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The Influence of Gradation and Type of Abrasive Material on Strength of Adhesive Joints of Steel Sheets

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ABSTRACT

The purpose of the work is to present issues related to the influence of surface treatment on the strength of adhesive joints of C45 steel sheets by grinding based on experimental research. These issues were related to determining the impact of the gradation and type of abrasive material on the strength of adhesive joints of the steel sheets. The grinding was carried out manually using an angle grinder with a disc diameter of 125 mm and a rotational speed of 11.060 min^{-1}, using abrasive materials with grains made of: ceramics, zirconium and electro-corundum with a gradation of P40, and sandpaper with grains made of electro-corundum with various grain sizes with three gradations P40, P220, P400 (according to European FEPA standards). To make the adhesive joints of steel sheets, the epoxy adhesive was used, which contains an epoxy resin based on bisphenol A and a triethyleneteramine curing agent. A profilographometer from Hommel - Etamic was used to determine selected 2D and 3D surface roughness parameters, and the strength tests of the steel sheets adhesive joints were performed on a ZWICK/ROELL Z150 testing machine. The analysis of the tests showed a significant impact of the surface treatment method on the attained shear strength of the steel sheets adhesive joints. Comparing the samples prepared with electrocorundum of the variable gradation, the tests exhibited that the samples prepared with P40 paper had the highest roughness, while samples prepared with P400 paper had the highest shear strength. Roughness analysis indicated that in the comparison group of samples prepared with abrasives of the various abrasive materials, ceramics showed the highest roughness parameters and the shear strength of the adhesive joints after this treatment.

Keywords: surface treatment, grinding, abrasive material, surface roughness parameters, adhesive joint, strength

INTRODUCTION

Preparing the surface for the bonding process is a widely analyzed issue due to the theoretical importance of adhesion as a surface phenomenon [1–3]. Roughening the surface is an essential element in obtaining a specific strength value [4, 5], because adhesive anchoring is only possible with a sufficiently large developing surface of the material [6, 7].

Surface treatment of adherends also takes into account creating appropriate stereometric development as well as obtaining proper activation [8–10]. Mechanical methods are one of the surface treatment basic methods, and their use allows for appropriate surface development, thus enabling proper adhesion [3].

To perform mechanical processing, abrasive materials with various properties are used [11] to achieve the best desired surface roughness Rm 7–25 μm. The selection of the abrasive materials should take into account the original geometry of the surface, as too high stress concentration may result in a reduction in the strength of the adhesive joints [12, 13]. The abrasive materials include natural abrasives such as: diamond, quartz corundum, pumice, kaolin and artificial abrasives: green and black corundum, electrocorundum (A, B, C), aluminum oxide and chromium oxide.

A grinding is one of the most recognizable methods of the mechanical surface treatment [14], which is an abrasive treatment that uses grinding wheels with flexible abrasive discs. The grinding wheel performs the main movement - rotation, while the feed movement can be performed by the tool, the object or both at the same time. Abrasive tools have the character of bonded grains whose geometry is undefined and irregular.

The ground surface made it possible to get rid of impurities that prevented a proper adhesive connection and created a diversified geometry of the surface layer, contributing to the creation of a surface roughness that will allow characterizing and determining the impact of the abrasive material used and its gradation on the strength of the obtained joints.

The analysis carried out in the following article consisted in determining the relationship between the type and gradation of the grinding abrasive used and the obtained surface roughness, which translates into the strength values of the tested adhesive joints. The variable factor for the surface preparation process was the type of the abrasive materials used and their gradation.

METHODS AND EXPERIMENTAL

The research process included the surface treatment of the selected construction material - C45 steel for bonding, determining selected surface roughness parameters, making the adhesive joints, taking into account the variants of the selected surface treatment method by grinding, and determining the strength of the adhesive joint.

Surface treatment

The variable factor for the surface treatment process was the type of abrasive materials used and their gradation. The mechanical machining process for each of the 60 samples was carried out in the same workshop conditions with a maximum rotational speed of the grinder used: 11.000 rpm and a grinding time of 20 seconds for each sample. For the grinder model used, grinding discs with a diameter of 125 mm with velcro fastening were used as the grinding wheel, in which the abrasive grain was placed on velvet paper in a resin bond.

