value of the coefficients and the critical value of the coefficients. If the determined critical value of the coefficient was greater than or equal to the calculated absolute value, then the null hypothesis had to be rejected and the alternative hypothesis adopted. Accepting the alternative hypothesis meant recognizing that a given coefficient of the regression equation had a statistically significant impact on the output variable of the equation. Confirmation of the null hypothesis meant, that the given coefficient had no statistically significant impact on the model result and could be removed from the regression equation. The calculated and critical values of the regression equation coefficients and the results of the significance assessment are presented in Table 10.

**Table 10.** Critical values of coefficients, calculated values of coefficients and significance assessment

| **Coefficient** | **Calculated value** | **Critical value** | **Significance of coefficient** | |
|---|---|---|---|---|
| $b_0$ | 2.026 | 0.093 | $\lvert b_0\rvert > b_{0kr}$ | Yes |
| $b_1$ | -0.061 | 0.069 | $\lvert b_1\rvert < b_{1kr}$ | No |
| $b_2$ | -0.456 | 0.069 | $\lvert b_2\rvert > b_{2kr}$ | Yes |
| $b_3$ | 0.213 | 0.069 | $\lvert b_3\rvert > b_{3kr}$ | Yes |
| $b_{11}$ | -0.065 | 0.108 | $\lvert b_{11}\rvert < b_{11kr}$ | No |
| $b_{22}$ | -0.826 | 0.108 | $\lvert b_{22}\rvert > b_{22kr}$ | Yes |
| $b_{33}$ | 0.135 | 0.108 | $\lvert b_{33}\rvert > b_{33kr}$ | Yes |
| $b_{12}$ | 0.288 | 0.084 | $\lvert b_{12}\rvert > b_{12kr}$ | Yes |
| $b_{13}$ | -0.519 | 0.084 | $\lvert b_{13}\rvert > b_{13kr}$ | Yes |
| $b_{23}$ | -0.102 | 0.084 | $\lvert b_{23}\rvert > b_{23kr}$ | Yes |

Based on the results of the significance assessment, it was decided to remove two coefficients ($b_1$ and $b_{11}$) from the regression equation. After eliminating insignificant coefficients, decoding the equation using appropriate values from Table 9 and ordering, the following regression equation was obtained (2):

$$\begin{aligned} y_{Sdr} = -2.85 + 0.025x_t + 5.312x_d \\ + 3.81x_p - 3.304{x_d}^2 \\ + 13.5{x_p}^2 + 0.01x_t x_d \\ - 0.087x_t x_p \\ - 2.04x_d x_p, \end{aligned} \tag{2}$$

where $y_{Sdr}$ is the surface roughness parameter *Sdr*, $x_t$ is the processing time variable, $x_d$ is the ball diameter variable and $x_p$ is the compressed air pressure variable. The regression equation (2) describe the effects of peening time, ball diameter and compressed air pressure on the surface *roughness* parameter *Sdr*. The obtained model is nonlinear. Tables 11-12 and Figure 6 show the *Sdr* parameter values obtained from measurements and calculated on the basis of the model (2).

**Table 11.** Results of measurements for the *Sdr* roughness parameter

| **Variant** | **Results of measurements** | | |
|---|---|---|---|
| | $y_1$ | $y_2$ | $y_3$ |
| 1 | 2.025 | 2.159 | 2.357 |
| 2 | 1.186 | 1.504 | 1.512 |
| 3 | 0.577 | 0.558 | 0.562 |
| 4 | 0.861 | 0.960 | 0.992 |
| 5 | 2.041 | 1.669 | 2.073 |
| 6 | 1.957 | 1.732 | 2.226 |
| 7 | 1.341 | 1.590 | 1.619 |
| 8 | 0.795 | 0.863 | 0.923 |
| 9 | 2.037 | 2.121 | 2.098 |
| 10 | 2.126 | 2.257 | 2.258 |
| 11 | 2.039 | 2.023 | 2.123 |

* $y_1, y_2, y_3$ – values of the *Sdr* parameter obtained in the first, second and third measurement.

