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Effect of Surface Abrasive Treatment on the Strength of Galvanised Steel Sheet Adhesive Joints

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ABSTRACT

The aim of this study was to determine the effect of abrasive treatment as a method of surface preparation on the strength of adhesive joints made of galvanised steel sheet. The subject of experimental investigations were adhesive joints of samples made of galvanised steel sheet DX51, 0.7 mm thick. The surfaces of the samples were abraded with coated abrasive tools of grain sizes P120, P180, P220, P400 and P600, and then degreased with PIK-KO extraction solvent. The surface properties in terms of roughness and 3D surface topography were examined using a Hommel-Etamic T8000 RC120-400. The adhesive joints were made using Epidian 53 epoxy resin adhesive composition and IDA curing agent in a 100:40 weight ratio. Samples of single-lap adhesive joints were tested for strength on a Zwick/Roell Z150 testing machine, in accordance with the PN - EN 1465:2009 standard. The tests showed that the samples mechanically processed with an abrasive tool of P220 gradation show the best strength properties. Adhesive joints, in which the surface of the joined elements was mechanically processed with an abrasive tool of P120 gradation, obtained negative results. The obtained test results were subjected to further statistical analysis. The Shapiro-Wilk test was used to assess the normality of the distribution. Then, the non-parametric Kruskal-Wallis test and the median test were applied, which showed that there were no significant differences in the results obtained between the adhesive joints whose surfaces were prepared with P220 and P400 abrasive paper, i.e. both methods of surface preparation can be considered as the most favourable among those analysed during the adhesive bonding of DX51 galvanised sheets.

Keywords: adhesive joints, strength, galvanised sheet metal, abrasive treatment.

INTRODUCTION

The surface preparation of joined elements has a great influence on the strength and resistance of adhesive joints. In selecting the appropriate method of surface preparation, knowledge of the type, structure and properties of the materials to be joined is necessary. It is important to perform this step carefully and correctly, as it should ensure the strongest possible adhesive bonds in the adhesive joint [1–5].

The interest in the issue of bonding galvanised sheets results from a number of difficulties connected with their joining. Commonly used methods, such as welding, very often cause defects, for example damage to the zinc coating in the area of joining [6, 7]. Often the surface of the galvanised product near the weld is damaged. An additional treatment is then necessary in order to prevent the damage from being spread to the surface [8]. The conducted research indicates that the adhesive technology may be a competitive method of bonding galvanised sheets as a technology which does not disturb the continuity of the zinc coating (does not cause damage to it) and does not require an additional operation to secure the adhesive joint [9, 10].

In industry, dip galvanised and electrolytically galvanised sheets are the most common. The protective properties of the coatings are proportional to their thickness, but are also dependent on the type of sheet to which the coating is applied [11]. It should be remembered that in order to obtain the required protection against corrosion, it is necessary to follow the requirements regarding the careful preparation of the galvanised surface. Galvanised zinc coatings are widely used in the area of corrosion protection for steel and cast iron. Galvanized sheets are used especially for roofing, also for roofs of factories and industrial warehouses [12, 13]. They are used to make gutters and build garages as well as tool and utility houses. Galvanised steel sheets are also used to construct doors, insulation, ventilation ducts and to make domestic appliances. Galvanised sheets are not only used in construction, but also in locksmith work, in the manufacture of everyday appliances and in architecture. It is difficult not to mention the automotive industry. Galvanised elements are now found in all cars, especially in the body of the car [14–16].

Galvanised sheet is a rather unfavourable substrate for many coatings due to the difficulty in obtaining proper adhesion to a smooth substrate, therefore when bonding galvanised sheet it is necessary to choose the correct method of surface preparation in order to develop the surface appropriately [17].

The surface preparation of galvanised steel for the bonding process can be carried out by several recommended methods: degreasing, abrasive treatment with coated tools, abrasive treatment with coated tools and degreasing, chemical treatment - etching.