The abrasive discs were used in three types of the abrasive grains and three gradations. The surface treatment was divided into two comparison groups (Table 1):

- the samples made with abrasive material of the same gradation, but a different type of abrasive grains (Fig. 1),
- the samples made with the same type of abrasive grains with variable gradation (Fig. 2).

The sheet metal samples were prepared in six series of ten samples according to the division presented in Table 1.

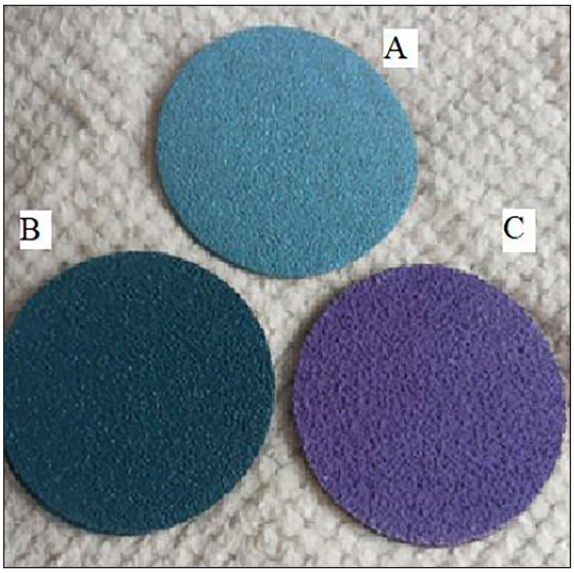

Figure 1. Grinding discs with abrasive grains: A) electrocorundum; B) zirconium; C) ceramic

Figure 2. Abrasive papers with electrocorundum grains in three gradations: P40, P220, P400

Table 1. Abrasive materials used and their gradations

Abrasive grain material	Gradation
Abrasive grains with the same gradation	
Ceramics	P40
Zirconium	P40
Electrocorundum	P40
Abrasive grains with different gradations	
Electrocorundum	P40
Electrocorundum	P220
Electrocorundum	P400

The grinded surface allowed for the removal of contaminants that prevented a proper adhesive connection from being made and created a diversified geometry of the surface layer, contributing to the creation of a surface roughness that will allow the characterization and determination of the impact of the abrasive material used and its gradation on the adhesive joints strength.

In the next stage of preparing the surface of the adherends for bonding process, the treated adherends surface after the grinding was degreased by once wiping the polished surface with a cloth soaked in acetone from ANED (Aned, Nowa Sucha, Poland)). Then, a minute was waited for the acetone to evaporate from the sample surface.

Adhesive and adhesive joints

The adhesive joints of steel sheets were prepared using the two-components epoxy adhesive prepared on the basis of the epoxy resin produced on the basis of bisphenol A (Epidian 5 basic resin, trade name, Sarzyna Resins, Nowa Sarzyna, Poland) and triethylenetetramine curing agent (Z-1 trade name, Sarzyna Resins, Nowa Sarzyna, Poland), where the recommended stoichiometric ratio was 100:10. The characteristics of the components of the adhesive used, marked E5/Z-1, are included in the works [15, 16].

The both components: the epoxy resin and the curing agent were mixed mechanically according to the mentioned stoichiometric ratio of 100 parts by weight of the epoxy resin and 10 parts by weight of the curing agent. A laboratory scale with an accuracy of 0.1 g was used to measure the ingredients (FAWAG S.A., Lublin, Poland). A mixing stand was used for mixing, using a special mechanical anchor mixer. The mixing process was carried out at a speed of 480 rpm for 120 s. The adhesive prepared in this way was applied with a spatula and a thin layer was applied to both adherends surfaces. The elements were joined together in accordance with the abrasive material used and its grain size. After applying the epoxy adhesive, the elements were joined together in an overlapping manner over a length of 20 mm. The diagram of the adhesive join is shown below (Fig. 3).

