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Double-criterion optimization of pneumatic ball peening operations for single-lap, adhesive joints of Ti6Al4V alloy sheet metal

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ABSTRACT

This work focused on single-lap adhesive joints made from 2 mm thick Ti6Al4V titanium alloy sheets, bonded with Araldite glue, and subjected to pneumatic ball peening treatment to enhance their shear strength. Studies on the influence of key processing parameters (supply pressure, ball diameter, and processing time) were conducted following the static, deterministic, sequential, polyselective Hartley PS/DS – P:Ha3 plan. These studies resulted in a mathematical model, represented as a second-degree polynomial, which describes the effects of these parameters on both the strength of the joints and the operational costs. Single-criterion optimization was performed for each criterion, revealing the existence of two distinct sets of optimal processing parameters. This finding was the premise for conducting double-criterion optimization, allowing for the identification of a compromise set of pneumatic ball peening parameters. The studies confirmed the effectiveness of pneumatic shot peening, demonstrating the potential to improve shear strength by up to 80%.

Keywords: bonding, lap joints, optimization, costs, shear strength

INTRODUCTION

Lap bonding of metal sheets is becoming increasingly popular due to its advantages, such as low labor intensity, ease of bonding, and the ability to join metals and their alloys that are difficult to join using other methods, including titanium and its alloys [1]. Despite the development of adhesives with improved properties, a significant drawback of these adhesive joints is their relatively low strength, often lower than that of the bonded metals. In an effort to improve the strength of such joints, adhesives with increasingly better properties are being developed, and various methods of preparing the surfaces to be joined are being tested to increase the adhesion of adhesives [2, 3]. Various attempts are also being made to improve the design and technology of joints, such as leaving adhesive flash at the edges of the overlap [4, 5] or making an undercut along the edge of the joint [6]. The strength of SLJs can also be improved by using bi-adhesive bondlines [7, 8] or gaps in the bond [9]. Good results are achieved by chamfering or beveling the outer or inner edges of the joined sheets [10, 11] and, to a lesser extent, by making one or more holes in the sheets in the bond area [12]. Where possible, pre-bending of the bonded plates can be used [13, 14]. Good results are achieved with support patches bonded to the lateral surfaces of the adherends [15, 16]. High-frequency ultrasonic vibration can be used effectively during the cross-linking of the adhesive [17, 18]. However, many of these methods are either not very effective or require additional machining operations, which can be challenging to perform in real-world applications, especially for thin, large sheets.

The gravity shot peening method [19, 20] is a very simple processing method, easily applicable to SLJs and bonded components of various shapes. This method involves shooting hard balls (preferably bearing balls) delivered in a stream of compressed air at the workpiece surface. The result is a non-directional, point-like surface structure with characteristic gentle depressions and a strengthened subsurface layer of the workpiece. This strengthening occurs by introducing compressive stresses into the surface layer, which, in the case of low-stiffness components (e.g., thin sheets), induces their deformation. This phenomenon is utilized in pneumatic shot peening of SLJs, where the deformations resulting from pneumatic shot peening exert pressure on the joint edges, counteracting the normal stresses (peel and tear stresses) concentrated in those areas, thus enhancing the joint's strength. Unlike industrially used shot peening equipment (shot peening, vacuum blasting, etc.), shot peening machines lack drive systems or ball separation systems; they are simple in design [21], durable, reliable, and very inexpensive. This makes the station's cost per operation negligible. However, both the effects and unit costs of the shot peening process primarily depend on its parameters; therefore, optimization is recommended, as described in this paper for single-lap adhesive joints of Ti6Al4V alloy sheets.

The scientific innovation of this work involved increasing the shear strength of single-lap adhesive joints of Ti6Al4V titanium alloy by strengthening the lap zone using a dispersive jet burnishing process (pneumatic coupling). The paper employs an innovative, dual-criteria optimization of the pneumatic coupling process, combining costs and the strength of the adhesive lap joints. This approach demonstrated the validity of this method.

RESEARCH METHODOLOGY

Bench testing

The test samples consisted of Ti6Al4V titanium alloy with the chemical composition detailed in Table 1 and properties outlined in Table 2. The samples tested were sheet metal measuring: 100 × 25 × 2 mm, bonded using Araldite 2014-1 adhesive composition. Prior to bonding, the surfaces of the each joined elements were prepared through electrocorundum abrasive blasting under the following conditions: grain size *wz* = 0.27 mm, air pressure p = 0.7 MPa, time t = 30 s, distance of the nozzle from the sandblasted surface approx. 300 mm, the samples were subsequently cleaned by washing them in acetone for 2 min. The two-component Araldite 2014-1 adhesive was mixed to a uniform consistency in a 1:1 weight ratio and applied to the degreased inner surfaces of the plates, which were then joined by overlapping for a length of 12.5 mm;