External surfaces of zinc coatings are usually degreased using organic solvents. Aqueous solutions containing weakly alkaline detergents are also used for this purpose. The choice of the appropriate agent depends on whether the sheet was dipped galvanised or electrolytically galvanised.

A. Rudawska and J. Kuczmaszewski have shown [18], that the preparation of dip galvanised sheet surfaces for the adhesive process using acetone and degreasing agents containing acetone, results in an increase in the strength of the adhesive joints of the mentioned sheets. However, in the case of electro-galvanised sheets, good strength results were obtained by applying agents which are based on a mixture of alcohol and hydrocarbon solvent [18].

A common method of preparing the surface of materials for bonding is abrasive processing. The most common tools used for this are coated abrasives [19–21]. The advantage of this type of tool is the convenience of use, relatively low cost and high availability. When selecting coated abrasive tools, particular attention should be paid to grain gradation. Larger grains are more effective in removing material layers, including physicosorption, but do not do a good enough job of developing the surface. Smaller grit sizes are more effective in terms of surface development, but too small a grit size is not sufficient to remove the physicosorption layer. As a result of mechanical processing with abrasive bulk tools, the residue fills the resulting micropores and depressions. The presence of these impurities is undesirable. Therefore, post-treatment degreasing is used.

In order to determine the effect of surface abrasive treatment on the strength properties of galvanised sheet adhesive joints, the surface of the elements to be bonded was subjected to mechanical abrasive treatment with coated abrasive tools of different grain sizes, and then degreased using PIKKO extraction solvent. The aim of this study was to determine the abrasive tool used to prepare the surface of galvanised sheets, which would contribute to obtaining the highest shear strength of adhesive joints.

METHODS OF RESEARCH

Material used in the studies

Specimens made from 0.7 mm thick hot dip galvanised steel sheet with a zinc coating thickness of approximately 18 μm per side, designated DX51, were used for the tests. Such coatings effectively protect steel structure elements against corrosion. Immersion (hot-dip) galvanising is a particularly durable and effective method of corrosion protection. It is an extremely tight coating that covers the entire surface of the galvanised element. Galvanised steel sheet is widely used outdoors where it is exposed to atmospheric conditions. It is also heat resistant. It is important to note that galvanised steel sheets are maintenance-free. They also have very good aesthetic qualities. Table 1 shows the chemical composition and mechanical properties of DX51 galvanised steel sheet [22].

Galvanised sheets have a very high luster and are characterised by high smoothness. It is possible to prolong the life of galvanised products by applying an additional coat of paint or varnish, thanks to which they are widely used in the engineering and automotive industries.

Table 1. Chemical composition and mechanical properties of DX51 galvanised steel used in the tests [22]

Type of material	Chemical composition						Mechanical properties	
	C	Si	Mn	P	S	Ti	Yield point, R_e [MPa]	Tensile strength, R_m [MPa]
DX51	0.18	0.50	1.20	0.12	0.045	0.30	140–300	270–500

Adhesive joints

Single-lap adhesive joints with an overlap length of lz = 15 mm were made for the tests. Geometrical dimensions of bonded elements and adhesive joints were:

- overlap length lz = 15 mm,
- sample length L = 100 mm,
- sheet thickness g_b = 0.7 mm,
- sample width b = 20 mm.

A schematic diagram of an adhesive joint is shown in Figure 1. The first step in making adhesive joints was to properly prepare the surfaces of the bonded elements. Surfaces of steel specimens were abraded with coated abrasive tools of various gradations. For this purpose, sandpaper of gradation: P120, P180, P220, P400 and P600. Table 2 shows the average sizes of abrasive grains for each gradation of tools used in this study.

The surface was machined using a BOSCH PSS 250AE oscillating grinder. The surface was treated for 1 minute. Then, after roughening, the surface was degreased to remove dust, dirt and machining residues using PIKKO extraction solvent. Ten adhesive samples were made for each surface preparation and, before bonding, the quality of the prepared surface was checked through roughness and surface topography tests.