The curing process of the adhesive joints took place in one stage a temperature of 22 ± 1 °C and air humidity of 19 ± 2%, using a load of 0.018 MPa for 7 days and was cold curing,

Tests

Two types of the tests were carried out during the research. The first test concerned the determination of the geometric structure of the surfaces of joint elements after the grinding process, using specific variants of the abrasive materials and their gradations. For this purpose, Hommel–Etamic T8000 RC120-400 profilographometer (JENOPTIC Industrial Metrology Germany GmbH, Schweninngen, Germany) were used. Measurements were performed in accordance with the PN-EN ISO 4287 (2D parameters) and ISO 25178 (3D parameters) standards. Measurements were made for 193 measurement points on the tested surface, taking into account the total length Lt = 4.8 mm and the elementary section with the length Lc = 0.8 mm and the measurement section 4 mm. The distance between distant points was set to 0.25 μm. The following surface roughness parameters (2D) were taken into account: Ra – arithmetic mean of the profile ordinates, Rz – the highest profile height, Rt – total height of the roughness profile. In addition to

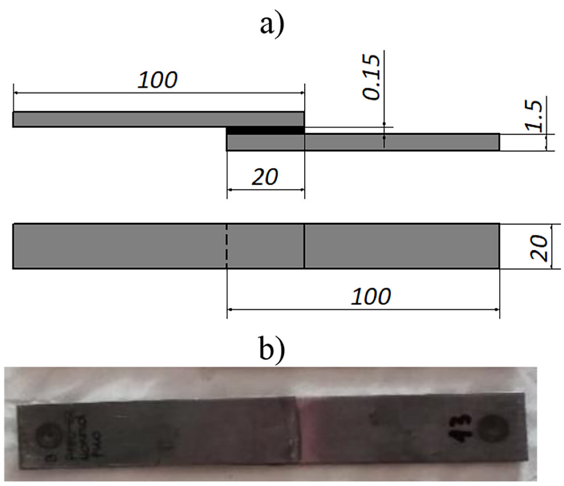

Figure. 3. Adhesive joints sample: a) scheme, b) view

the compiled amplitude parameters, 3D surface topography charts were made and the values of 3D parameters were determined, such as: Sq – mean square height of the surface, Sp – maximum height of the peak, Sv – maximum height of surface depressions, Sz – maximum surface height, Sa – arithmetic mean surface height.

The second type of research concerned the determination of the strength of the adhesive joints of steel sheets, the surfaces of which were ground with various variants of abrasive materials and their gradations. The strength tests were executed on a ZWICK/ROELL Z150 testing machine (ZwickRoell GmbH&Co. KG, Ulm, Germany) in accordance with the DIN EN 1465 standard, at a testing speed of 5 mm/min.

Correlation

The results of the adhesive joints strength and surface roughness parameters of adherends were assessed using the correlation method to determine the correlation between the variables. The Pearson linear correlation coefficient r (X, Y) was used as a measure of correlation of the analyzed variables [17]. The correlation coefficient ranges from -1 to 1. In order to interpret the results of the correlation coefficient, the following ranges were adopted, indicating the strength of the correlation: a) from 0 to 0.2 – this is a very weak relationship, b) from 0.2 to 0.4 – this is a weak relationship, c) from 0.4 to 0.6 – this is a moderate relationship, d) from 0.6 to 0.8 – this is a strong relationship, e) from 0.8 to 1 – this is a very strong relationship.

RESULTS

Surface roughness parameters

The results of the surface roughness tests obtained after the processing with three types of the abrasive materials: ceramics, zirconium and electrocorundum are presented in Figure 4.

Based on the results presented in Figure 4, it was noticed that both the total height of the roughness profile (Rt), the arithmetic mean of the profile ordinates (Ra) of the roughness profile, and the highest profile height (Rz) were obtained for ceramic grains. These values indicate the value of Rt = 15.41 μm for ceramics, which is significantly higher than the value of this parameter when zirconium and electrocorundum are used, which are similar to each other. Similar properties are demonstrated by the remaining Ra and Rz surface roughness parameters, where for ceramic grains Ra is 2.11 μm. For zirconia and electrocorundum grains, these values were obtained at the level of Ra = 1.42 μm and Ra = 1.37 μm, while the highest profile height (Rz) was 11.2 μm.

The obtained results (Fig. 4) indicate that the highest surface roughness using the same grit of sandpaper was achieved by using ceramic grains characterized by high hardness and self-sharpening of the grains, which makes the processing very efficient and accurate.

The second comparison group of abrasive materials was the use of sandpaper with the same grain material – electrocorundum, but with a different grain size: P40, P220 and P400. The chart below (Fig. 5) presents the values obtained from surface roughness measurements.