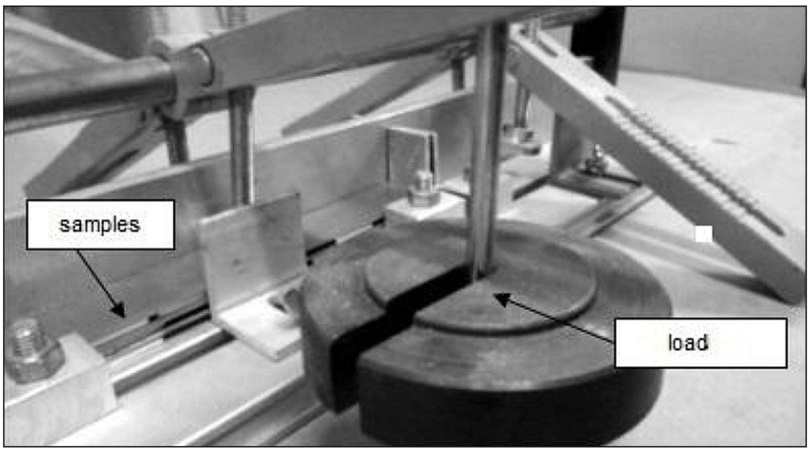

Figure 1. The process of cross-linking the joints: the method of placing the samples in the device

Table 1. Chemical composition and percentage content of individual components of the Ti6Al4V titanium alloy used for testing

V	Fe	N	C	Al	Mn	Mo	Sn	Zr	Cr	Cu	Pd	Si	Ti
4.576	0.144	0.186	0.023	6.628	0.013	0.218	0.005	0.001	0.038	0.001	0.001	0.025	88.32

Table 2. Physical and mechanical properties of the Ti6Al4V titanium alloy

Elasticity module *E* [Gpa]	Tensile strength *Rm* [MPa]	Yield strength *Rp0.2* [MPa]	Fatigue strength*Rz* [MPa] for 10^7 cycles	Density *ρ* [g/cm³]
110 ÷ 114	960 ÷ 970	850 ÷ 900	620 ÷ 725	4.5

the adhesive layer thickness was approximately 0.4 mm. For a cross-linking period of 7 days, the overlaps were placed in a device (Figure 1) that ensured a constant pressure of 0.05 MPa; the cross-linking process occurred at an ambient temperature of 24±2 °C. The finishing process involved mechanically removing excess adhesive and visually inspecting the quality of the joints. The samples were then subjected to pneumatic peening as illustrated in Figure 2.

Pneumatic shot peening was performed on both sides of the overlap using the device shown in Figure 3 [20], where the balls are moved upward (toward the workpiece) by compressed

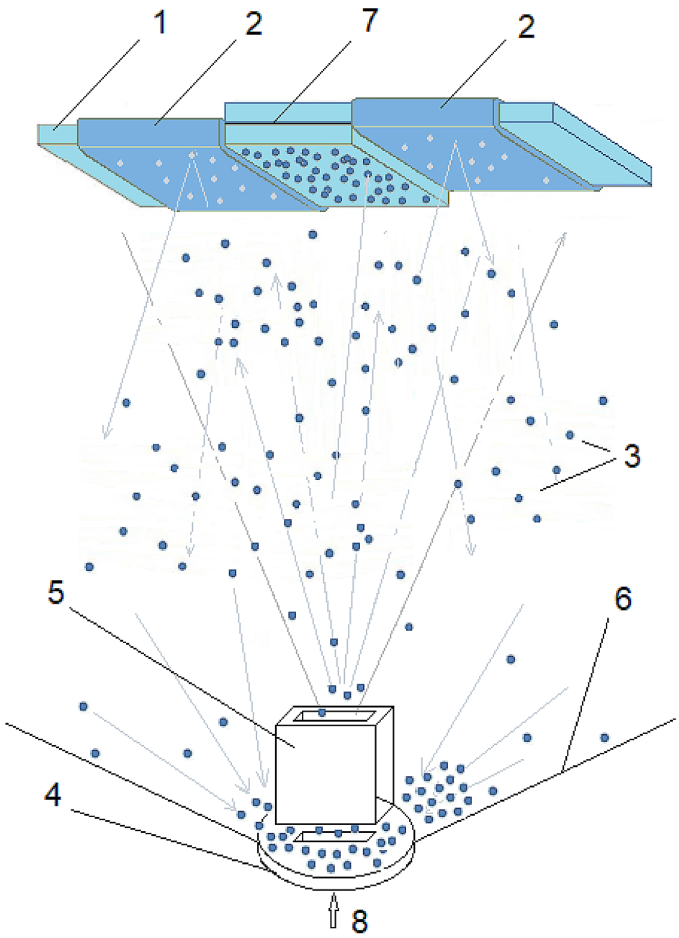

Figure 2. Process diagram and general view of the pneumatic shot peening station: 1 – processed overlap, 2 – protective cover against shot peening, 3 – steel balls, 4 – compressed air supply nozzle, 5 – de Laval nozzle accelerating the speed of the ball stream, 6 – bottom of the working chamber where the balls collect, falling under the influence of gravity after hitting the processed surface of the overlap, 7 – glue layer, 8 – compressed air supply

Figure 3. General view of the pneumatic shot peening station

air released from a slot nozzle. After striking the workpiece surface, the balls fall under gravity into the nozzle zone and are ejected upward again.