Selection of adhesive type and method of bonding is determined by the type of bonded materials, working conditions of the joint and the required strength of the joint. The adhesive composition of Epidian 53 epoxy resin from CIECH Sarzyna S.A. and IDA curing agent in stoichiometric ratio 100:40 (E53/IDA/100:40) was used in the study. The composition used is recommended by manufacturers of adhesives [24] for bonding sheets with even coatings, and several studies have been conducted which show the beneficial effects of using epoxy adhesives for bonding galvanised sheets [8, 25].

Epidian 53 is a mixture of epoxy resin derived from bisphenol A and epichlorohydrin with an average molecular weight ≤700 and styrene. Epidian 53 resin is characterised by high shear strength at approximately 110 °C [26, 27]. Due to perfect electrical insulating and strength properties, it can be used in radiotechnics, automotive industry, aerospace and optics. The properties of this epoxy resin are presented in Table 3.

Table 2. Average grit sizes for individual tool grades [23]

Gradation	Average grit size [μm]
P120	125–106
P180	90–63
P220	75–53
P400	18.30–16.30
P600	15.0

Table 3. Properties of epoxy resin Epidian 53 [27]

Property	Value	Unit
Boiling point	141	°C
Flash point	75	°C
Self-ignition temperature	460	°C
Epoxy number	≥0.41	mol/100 g
Density at 20°C	1.11–1.15	g/cm³
Viscosity at 25°C	900–1500	mPas

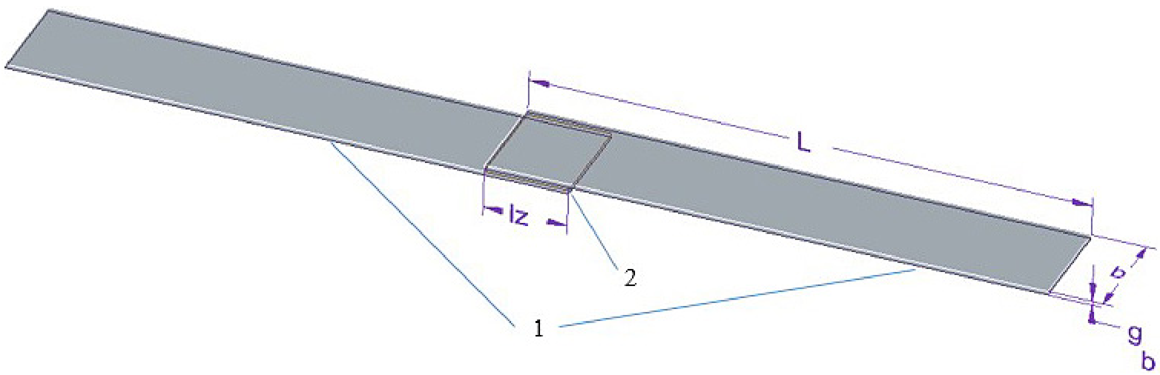

Fig. 1. Example of a single-lap adhesive joint: 1 - joined elements, 2 - adhesive layer

Table 4. Strength parameters of E53/IDA/100:40 epoxy composition after curing for 7 days at room temperature [24]

Parameter tested	E53/IDA/100:40	
	Value	Unit
Breaking stress	20–30	MPa
Bending strength	40–50	MPa
Compressive strength	35–45	MPa
Hardness by ball indentation	80–90	MPa
Martens deflection temperature	35–40	°C

IDA curing agent provides good mechanical and chemical resistance properties. IDA hardener can be used to harden low molecular weight epoxy resins [28]. Table 4 shows the strength parameters of the E53/IDA/100:40 epoxy composition used in the study.