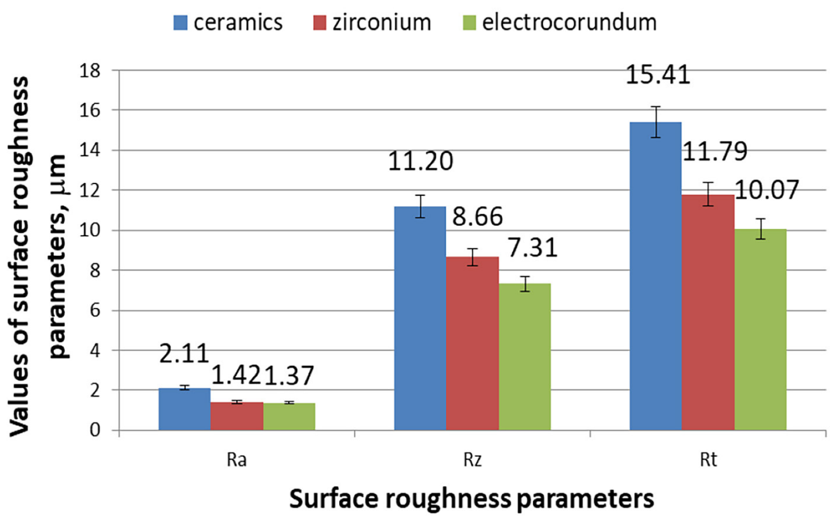

Figure 4. Summary of 2D surface roughness parameter results depending on the type of abrasive material

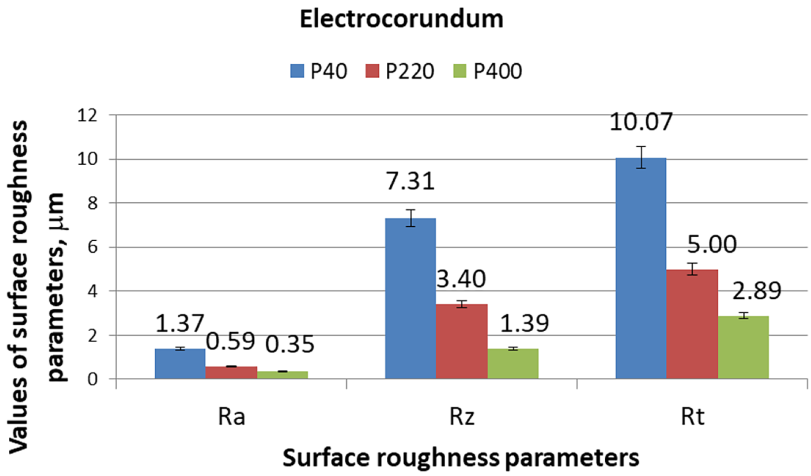

Figure 5. Surface roughness parameters of adherends after treatment with electrocorundum with gradations: P40, P220, P400

The average surface roughness parameters for samples whose surfaces were prepared with electrocorundum abrasive papers of various grain sizes (Fig. 5) indicate that the highest values of all parameters were obtained with P40 grain size. The total height of the roughness profile (Rt) was 10.07 µm when preparing the surface with P40 gradation paper, the value for this parameter with P220 gradation was half as much – 5 µm. It is visible in the graph that all roughness parameters decrease with the increase in grain size, which allows us to notice that the increase in the value of surface roughness parameters is inversely proportional to the gradation of the abrasive material used for roughening.

The surface roughness analysis was extended to include 2D surface charts and 3D topographic maps. The figures below present 2D and 3D surface views for two comparison groups: (i) the sample surfaces prepared with sandpaper with the same grain size P40, but a different type of the abrasive material, i.e. ceramics, zirconium, and electrocorundum (Fig. 6), (ii) the sample surfaces prepared with the sandpaper made of the same abrasive material, i.e. electrocorundum of different gradations: P40, P220, P400 (Fig. 7).

The surface roughness parameters shown in Figure 4 correspond to those shown in Figure 6 2D and 3D surface roughness charts. As shown in the chart (Fig. 6), the highest roughness values are visible when shaping the surface with ceramic grains. The surface structure after grinding with a disc with ceramic grains shows the largest fluctuations in parameters from 7.5–17.5 µm with local irregularities of up to 22.5 µm (Fig. 6a).

Referring to the numerical values in Figure 4 and the scale in the graph (Fig. 6b) presenting the surface structure of samples after processing with zirconium grains, it is visible that the parameter values range from 6–9 µm. The graph shows the heterogeneity of the surface and its occurrences in the form of cyclically repeating linear occurrences. The structure shows alternating surface elevations and depressions every 0.2 mm on average.