The tests followed the static, deterministic, sequential, polyselective Hartley *PS/DS – P:Ha3* plan with three-time repeatability. This plan facilitates the determination of the relationship between input factors (process parameters) and the output factor, represented as a second-degree equation. Its implementation required conducting 11 experiments with a specific configuration of input factors. Based on previous studies, the input factors were: supply pressure, ball diameter, and processing time. Steel bearing balls with diameters of 1.5, 2.0, and 2.5 mm were used, and the nozzle outlet was positioned 100 mm from the machined surface. In individual experiments, the air pressure was 0.2, 0.3, and 0.4 MPa, and the machining time was 60, 120, and 180 s. Under these conditions, complete surface coverage with machining marks was achieved. The output factors comprised the unit cost of the pneumatic shot peening operation for each experiment and the shear strength of the bonded overlaps. Calculations were performed at a significance level of $\alpha = 0.05$. The strength tests were conducted using an INSTRON ElectroPlus™ E10000 machine, applying an axial force to the samples at a speed of 5 mm/min. The method of mounting and loading the samples (Figure 4) was selected to ensure that the adhesive joint was subjected to shear stresses.

Pneumatic shot peening cost analysis

The unit costs of the pneumatic shot peening operation include: the cost of the ball batch

Figure 4. Method of mounting samples for strength tests

(in this case, 200 ml), the cost of compressed air (which depends on the volume of air drawn for the operation at a specified operating pressure), and the cost of electricity consumed (which depends on the price of energy and the duration of the operation). Due to the very simple and inexpensive design of the device and the very long durability of the balls, the cost of the working station was considered negligible.

Based on the manufacturers' data, previous experience, and long-term practice in pneumatic shot peening technology, the input data (durability of balls t_k, weight of a batch of 200 ml of balls w_k, and price c_k of balls of different diameters, as well as the cost of electricity (c_e= 0.55 PLN/kW) and the amount of electricity needed to produce 1 m^3 of air e_{pow}= 0.15 kWh/m^3) were adopted (see Table 3) to calculate the individual components and unit production costs (variable costs of the pneumatic shot peening operation for each experiment), which were calculated using the formula:

$$K_w = v_p \times e_{pow} \times c_e \times 2t + \\ + \frac{w_k \times c_k \times 2t}{t_k \times 3600} \text{PLN} \quad (1)$$

The calculation results are presented in Table 4 (1 USD - 3.6317 PLN). The tests followed the static, deterministic, sequential, polyselective Hartley PS/DS – P:Ha3 plan with three-time repeatability, as described in [22]. This plan facilitates the determination of the relationship between input factors (process parameters) and the output factor, represented as a second-degree equation. Its implementation required conducting 11 experiments with a specific configuration of input factors. Based on the results of previous studies, the input factors were: supply pressure, ball diameter, and processing time. The output factors comprised the unit cost of the pneumatic shot peening operation for each experiment and the shear strength of the bonded overlaps.

TEST RESULTS AND OPTIMIZATION

The results of the strength tests and cost calculations are presented in Table 4. After executing the appropriate calculation procedure [22], the following relationships were obtained:

Table 3. Input data for calculating the unit costs of pneumatic shot peening operations

Pressure value p [MPa]	Experimentally determined compressed air flow rate V_p[m^3/h]	Ball diameter d [mm]	Ball durability t_k [h]	Ball batch weight w_k [kg]	Ball price ck [PLN/kg]
0.2	11.3	1.5	500	1.0631	65
0.3	14.5	2.0	750	1.0563	60
0.4	18.8	2.5	1000	1.0205	60

Table 4. Results of tests and auxiliary calculations of the shear strength of single-lap adhesive joints; *Rt* – shear strength, i.e., the force ([N]) causing the joint to break, *Kw* – operation cost [PLN], x1 - supply pressure [MPa], x2 - ball diameter [mm], x3 - processing time [s]

No.	x_1	x_2	x_3	R_{t1}	R_{t2}	R_{t3}	$\overline{R_t}$	K_w
1	0.4	2.5	180	7638	8241	8120	8000	0.161
2	0.4	1.5	60	6423	5297	7402	6374	0.057
3	0.2	2.5	60	5954	7144	6915	6671	0.033
4	0.2	1.5	180	8001	7813	7940	7918	0.107
5	0.4	2.0	120	5901	5696	6836	6144	0.109
6	0.2	2.0	120	6112	6389	5417	5973	0.068
7	0.3	2.5	120	7882	7526	7032	7480	0.084
8	0.3	1.5	120	6184	6859	7062	6702	0.089
9	0.3	2.0	180	7751	7873	6723	7449	0.128
10	0.3	2.0	60	5958	6288	5587	5944	0.043
11	0.3	2.0	120	6075	7886	7805	7255	0.085

Note: The average strength of the samples without ball peening was 5036 N.

$$R_t = 24403 + 2661d^2 - 2872p - \\ - 14954d + 12t + 14360pd \quad (2)$$

$$K_w = 0.7020 - 1.9166p - 0.3540d - \\ - 0.009t + 0.3083p^2 - 0.0043d^2 + 0.00001t^2 \\ +0.8900pd + 0.0013pt + 0.0006dt \quad (3)$$

This expresses the influence of three basic pneumatic shot peening parameters on the strength of single-lap adhesive joints and the cost of the pneumatic shot peening operation. The resulting models were employed to perform single-criterion optimization twice: first, using the shear strength of the joints as the optimization criterion, and second, using the unit cost of the pneumatic shot peening operation. Given that the models obtained from the experiment are nonlinear and describe an irregular adequate region, optimization was performed using the iterative search method of the adequate region, following the algorithm presented in Figure 5. The adequate region is defined as a three-dimensional factor space – comprising three input parameters (variables) of the pneumatic shot peening process, consistent with the basic research. This region was searched iteratively with a triple FOR-NEXT loop, and only results better than the cut-off levels of 7500 N and 0.14 PLN were printed (see Tables 5 and 6).