Adhesive composition was prepared directly before the process of bonding. The components of the mixtures were carefully weighed using a KERN CKE 3600-2 laboratory scale with a measurement accuracy of 0.01 g. Then mixed with a mechanical mixer (Güde GTB 16/5 A) equipped with a propeller mixer. The mixing process with the speed of 460 rpm lasted 2 minutes. Next, the adhesive compositions were deaerated for 2 minutes in order to remove gas bubbles formed as a result of mixing the components. Finished adhesive compositions were applied to the surfaces to be bonded using a brush for adhesive application, which made it possible to achieve a homogeneous thickness of the joint across the entire adhesive surface. In the next stage, the elements were joined together. The joints thus formed were subjected to a single-step curing process at ambient temperature at a load of 1 kg. The total curing time was 7 days.

The entire process of adhesive bonding, including surface preparation, was carried out in laboratory conditions at a temperature of 21 ± 2 °C and an air humidity of 28 ± 2%.

Surface roughness and topography tests

Testing of the surface topography was performed using a T8000 RC120-400 contour, roughness and 3D topography measuring device from Hommel-Etamic. Tests were carried out according to PN-EN ISO 25178 standard (product geometry specifications (GPS) - geometric structure of the surface: spatial) [29]. TURBO WAVE V7.55 was the software used to operate the device and conduct the measurements. A TKU300 measuring tip was used in the tests. The area scanned included a 4.8 × 4.8 mm section of the surface and the roughness profile parameters were determined from 241 measurements. The tests were carried out at a speed of 0.50 mm/s.

Strength tests

After the assumed curing time all adhesive joints were exposed to destructive strength tests on a Zwick / Roell Z150 testing machine. Shear strength was determined. These tests were conducted in accordance with the PN-EN 1465:2009 standard [30]. This is the standard for determining the tensile shear strength of adhesive joints. The crosshead speed during the test was 5 mm/min with a pre-test force of 5 N.

RESULTS

Surface roughness and topography tests

In the study, parameters such as Ra, Rp, Rv and Rt were determined and compared. The following roughness profile parameters were selected because these are the parameters most commonly used in engineering and industrial practice. Parameters are also presented for a reference surface that has not been subjected to any abrasive treatment, in order to compare the effect of abrasive treatment with coated tools on the stereometric properties of the surface. Figure 2 shows the influence of the surface preparation method on the roughness parameter Ra. The results show that the arithmetic mean of the ordinates of the profile obtained for surfaces prepared with P120 and P180 grit sandpaper is similar and amounts to Ra ≈ 0.77 µm. Similarly, in the case of machining with P220 and P400 tools, the Ra parameter was similar and amounted to approximately 0.65 µm. The lowest value was obtained for the surface treated with P600, and the distribution of results in this case was the greatest.

Analysing the profile height parameters Rp, Rv and Rt, shown in Figure 3, it can be seen that the distribution of results is similar to that of the Ra parameter. It can be observed that the surface treated with P180 and P220 abrasive tools is characterised by a similar distribution of the height of the highest peak and the greatest depth of the profile, i.e. the parameters Rp and Rv for individual surfaces are at a similar range. When the surface

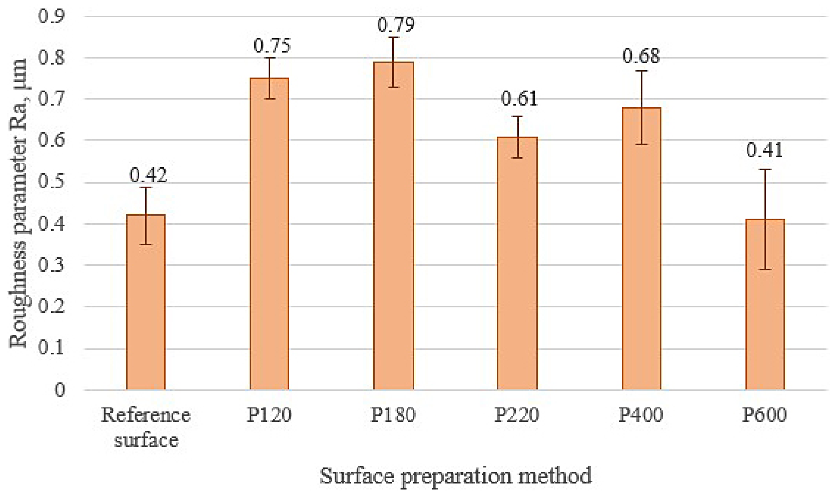

Fig. 2. Surface preparation with different abrasive tools versus arithmetic average of profile roughness

is treated with the highest abrasive grit P600, it can be observed that the micro irregularities of the surface are flattened (reduction of roughness profile Rt). Finer abrasive grains may lead to deformation of the tops of micro irregularities, as a result of which the maximum peak height of the profile Rp for a given surface decreases significantly in comparison with other treatments where the grain size is larger.