The second comparison group presented in Figure 7 is the adherend surfaces treated with the same material but with different gradations. As can be seen in the attached charts (Fig. 7), the structure of the treated surfaces differs significantly from the first tested group (Fig. 6). The surface treated with the sandpaper with the electrocorundum grains and P220 gradation showed a test value of the total height of the roughness profile of 5 µm (Fig. 7b). The most characteristic surface after the grinding was obtained using P400 electrocorundum abrasive material (Fig. 7c), where the surface remains at a constant level of 5 µm with point changes in structure and values ranging from 2.5–4 µm.

The presented structure of the surface treated with electrocorundum sandpaper with P40 grain, shown in Figure 6c and Figure 7a, is at the level of average Rt = 10 µm. The surface mostly shows alternating values from 7 to 11 µm and the occurrences are much wider than when grinding with zirconium grains. The surface roughened with the electrocorundum abrasive grains, similarly to the P40 graded materials, shows the linearity of the machining marks, while machining with this type of the abrasive material shows that the spots are up to 1 mm wide in places.

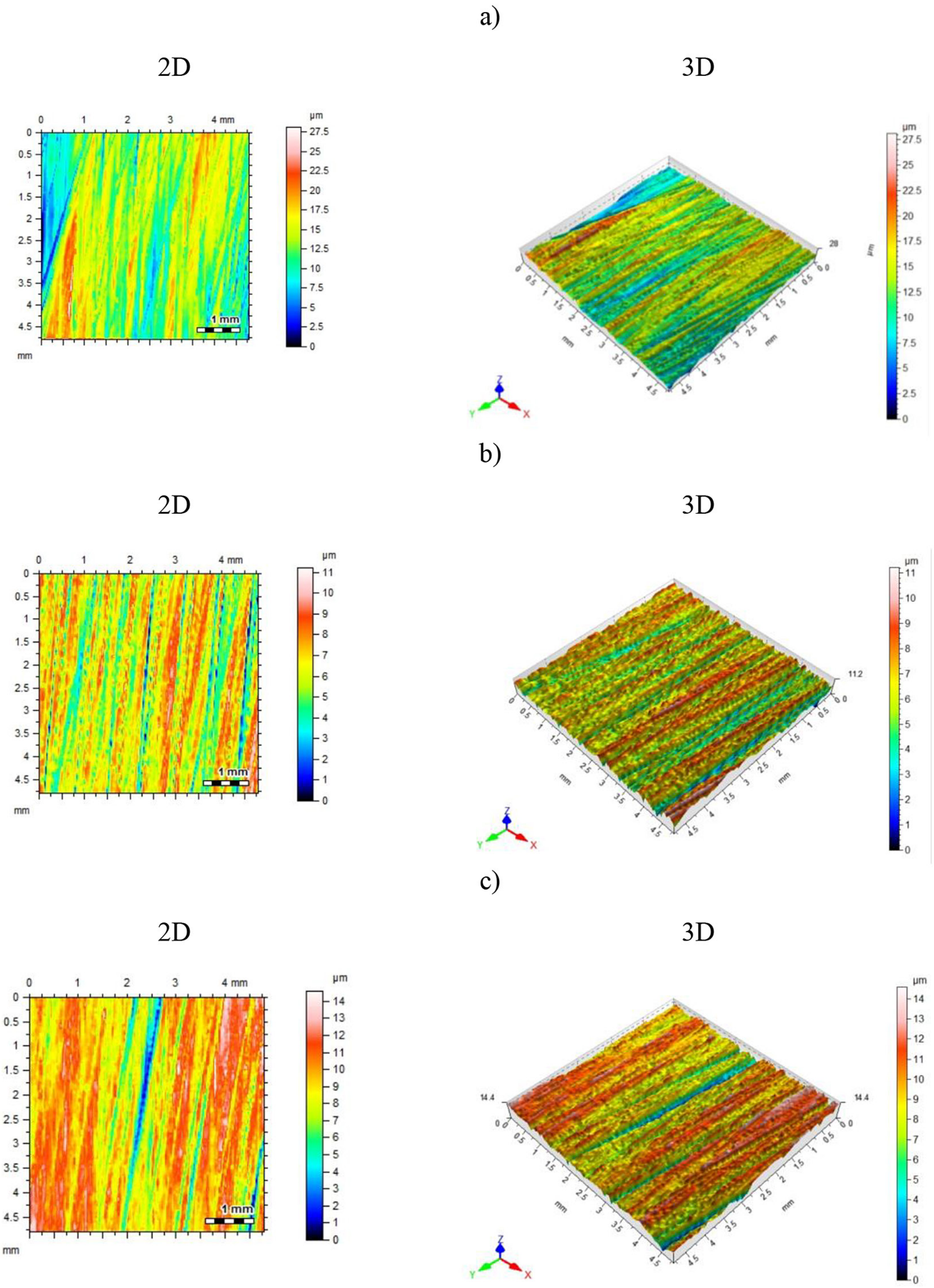

Figure 6. 2D and 3D surface roughness maps for adherends surfaces prepared with various types of abrasive grains: a) P40 ceramics, b) P40 zirconium, c) P40 electrocorundum

The structure of the joined surfaces indicates mechanical processing by grinding, as it leaves characteristic continuous surface irregularities on the surface of the materials.

Strength of adhesive joints

When carrying out the strength analysis, two variables of the prepared samples were taken into account: the type of the abrasive grain and its gradation. The shear strength of the adhesive joints depending on the type of the abrasive material used to prepare the surface of adherends and its gradation is shown in Figure 8.

The values obtained in the graph above (Fig. 8) indicate the relationship between the surface roughness of the joined samples and the shear strength of the adhesive joints. The