The conducted research indicates that the optimal parameters for strength differ from those that yield the lowest operating costs. Specifically, while the optimal pressure remains the same (0.2 MPa), the optimal values for ball diameter and machining time differ. This finding led to the necessity for conducting a double-criterion optimization, performed using the min-max method. This method minimizes

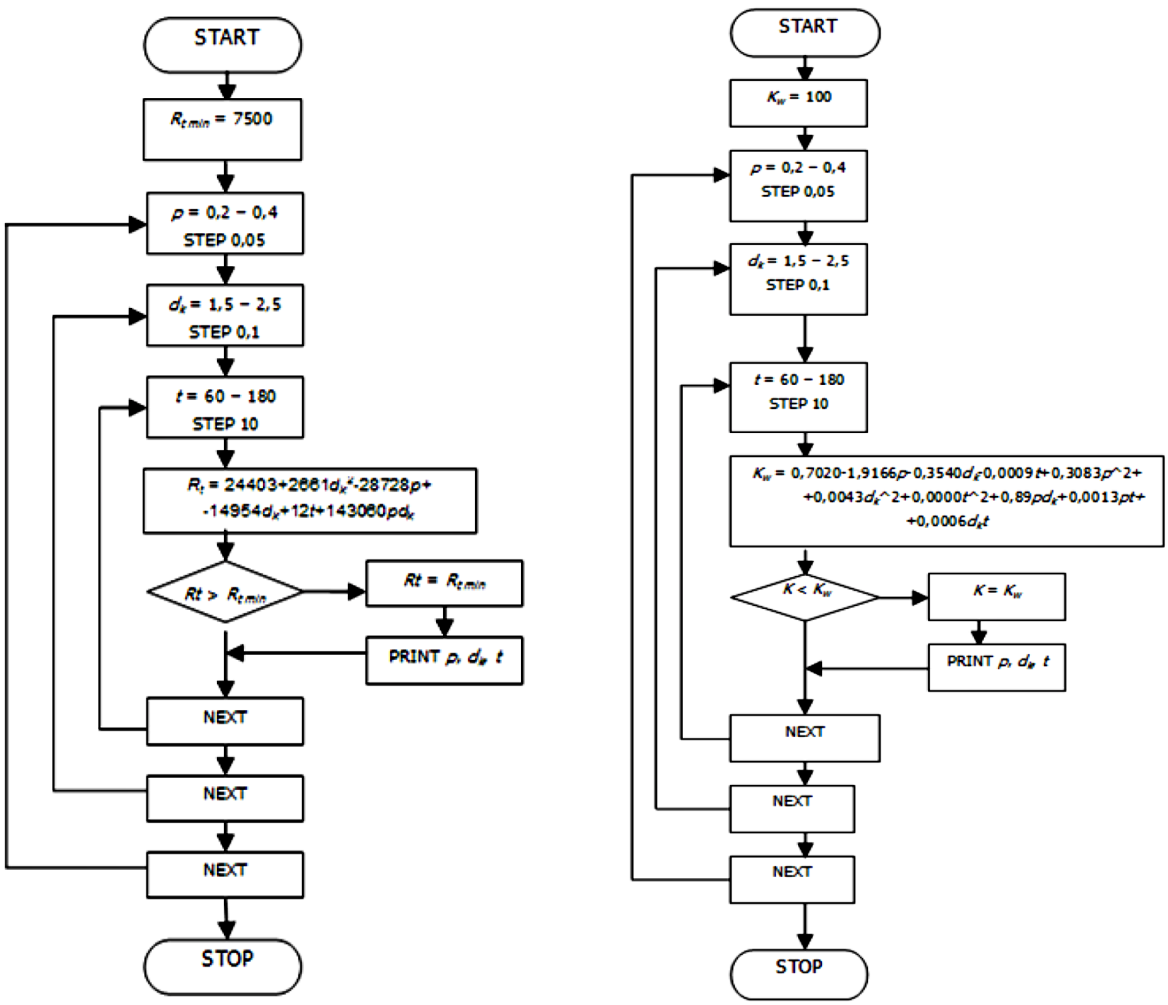

Figure 5. Optimization calculation algorithms: a) for optimization with respect to the strength of the overlaps, b) for optimization of the costs of the pneumatic shot peeningoperation

the maximum deviations from the optimal (extreme) values previously obtained for each of the individual criteria. These deviations were calculated as follows:

$$\Delta'_i(x) = \frac{|f_i(x) - F_i^o|}{|F_i^o|} \quad (4)$$

$$\Delta''_i(x) = \frac{|f_i(x) - F_i^o|}{|f_i(x)|} \quad (5)$$

where: F_i^o – optimal value of the i-th result function (objective function), $f_i(x)$ – value of the i-th result function calculated for specific machining parameters from models (3) and (4). In this case, i = 2 means that the values of two result functions were calculated: the costs of the pneumatic shot peening operation and the shear strength of the joints.