Analysing the surface topography presented in Figure 4, it can be seen that in the case of surfaces treated with tools of lower gradation (P120, P180), local concentrations of depressions occur. The occurrence of this type of defects could be due to the impact of large abrasive grains. However, it should be noted that the use of abrasive paper made it possible to obtain, in all cases, an undirected distribution of irregularities, which is advantageous when preparing the surface for the adhesive process [19].

Analysing the surface topography after treatment with an embossing tool of P220 gradation, it can be observed that there are visible scratches on the whole analysed surface, and it has numerous peaks and valleys. Analysing the Sa parameter defining the average deviation of the height of surface irregularities, it can be observed that this surface is characterised by the lowest value of Sa = 0.79 µm. Comparing the surfaces treated with sandpaper of higher gradation P400 and P600 (Figs. 4e and 4f) with the others, it can be observed that the already mentioned flattening of the profile tops occurs.

From the point of view of the possibility of surface joining, the most important parameter seems to be the deviation of the height of surface irregularities from the reference plane - Sa (Sz), as it can be concluded on which surface the process of glue anchoring in surface irregularities will be best observed. Analysing the Sz parameter, it can

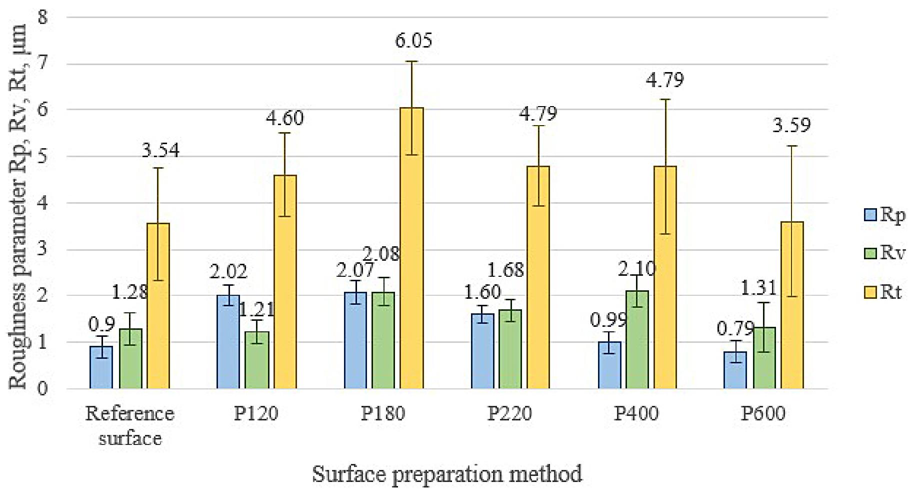

Fig. 3. Surface preparation with different abrasive tools versus profile height parameters (Rp, Rv, Rt)