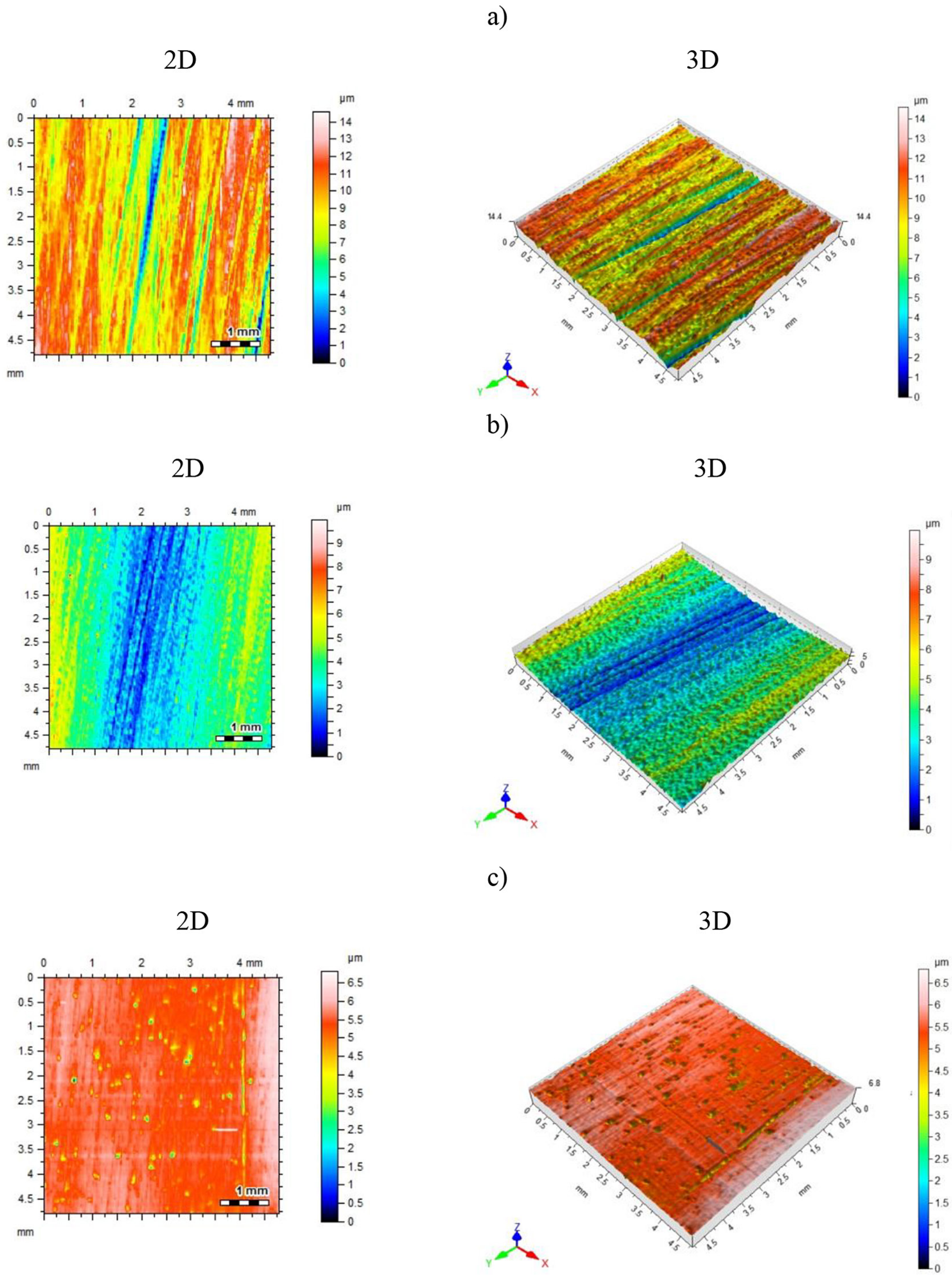

Figure 7. 2D surface roughness charts for adherends surfaces prepared with the same abrasive material (electrocorundum) with different gradations: a) P40 b) P220, c) P400

strength values for the adherends whose surface was prepared with ceramic material show the highest value of 6.91 MPa, for the surfaces of joined samples prepared with zirconium abrasive grains – 5.19 MPa and 4.33 MPa for electrocorundum abrasive. These indications correspond to the surface roughness values and appear similarly on the graph. The last of the studied comparative groups is a graph (Fig. 9) of the shear strength for steel sheets samples whose surface was prepared using the electrocorundum abrasive with variable gradation.