To determine the input parameters of the pneumatic peening process for which the individual objective functions yield results that are as similar as possible and as close as possible to the extremes of both functions (i.e., for which the increases and decreases of both objective functions are the same and as small as possible), the following formula was used:

$$\underset{i \in I}{\Lambda}\left(\Delta_i(x) = \max\{w_i\Delta'_i(x), w_i\Delta''_i(x)\}\right) \quad (6)$$

where: i – number of objective functions, w_i– weighting factor of the i-th objective function. In this case, both criteria (strength and costs) were treated equally, with a weight of $w_i = 1$.

All calculations were performed using appropriately programmed EXCEL spreadsheets. The results are presented in Table 7, highlighting the best outcomes and the optimal set of machining parameters with respect to both criteria simultaneously.

Table 5. Calculation results for optimization with respect to shear strength

No.	Pressure p [MPa]	Ball diameter d [mm]	Time t [s]	Strength $R_{tśr}$ [N]
1	0.2	1.5	140	7618
2	0.2	1.5	150	7738
3	0.2	1.5	160	7858
4	0.2	1.5	170	7978
5	0.2	1.5	180	8098
6	0.2	1.6	170	7556
7	0.2	1.6	180	7676
8	0.25	1.5	180	7593

Table 6. Search results for the adequate region of cost optimization

No.	Pressure p [MPa]	Ball diameter d [mm]	Time t [s]	Operation cost K_w[PLN]
1	0.2	2.1	60	0.133
2	0.2	2.2	60	0.125
3	0.2	2.3	60	0.118
4	0.2	2.4	60	0.110
5	0.25	2.1	60	0.140
6	0.25	2.2	60	0.136
7	0.25	2.3	60	0.133
8	0.25	2.4	60	0.129
9	0.35	1.5	60	0.126
10	0.35	1.6	60	0.131
11	0.35	1.7	60	0.136
12	0.4	1.5	60	0.111

Table 7. Results of the double-criterion optimization of the pneumatic shot peening process of the overlaps

Ball diameter [mm]	Time [s]	Operation cost k_{jz} [PLN]	Strength P_t [MPa]	Δ'_{kjz}	Δ''_{kjz}	Δ'_{Rt}	Δ''_{Rt}	$\lvert\Delta'_{kjz}-\Delta''_{kjz}\rvert$	$\lvert\Delta'_{Pt}-\Delta''_{Pt}\rvert$	$\lvert\Delta'_{kjz}-\Delta''_{kjz}\rvert - \lvert\Delta'_{Pt}-\Delta''_{Pt}\rvert$
1.5	180	0.611	8098	4.55	0.82	0.00	0.00	3.73	0.00	3.73458
1.6	60	0.174	6236	0.58	0.37	0.23	0.30	0.21	0.07	0.14534
1.6	70	0.2	6356	0.82	0.45	0.22	0.27	0.37	0.06	0.30922
1.6	80	0.228	6476	1.07	0.52	0.20	0.25	0.56	0.05	0.50501
1.6	90	0.258	6596	1.35	0.57	0.19	0.23	0.77	0.04	0.72957
1.6	100	0.29	6716	1.64	0.62	0.17	0.21	1.02	0.04	0.98055
1.6	110	0.324	6836	1.95	0.66	0.16	0.18	1.28	0.03	1.25619
1.6	120	0.36	6956	2.27	0.69	0.14	0.16	1.58	0.02	1.55513
1.6	130	0.398	7076	2.62	0.72	0.13	0.14	1.89	0.02	1.87633
1.6	140	0.438	7196	2.98	0.75	0.11	0.13	2.23	0.01	2.21899
1.6	150	0.48	7316	3.36	0.77	0.10	0.11	2.59	0.01	2.58248
1.6	160	0.524	7436	3.76	0.79	0.08	0.09	2.97	0.01	2.96628
1.6	170	0.57	7556	4.18	0.81	0.07	0.07	3.37	0.00	3.37000
1.6	180	0.618	7676	4.62	0.82	0.05	0.05	3.80	0.00	3.79331
1.7	60	0.166	5867	0.51	0.34	0.28	0.38	0.17	0.10	0.06698
1.7	70	0.193	5987	0.75	0.43	0.26	0.35	0.32	0.09	0.23258
1.7	80	0.223	6107	1.03	0.51	0.25	0.33	0.52	0.08	0.44039
1.7	90	0.254	6227	1.31	0.57	0.23	0.30	0.74	0.07	0.67274
1.7	100	0.287	6347	1.61	0.62	0.22	0.28	0.99	0.06	0.93271
1.7	110	0.323	6467	1.94	0.66	0.20	0.25	1.28	0.05	1.22612
1.7	120	0.36	6587	2.27	0.69	0.19	0.23	1.58	0.04	1.53548
1.7	130	0.399	6707	2.63	0.72	0.17	0.21	1.90	0.04	1.86734
1.7	140	0.44	6827	3.00	0.75	0.16	0.19	2.25	0.03	2.22078
1.7	150	0.484	6947	3.40	0.77	0.14	0.17	2.63	0.02	2.60372
1.7	160	0.529	7067	3.81	0.79	0.13	0.15	3.02	0.02	2.99845
1.7	170	0.576	7187	4.24	0.81	0.11	0.13	3.43	0.01	3.41307
1.7	180	0.626	7307	4.69	0.82	0.10	0.11	3.87	0.01	3.85605
1.8	60	0.158	5552	0.44	0.30	0.31	0.46	0.13	0.14	-0.01171
1.8	70	0.186	5672	0.69	0.41	0.30	0.43	0.28	0.13	0.15408
1.8	80	0.217	5792	0.97	0.49	0.28	0.40	0.48	0.11	0.36618
1.8	90	0.25	5912	1.27	0.56	0.27	0.37	0.71	0.10	0.61284
1.8	100	0.284	6032	1.58	0.61	0.26	0.34	0.97	0.09	0.88169
1.8	110	0.321	6152	1.92	0.66	0.24	0.32	1.26	0.08	1.18478
1.8	120	0.359	6272	2.26	0.69	0.23	0.29	1.57	0.07	1.50433
1.8	130	0.4	6392	2.64	0.73	0.21	0.27	1.91	0.06	1.85508
1.8	140	0.443	6512	3.03	0.75	0.20	0.24	2.28	0.05	2.22783
1.8	150	0.487	6632	3.43	0.77	0.18	0.22	2.65	0.04	2.61308
1.8	160	0.534	6752	3.85	0.79	0.17	0.20	3.06	0.03	3.02736
1.8	170	0.582	6872	4.29	0.81	0.15	0.18	3.48	0.03	3.45287
1.8	180	0.633	6992	4.75	0.83	0.14	0.16	3.93	0.02	3.90668
1.9	60	0.15	5289	0.36	0.27	0.35	0.53	0.10	0.18	-0.08729
1.9	70	0.179	5409	0.63	0.39	0.33	0.50	0.24	0.17	0.07669
1.9	80	0.211	5529	0.92	0.48	0.32	0.46	0.44	0.15	0.29208
1.9	90	0.245	5649	1.23	0.55	0.30	0.43	0.68	0.13	0.54512
1.9	100	0.281	5769	1.55	0.61	0.29	0.40	0.95	0.12	0.82987
1.9	110	0.319	5889	1.90	0.66	0.27	0.38	1.24	0.10	1.14248