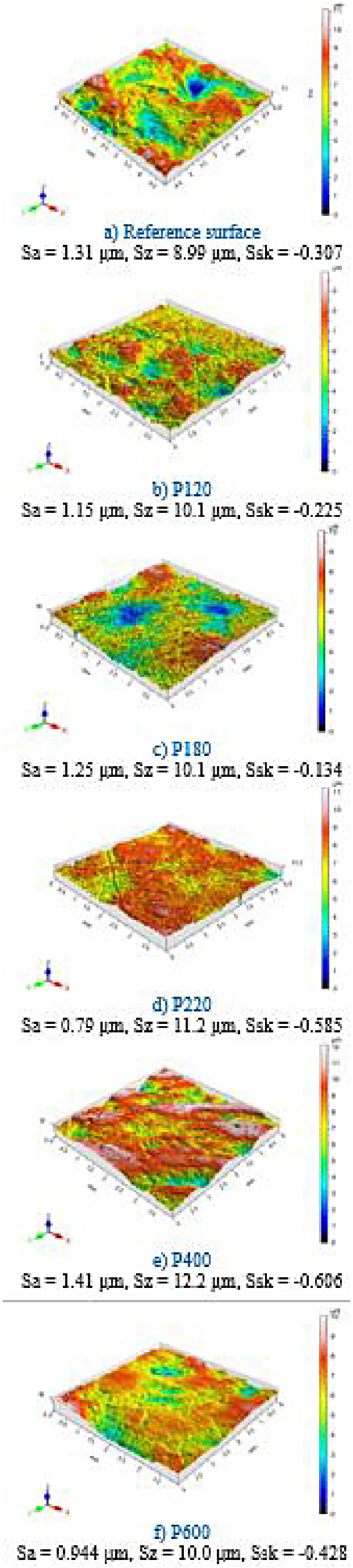

Fig. 4. Surface preparation with different abrasive tools versus surface topography: a) Reference surface, b) P120, c) P180, d) P220, e) P400, f) P600

be observed that in the case of a surface treated with a tool of P220 and P400 gradation, the value of the parameter is the highest.

When analysing the parameter describing the skewness, or in other words the asymmetry coefficient Ssk, it can be observed that for all the surfaces analysed, a negative value was obtained, which indicates that the elevations have a plateau character. It can also be noticed that the results for the two mentioned ways of surface preparation differ from the others, taking the highest negative value.

Strength test results

Figure 5 shows the results of strength tests of the analysed adhesive joints. The strength of adhesive joints is one of the most important criteria for evaluating such joints. However, for a comprehensive assessment of the strength results to be possible, a statistical analysis of the results obtained is necessary. The statistical analysis was carried out using the Statistica program. Table 5 presents the results of descriptive statistics. A normality check of the distribution of the obtained results was also performed. The Shapiro-Wilk test was carried out with the assumed confidence level of $\alpha = 0.05$. The results of the test and the assessment of normality of distribution are also presented in Table 5.

Based on the obtained results presented in Figure 5 and Table 5, it can be observed that the best shear strength in the tensile test was characterised by adhesive joints, the surface of which was prepared with an abrasive tool of P220 gradation – 2.87 MPa. The joints whose surface was prepared with P120 abrasive paper had the lowest strength – 1.27 MPa. When analysing the results of the Shapiro-Wilk test, it can be seen that the assumption of the normality of distribution is not fulfilled, therefore, in the further part of the analysis, the test of non-parametric statistics was used. The Kruskal-Wallis test and the median test, which is the non-parametric equivalent of the parametric ANOVA, were applied. The results of this test are presented in Tables 6 and 7.

For the Kruskal-Wallis test, the computer significance level is 0.0020, which is less than 0.05, so it can be concluded that the mean values for the different surface preparation methods are not the same. The median test can be interpreted similarly. However, the tests performed do not indicate which groups are significantly different. In order to find this out, the method of multiple