Based on the results obtained, it can be seen that the use of P400 electrocorundum allowed obtaining the highest shear strength of 5.09 MPa. The lowest strength was achieved by adhesive joints whose sample surfaces were treated with P220 grade electrocorundum.

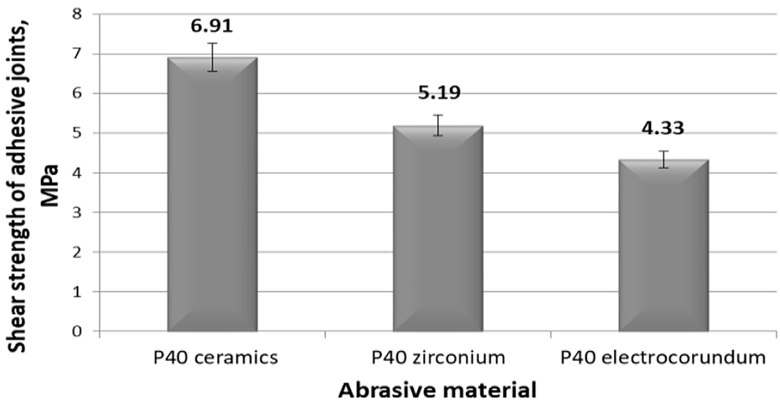

Figure 8. Shear strength of adhesive joints whose adherends surfaces have been ground using three abrasive materials: ceramics, zirconium, electrocorundum

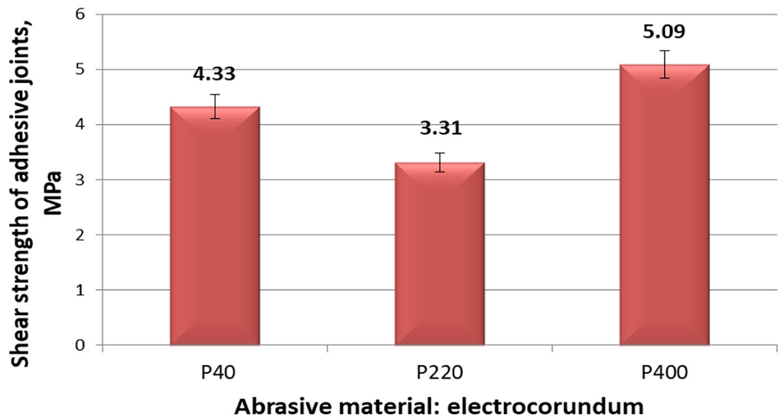

Figure 9. Shear strength of adhesive joints whose adherends surfaces have been ground using three grades of electrocorundum: P40, P220, P400