**Table 12.** Results of calculations for the *Sdr* roughness parameter

| **Variant** | $\bar{y}_i$ | $S^2(y)_i$ | $\hat{y}_i$ | $(\bar{y}_i - \hat{y}_i)^2$ |
|---|---|---|---|---|
| 1 | 2.180 | 0.0279 | 2.625 | 0.1977 |
| 2 | 1.401 | 0.0346 | 1.545 | 0.0208 |
| 3 | 0.566 | 0.0001 | 0.000 | 0.3200 |
| 4 | 0.938 | 0.0047 | 0.489 | 0.2013 |
| 5 | 1.928 | 0.0504 | 1.786 | 0.0201 |
| 6 | 1.972 | 0.0612 | 1.810 | 0.0261 |
| 7 | 1.517 | 0.0234 | 1.428 | 0.0079 |
| 8 | 0.860 | 0.0041 | 0.516 | 0.1186 |
| 9 | 2.085 | 0.0019 | 1.783 | 0.0914 |
| 10 | 2.214 | 0.0058 | 2.083 | 0.0171 |
| 11 | 2.062 | 0.0029 | 1.798 | 0.0695 |

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

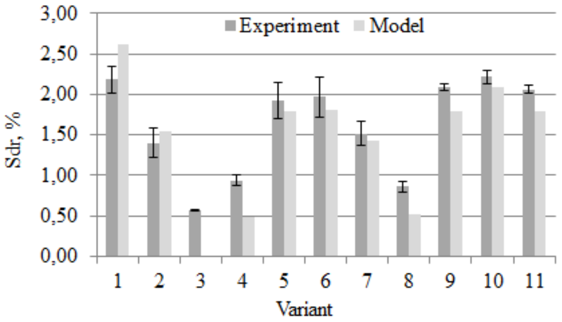

**Fig. 6.** Results of measurements and calculations for the roughness parameter *Sdr*

The model and experimental values are similar. The linear correlation coefficient is 0.95. Figures 7-9 shows graphs developed from the regression equation (2).

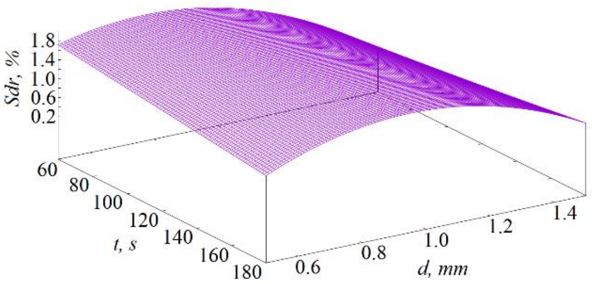

**Fig. 7.** Graph showing the influence of time *t* and ball diameter *d* on the value of the roughness parameter *Sdr* (*p* = 0.4 MPa)

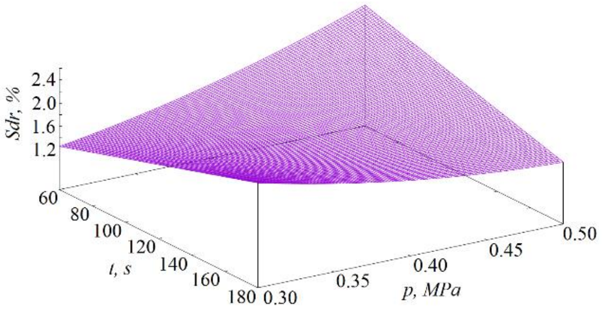

**Fig. 8.** Graph showing the influence of time *t* and pressure *p* on the value of the roughness parameter *Sdr* (*d* = 1 mm)

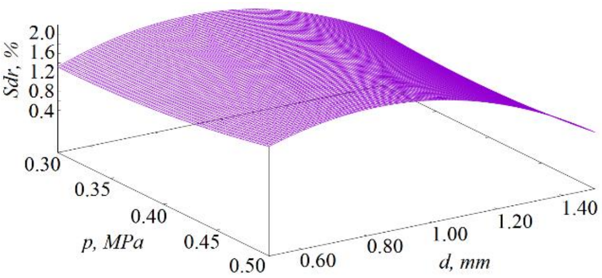

**Fig. 9.** Graph showing the influence of ball diameter *d* and pressure *p* on the value of the roughness parameter *Sdr* (*t* = 60 s)

Based on the regression equation (2) and the graphs presented in the Figures 7-9, it can be concluded that for the assumed range of input factors variability, the influence of the ball diameter and compressed air pressure on the value of the *Sdr* parameter is non-linear. In the case of the diameter of the balls, the extreme (maximum value of the output parameter) is observed for balls with a diameter of 1 mm. However, in the case of compressed air pressure, the extreme (minimum value of the output parameter) is observed in the case of treatment with a pressure of 0.4 MPa. The complex interaction of the peening time and the diameter of the balls contributed to the increase in the value of the *Sdr* parameter. The complex interaction of machining time and pressure as well as ball diameter and pressure contributes to a reduction in the *Sdr* value.