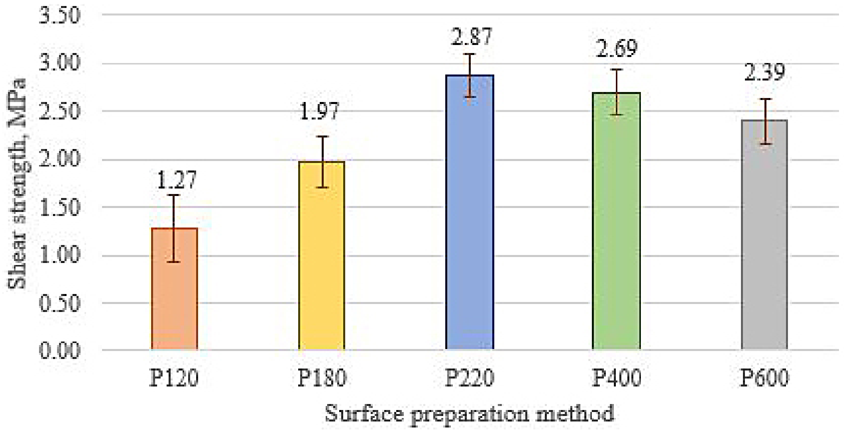

Fig. 5. Shear strength of adhesive joints analysed

Table 5. Results of descriptive statistics and the Shapiro-Wilk normality test

Method of surface preparation	Average shear strength, MPa	Standard deviation	Variance	Shapiro-Wilk statistics W	Probability level p	Normal distribution
P120	1.27	0.34	0.12	0.85	0.23	Yes
P180	1.97	0.26	0.07	0.95	0.75	Yes
P220	2.87	0.23	0.05	0.77	0.03	No
P400	2.69	0.23	0.05	0.87	0.27	Yes
P600	2.39	0.24	0.06	0.91	0.48	Yes

comparisons was applied, which makes it possible to indicate significant differences in mean values at the assumed confidence level between independent groups. The results of the multiple comparison test are presented in Table 8.

Table 6. Results of the Kruskal-Wallis rank ANOVA test

Kruskala-Wallisa test: H (4, N=50) = 16.90, p=0.0020		
Method of surface preparation	Rang total	Average rank
P120	10.00	2.50
P180	29.00	7.25
P220	109.00	18.16
P400	82.00	16.40
P600	46.00	11.50

The performed statistical tests show that significant differences in the mean values of shear strength in the tensile test for particular ways of bonded elements surface preparation occurred in the case of surfaces treated with P120, P180, P600 and P220 and P400 abrasive paper. This means that there are no significant differences in the results obtained between the adhesive joints whose surfaces were prepared with P220 and P400 abrasive paper, i.e. both methods of surface preparation can be treated as the most favourable ones among those analysed for bonding DX51 galvanised sheets. It should be remembered, however, that this conclusion is correct only in relation to the methodology applied in the study.

Table 7. Median test results

Median test, overall median = 2.39, Chi square = 16.79, df = 4, p = 0.0021						
Subject to: Shear strength	Method of surface preparation					Total
	P120	P180	P220	P400	P600	
≤ Medians: observed	4.00	4.00	0.00	1.00	3.00	12.00
Expected	2.09	2.09	3.13	2.60	2.09	
Observed-expected	1.91	1.91	-3.13	-1.61	0.91	
> Medians: observed	0.00	0.00	6.00	4.00	1.00	11.00
Expected	1.91	1.91	2.87	2.39	1.91	
Observed-expected	-1.91	-1.91	3.13	1.61	-0.91	
Total: observed	4.00	4.00	6.00	5.00	4.00	23.00

Table 8. Results of the multiple comparison test

p-value for multiple comparisons Kruskal-Wallis test: H (4, N = 50) = 16.90, p = 0.0020					
Method of surface preparation	P120	P180	P220	P400	P600
P120		1.00	0.00	0.02	0.61
P180	1.00		0.13	0.44	1.00
P220	0.00	0.13		1.00	1.00
P400	0.02	0.44	1.00		1.00
P600	0.61	1.00	1.00	1.00	

DISCUSSION

In the case of machining, some are used not only to treat the surface of structural materials prior to bonding processes, but also to modify surface properties, such as abrasive blasting. This treatment includes treatment with abrasive tools, sandblasting, shot peening and shot peening. Such modification can contribute to increasing the fatigue strength of components that are subjected to high stresses. For example, machined components (e.g. after milling, cutting or heat treatment) contain residual tensile stresses. Additional treatment, such as shot peening, converts these residual stresses into compressive stresses, which significantly increases the service life of these components. The surface undergoing shot peening undergoes slight plastic deformation, which causes a change in the direction and nature of the stresses present in the surface layer. This issue has been highlighted in many works, e.g. Al-Obaid [31]. Blasting is similar to sandblasting except that it operates on the principle of a plastic mechanism rather than an abrasive one.