DISCUSSIONS

When comparing the analyzed influence of both factors: abrasive material and gradation, it was noticed that the values of the roughness parameters depend on the type of abrasive material used when the same gradations are used (Fig. 4 and Fig. 5). In addition, the structure is also influenced by the gradation of abrasive material used for processing, comparing it with the same abrasive material (Fig. 5). Ghumatkar et al. [6] analyzed the influence of various steel surface roughness's, through the mechanical abrasion using an emery paper of different grade, on the strength of the adhesive joints. It has been shown that the optimum values of the surface roughness occur in different ranges with respect to the joints of the bonded materials. The presented graphs of surfaces (Fig. 6 and Fig. 7) prepared for bonding by grinding indicate a tendency for the surface roughness measurement values to decrease with increasing abrasive material gradation. Rudawska et al. [9] observed that both the surface roughness parameters and the adhesive properties are influenced to a greater extent by the type of the abrasive material applied, and to a lesser extent by the technological parameters of the sandblasting.

Table 2 lists the values of the correlation coefficient between the 2D parameters of the surface roughness of the joined elements and the shear strength of the adhesive joints taking into account the same type of material - electrocorundum, but with different gradations.

Analyzing the Pearson correlation coefficient between the shear strength of adhesive joints and 2D parameters, it can be noticed that the correlation between these values can be considered weak and negative. This means that as the surface roughness parameters increase, the strength decreases. In the case of the relationship between the shear strength of the adhesive joints and 3D surface roughness parameters, it was noticed that the strongest relationship occurs between the shear strength of adhesive joints and the Sp parameter (-0.93), and the weakest between the shear strength of adhesive

Table 2. *C*orrelation coefficient between 2D parameters of surface roughness of adherend and shear strength of adhesive joints

Surface roughness parameters after processing with electrocorundum with P40, P220, P400 gradations (X) vs Shear strength of adhesive joints (Y)		
Parameters		Correlation coefficient r (X,Y)
2D	Ra	-0.14
	Rz	-0.25
	Rt	-0.20
3D	Sa	-0.47
	Sz	-0.32
	Sp	-0.93
	Sv	0.42
	Sq	-0.39

joints and the Sz parameter (-0.32 – weak dependence). It was also noticed that, apart from one 2D parameter – Sv), the correlation between the shear strength of adhesive joints and 3D parameters is negative, i.e. as the surface roughness parameters increase, the strength decreases. These statements were based only on analysed the surface roughness parameters.

It can therefore be assumed that the issues of the relationship between the shear strength of adhesive joints and the 2D and 3D surface roughness parameters are complex and require further analysis. Dam et al. [10] showed that the occurrence of the complex texture or morphology has a more significant impact on the initial adhesion and the durability of the interfacial adhesion than the average roughness.

Rudawska [5, 13] analyzed the impact of the mechanical treatment on the surface roughness and noticed that the geometric structure of the adherends surface, which determines the ability of a the dhesive to penetrate, is more important than the surface area. This context can be related to the obtained 2D and 3D roughness parameters. It is worth noting, however, that, as shown by Podulka in [18], surface roughness analysis can also be extended with other valuable analyzes based on texture direction graphs, autocorrelation function, power spectral densities and spectral characterization, in order to broaden the description of surface topography.

CONCLUSIONS

The article attempts to assess the impact of the method of surface treatment of C45 steel sheets, and more specifically, the impact of the gradation and type of abrasive material on the strength of the adhesive joints of steel sheets.

The steel sheets samples were ground with three P40 – grade abrasive papers with abrasive grains made of: ceramics, zirconium and electrocorundum. The second test group included samples prepared with electrocorundum abrasive papers with variable paper gradation: P40, P220, P400. The prepared samples were subjected to tests to determine the surface roughness (2D and 3D surface roughness parameters and surface topography), and then the adhesive joints made of them were subjected to strength tests.

The analysis of the tests showed a significant impact of the surface treatment method on the obtained adhesive joints strength.

The roughness analysis indicated that in the comparative group of the samples prepared with the abrasives of various abrasive materials, the ceramic material would allow obtaining the highest parameters of the surface roughness and the shear strength of the adhesive joints in which the joined materials were prepared with this abrasive.

Comparing the samples prepared with electrocorundum of variable gradation, the tests exhibited that the steel sheets samples prepared with P40 paper had the highest roughness, while the samples prepared with P400 paper had the highest shear strength.

It can therefore be assumed that the issues of the relationship between the shear strength of the steel sheets adhesive joints and the 2D and 3D surface roughness parameters are complex and require further analysis.

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