1.9	120	0.359	6009	2.26	0.69	0.26	0.35	1.57	0.09	1.48034
1.9	130	0.401	6129	2.65	0.73	0.24	0.32	1.92	0.08	1.84163
1.9	140	0.445	6249	3.05	0.75	0.23	0.30	2.29	0.07	2.22506
1.9	150	0.491	6369	3.46	0.78	0.21	0.27	2.69	0.06	2.62969
1.9	160	0.539	6489	3.90	0.80	0.20	0.25	3.10	0.05	3.05480
1.9	170	0.588	6609	4.35	0.81	0.18	0.23	3.53	0.04	3.49109
1.9	180	0.64	6729	4.82	0.83	0.17	0.20	3.99	0.03	3.95565
2.0	60	0.141	5080	0.28	0.22	0.37	0.59	0.06	0.22	-0.15954
2.0	70	0.173	5200	0.57	0.36	0.36	0.56	0.21	0.20	0.00904
2.0	80	0.206	5320	0.87	0.47	0.34	0.52	0.41	0.18	0.22749
2.0	90	0.241	5440	1.19	0.54	0.33	0.49	0.65	0.16	0.48689
2.0	100	0.278	5560	1.53	0.60	0.31	0.46	0.92	0.14	0.77982
2.0	110	0.317	5680	1.88	0.65	0.30	0.43	1.23	0.13	1.10164
2.0	120	0.359	5800	2.26	0.69	0.28	0.40	1.57	0.11	1.45755
2.0	130	0.402	5920	2.65	0.73	0.27	0.37	1.93	0.10	1.82917
2.0	140	0.447	6040	3.06	0.75	0.25	0.34	2.31	0.09	2.22308
2.0	150	0.494	6160	3.49	0.78	0.24	0.31	2.71	0.08	2.63824
2.0	160	0.543	6280	3.94	0.80	0.22	0.29	3.14	0.07	3.07391
2.0	170	0.595	6400	4.41	0.82	0.21	0.27	3.59	0.06	3.53829
2.0	180	0.648	6520	4.89	0.83	0.19	0.24	4.06	0.05	4.01346
2.1	60	0.133	4924	0.21	0.17	0.39	0.64	0.04	0.25	-0.21661
2.1	70	0.166	5044	0.51	0.34	0.38	0.61	0.17	0.23	-0.05671
2.1	80	0.2	5164	0.82	0.45	0.36	0.57	0.37	0.21	0.16223
2.1	90	0.237	5284	1.15	0.54	0.35	0.53	0.62	0.19	0.43353
2.1	100	0.275	5404	1.50	0.60	0.33	0.50	0.90	0.17	0.73407
2.1	110	0.316	5524	1.87	0.65	0.32	0.47	1.22	0.15	1.07264
2.1	120	0.358	5644	2.25	0.69	0.30	0.43	1.56	0.13	1.42997
2.1	130	0.403	5764	2.66	0.73	0.29	0.41	1.94	0.12	1.81981
2.1	140	0.449	5884	3.08	0.76	0.27	0.38	2.33	0.10	2.22387
2.1	150	0.498	6004	3.53	0.78	0.26	0.35	2.75	0.09	2.65791
2.1	160	0.548	6124	3.98	0.80	0.24	0.32	3.18	0.08	3.10392
2.1	170	0.601	6244	4.46	0.82	0.23	0.30	3.65	0.07	3.57863
2.1	180	0.655	6364	4.95	0.83	0.21	0.27	4.12	0.06	4.06409
2.2	60	0.125	4821	0.14	0.12	0.40	0.68	0.02	0.28	-0.25879
2.2	70	0.159	4941	0.45	0.31	0.39	0.64	0.14	0.25	-0.11189
2.2	80	0.195	5061	0.77	0.44	0.38	0.60	0.34	0.23	0.11170
2.2	90	0.233	5181	1.12	0.53	0.36	0.56	0.59	0.20	0.38741
2.2	100	0.273	5301	1.48	0.60	0.35	0.53	0.88	0.18	0.70244
2.2	110	0.314	5421	1.85	0.65	0.33	0.49	1.20	0.16	1.04155
2.2	120	0.358	5541	2.25	0.69	0.32	0.46	1.56	0.15	1.41604
2.2	130	0.404	5661	2.67	0.73	0.30	0.43	1.95	0.13	1.81540
2.2	140	0.452	5781	3.11	0.76	0.29	0.40	2.35	0.11	2.23773
2.2	150	0.502	5901	3.56	0.78	0.27	0.37	2.78	0.10	2.68170
2.2	160	0.553	6021	4.03	0.80	0.26	0.35	3.23	0.09	3.13767
2.2	170	0.607	6141	4.52	0.82	0.24	0.32	3.70	0.08	3.62235
2.2	180	0.663	6261	5.03	0.83	0.23	0.29	4.19	0.07	4.12659
2.3	60	0.118	4771	0.07	0.07	0.41	0.70	0.00	0.29	-0.28157
2.3	70	0.153	4891	0.39	0.28	0.40	0.66	0.11	0.26	-0.14981
2.3	80	0.19	5011	0.73	0.42	0.38	0.62	0.31	0.23	0.07137