In the study conducted, it was noted that the parameter determining the gradation of the abrasive tool has a significant influence on the strength of adhesive joints. In [32], it was shown that both surface roughness and adhesion properties are more dependent on the type of abrasive used and not on differences in the abrasive process itself. In the present work, increasing the ratio of valley depth to tip height as a result of changing the abrasive grain size, as evidenced by changes in the surface roughness parameters Ra, Rp, Rt and Rv, has a beneficial effect on the strength of adhesive joints. Rudawska et al [33] indicated that the properties of adhesive surfaces obtained after abrasive treatment with coated tools affect the strength of adhesive joints, and also indicated that the abrasive grain size significantly affects the strength of adhesive joints.

Comparison of the obtained results of shear strength and surface roughness profile parameters shows that the application of abrasive treatment with coated tools of the appropriate gradation produced the desired results for adhesive joints made with E53/IDA/100:40. Mechanical treatment with coated tools of different gradations leads to the formation of numerous pits on the surface of the samples, which represent potential surface irregularities penetrated by adhesives. On a surface with extensive topography, there is a natural 'interlocking' of the adhesive with the material surface, as the liquid adhesive fills in irregularities on the adhesion surface before curing.

CONCLUSIONS

In the case of structures containing adhesive joints, the development of the appropriate technology is fundamental, and one of the most important steps is the correct choice of surface preparation of the bonded parts. Abrasive machining is the preferred method of surface preparation, because it is characterised by ease and availability of necessary materials. The proper selection of the machining technology has a significant effect on the strength achieved and depends on many factors, which include the type of the bonded material or the type of adhesive used. The aim of this work was to determine the effect of abrasive processing as a method of surface preparation on the strength of adhesive joints made of DX51 galvanised steel sheet, bonded with Epidian 53 epoxy resin adhesive composition and IDA curing agent. Surfaces of the bonded elements were subjected to abrasive processing using P120, P180, P220, P400, P600 graded abrasive tools, and degreasing with PIKKO extraction thinner.

After carrying out the experimental tests and analysing the results obtained, it was noted that:

- The highest shear strength and the highest repeatability of results were obtained in the case of adhesive joints of elements whose surface was prepared with P220 abrasive tool;
- Analysing the geometrical structure of the surface after treatment with P220 abrasive tool, it can be observed that on the whole surface of the overlap there are numerous peaks and valleys, which consequently influences the increase of cohesion forces in the adhesive joint, because the adhesive on such a surface anchors better;

- The joints with the lowest strength were those whose surface was prepared using P120-grit sandpaper. In the case of these joints, the repeatability of results was also the lowest. This may be due to the surface structure after machining, which is shown on the surface topography map. The surface machined with P120 grit was characterised by localised concentrations of depressions that may have occurred as a result of large abrasive grain sizes. Too deep craters on the surface to which the adhesive was applied could cause local non-stick effects, which then translate into reduced strength.

Analysing the determined results of the measurement of the roughness and topography of the surface in comparison with the obtained shear strength, it may be noticed that:

- The preparation of the surface with tools of a lower gradation (P120, P180) results in a decrease in the strength of the joints, which may be caused by the presence of numerous craters left after the abrasive material;
- After exceeding the optimum abrasive grain size for obtaining the best strength results, which, as it turned out on the basis of the conducted tests, is in the case of the abrasive tool of P220 gradation - 75-53 μm, the strength of connections again decreases. This may be caused by flattening of the tops of the roughness profile, which could be observed in the case of surfaces treated with P600 abrasive paper.

The information presented can have a significant impact on the planning of the technology of joining galvanised sheets. It should be expected that in further studies other methods of surface preparation for the process of joining the analysed material will be used.

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