## 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 the load capacity of adhesive joints made of EN AW-2024-T3 aluminum alloy after shot peening is the *Sdr* parameter,
- the value of the linear correlation coefficient between the *Sdr* parameter and the load capacity of the adhesive joints is 0.635, which means that with the increase of the *Sdr* parameter, the load capacity increases,
- according with the mathematical model describing the impact of the shot peening parameters on the value of the *Sdr* parameter, it can be stated that the impact of the ball diameter and compressed air pressure on the value of the *Sdr* parameter is non-linear (the maximum value of the output parameter is observed for balls with a diameter of 1 mm, and the minimum value for with a pressure of 0.4 MPa), the complex interaction of shot peening time and ball diameter contributes to an increase in *Sdr*, and the combined interaction of shot peening time and pressure, and ball diameter and pressure contributes to a decrease in *Sdr*.

To sum up, the *Sdr* parameter can be used to predict the load capacity of adhesive joints after shot peening and to assess the strengthening treatment (within the assumed range of input parameters variability). The method of evaluating the strengthening treatment based on the measurement of roughness in the 3D system can therefore be an alternative to the Almen strip test, which was proposed in [10]. Compared to the Almen strip test, roughness measurements are simpler and cheaper, which makes them more attractive to those who would like to use shot peening to strengthen adhesive joints and would seek an effective method to control such strengthening treatment.

## References

1. Grzesik W. (2016). Influence of surface textures produced by finishing operations on their functional properties. *Journal of Machine Engineering* 16(1), 15-23.
2. International Organization for Standardization. (2021). *Geometrical product specifications (GPS) — Surface texture: Areal — Part 2: Terms, definitions and surface texture parameters* (ISO 25178-2:2021).
3. Korzyńska K. (2019). *Badania wpływu procesu pneumokulowania na wytrzymałość zakładkowych połączeń klejowych*. [Doctoral dissertation, Lublin University of Technology].
4. 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 peenin. *Journal of Adhesion Science and Technology* 32(17), 1849–1860. https://doi.org/10.1080/01694243.2018.1450108.
5. Korzyński M. (2013). *Metodyka eksperymentu. Planowanie, realizacjia i statystyczne opracowanie wyników eksperymentów technologicznych*. Wydawnictwo Naukowo-Techniczne WNT.
6. Polish Committee for Standardization. (2009). *Adhesives - Determination of tensile lap-shear strength of bonded assemblies* (PN-EN 1465:2009).
7. 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* (pp. 773–810). Springer. https://doi.org/10.1007/978-3-319-55411-2_27.
8. Zaleski K. (2018). *Technologia nagniatania dynamicznego*. Wydawnictwo Politechniki Lubelskiej. https://bc.pollub.pl/dlibra/publication/13542/edition/13216/content?ref=desc.
9. Zielecki W., Perłowski R., Trzepieciński T. (2007). Analiza stanu naprężeń w spoinie połączenia klejowego umocnionego metodą pneumokulkowania *Technologia i Automatyzacja Montażu (Assembly Techniques and Technologies)*, 1, 31-33.
10. 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. https://doi.org/10.1007/s00170-021-08587-x.
11. Zielecki, W., Godzimirski, J., Ozga, E. (2022). The influence of shot peening on the stress state in the adhesive layer and the load capacity of adhesive joints. *Technologia i Automatyzacja Montażu (Assembly Techniques and Technologies)*, 116(2), 32-40. https://doi.org/10.7862/tiam.2022.2.5.
12. Zielecki, W., Ozga, E. (2022). Relationship between surface roughness and load capacity of adhesive joints made of aluminum alloy 2024-T3 after shot peening. *Technologia i Automatyzacja Montażu (Assembly Techniques and Technologies)*, 118(4), 34-45. https://doi.org/10.7862/tiam.2022.4.4.