2.3	90	0.229	5131	1.08	0.52	0.37	0.58	0.56	0.21	0.35030
2.3	100	0.27	5251	1.45	0.59	0.35	0.54	0.86	0.19	0.67133
2.3	110	0.313	5371	1.85	0.65	0.34	0.51	1.20	0.17	1.02591
2.3	120	0.358	5491	2.25	0.69	0.32	0.47	1.56	0.15	1.40895
2.3	130	0.405	5611	2.68	0.73	0.31	0.44	1.95	0.14	1.81729
2.3	140	0.454	5731	3.13	0.76	0.29	0.41	2.37	0.12	2.24883
2.3	150	0.505	5851	3.59	0.78	0.28	0.38	2.81	0.11	2.70216
2.3	160	0.559	5971	4.08	0.80	0.26	0.36	3.28	0.09	3.18503
2.3	170	0.614	6091	4.58	0.82	0.25	0.33	3.76	0.08	3.67930
2.3	180	0.671	6211	5.10	0.84	0.23	0.30	4.26	0.07	4.19313
2.4	60	0.11	4775	0.00	0.00	0.41	0.70	0.00	0.29	-0.28567

CONCLUSIONS

Pneumatic shot peening has proven to be an effective method for increasing the strength of individual lap joints, with all pneumatic shot-peened samples demonstrating higher shear strength than those without treatment. Depending on the processing parameters, strength improvements can range from 18% to as much as 80%.

The parameters of the pneumatic shot peening process significantly impact both the strength and cost of the operation, making their optimization essential. Single-criterion optimization using the iterative search of the adequate region method does not require extensive mathematical techniques and yields good results regardless of the mathematical model being tested.

The increase in the shear strength of the adhesive joint obtained in the tests after shot peening is due to the pressure exerted on the edges of the overlaps, which eliminates the unfavorable effect of stress concentration in the adhesive layer adjacent to the edge.

Different criteria lead to varying optimal pneumatic shot peening parameters, providing a strong basis for conducting double-criterion optimization. The min-max method facilitates the relatively easy implementation of this procedure by considering the weighting of individual criteria.

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REFERENCES

1. Wei Y., Jin X., Luo Q., Li Q., Sun G. Adhesively bonded joints – A review on design, manufacturing, experiments, modeling and challenges. Composites Part B: Engineering 2024; 276: 111225. https://doi.org/10.1016/j.compositesb.2024.111225
2. Peng H., Zhou T., Fan Y., Shangguan L., Zhang N. Recent advances in aluminum alloy surface treatment technology and bonding properties. Physica Status Solidi A Applications and Materials Science 2025; 222(6): 2400715.https://doi.org/10.1002/pssa.202400715
3. Naat N., Boutar Y., Naïmi S., Mezlini S., Da Silva L.F.M. Effect of surface texture on the mechanical performance of bonded joints: A review. The Journal of Adhesion 2023; 99(2): 166-258. https://doi.org/10.1080/00218464.2021.2008370
4. Ramaswamy K., O`Higgins R.M., McCarthy M.A., McCarthy C.T. Influence of adhesive spew geometry and load eccentricity angle on metal-composite bonded joints tested at quasi-static and dynamic loading rates. Composite Structures 2022; 279: 114812. https://doi.org/10.1016/j.compstruct.2021.114812
5. Zheng G., Liu Ch., Han X., Li W. Effect of spew fillet on adhesively bonded single lap joints with CFRP and aluminum-alloy immersed in distilled water. International Journal of Adhesion & Adhesives 2020; 99: 102590. https://doi.org/10.1016/j.ijadhadh.2020.102590.
6. Zielecki W. Determinants determining the strength properties of adhesive joint. Habilitation Thesis, Technical University of Košice, Košice, Slovakia, 2008.
7. Monajati L., Vadean, A., Boukhili, R. Mechanical behavior of adhesively bonded joints under tensile loading: A synthetic review of configurations, modeling, and design considerations. Materials 2025; 18(15): 3557. https://doi.org/10.3390/ma18153557
8. Demir S, Yüksel C. Mechanical performance of bi-adhesive single-lap joints produced by FDM

with PLA adherends. Rapid Prototyping Journal 2025. https://doi.org/10.1108/RPJ-07-2025-0309

9. Ivanova J., Valeva V. Influence of interface gap on the stress behaviour of smart single lap joints under time harmonic load. Journal of Theoretical and Applied Mechanics 2017; 47(2): 83–99. https://doi.org/10.1515/jtam-2017-0011
10. Marchione F. Finite element analysis of single-lap adhesive joints with tapered adherends, International Journal of Engineering, Transactions A: Basics 2021; 34(10): 2213–2218.https://www.ije.ir/article_133040.html
11. Soykok I.F. (2015). End geometry and pin-hole effects on axially loaded adhesively bonded composite joints, Composites Part B 2013; 77: 129e138. https://doi.org/10.1016/j.compositesb.2015.03.031
12. Pinto A.M.G., Campilho R.D.S.G., Mendes I.R., Aires S.M., Baptista A.P.M. Effect of hole drilling at the overlap on the strength of single-lap joints. International Journal of Adhesion & Adhesives 2011; 31: 380–387. https://doi.org/10.1016/j.ijadhadh.2010.11.016
13. Bodepudi, R., Hughes, D.J., Pradhan, A.K. Evaluation of optimum configuration of adhesively bonded reverse bent joints. International Journal of Adhesion & Adhesives 2017; 77: 78–84. https://doi.org/10.1016/j.ijadhadh.2017.04.003
14. Temiz S., Akpinar S., Aydin M. D., Sancaktar E.Increasing single-lap joint strength by adherend curvature-induced residual stresses. Journal of Adhesion Science and Technology 2013; 27(3): 244–251. https://doi.org/10.1080/01694243.2012.705509
15. Çalık, A. Optimizing support patch geometries in adhesively bonded single lap joints: A finite element analysis approach. Strojniški Vestnik - Journal of Mechanical Engineering 2025; 71(3–4): 92–102. https://doi.org/10.5545/sv-jme.2025.1265
16. Taş, H. Effects of support patches on the mechanical characteristics of adhesively bonded aluminium alloy single lap joints. The Journal of Adhesion 2025; 101(12): 1471–1496. https://doi.org/10.1080/00218464.2025.2472710
17. Xu Y., Tao B., Peng Z. Synergistic optimization of adhesive joint process parameters via high-frequency ultrasonic vibration and response surface methodology: Mechanisms for shear performance enhancement. International Journal of Adhesion and Adhesives 2026; 145: 104219. https://doi.org/10.1016/j.ijadhadh.2025.104219
18. Sundukov S.K. Ultrasonic vibration mechanism in making permanent joints. Steel in Translation 2024; 54(1): 10–15. https://doi.org/10.3103/S0967091224700190
19. Korzyńska K. Badania wpływu pneumokulkowania na wytrzymałość zakładkowych połączeń klejowych (in Polish). (PhD Thesis) Lublin University of Technology, 2019.
20. Zielecki W., Korzyńska K. Umacnianie zakładkowych połączeń klejowych stopu tytanu Ti6Al4V metodą pneumokulkowania (in Polish). Technologia i Automatyzacja Montażu 2016; 1: 44–47. https://journals.prz.edu.pl/tiam/article/view/1374/1058
21. Pneumatic Ball Peening: https://www.youtube.com/watch?v=p1boxrakqs0
22. Korzyński M. Metodyka eksperymentu (in Polish). Wydawnictwa Naukowo-Techniczne, Warszawa, 2017.