Sylwester Chłopek, Grzegorz Michta

Strength Analysis of Dissimilar Adhesive-Bonded Joints

Abstract: The article discusses aspects related to material surface engineering and the strength of adhesive-bonded joints as well as presents results concerning the surface wetting angle and the free surface energy of steel S335, aluminium alloy AW7075 (T6) and the CFRP composite material in relation to three surface treatment conditions. The authors emphasize that surface preparation is of key importance as regards the obtainment of potentially high-strength joints. The article also discusses results concerning the roughness of the surface of the steel and the aluminium alloy in relation to various grades of abrasive paper granularity. The final part of the article presents test results concerning the shear strength of dissimilar adhesive-bonded joints (i.e. steel S335 – CFRP composite and aluminium alloy AW 7075 (T6) – CFRP composite) and discusses related images of ruptured joints.

Keywords: adhesive bonding, adhesive-bonded joints, adhesive

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Introduction

In addition to welded or, less popular, brazed joints, adhesive-bonded joints constitute an important area of permanent joints. Because of their high strength properties, adhesives are becoming increasingly popular joining factors. Thermosetting structural adhesives, based on synthetic chemicals, include, among other things, epoxy, amino or polyurethane resins. The growing popularity of adhesive bonded-joints is manifested by the fact that there are approximately 750 chemical companies worldwide dealing with the production of industrial adhesives [1]. Adhesive-bonded joints are often used as supplementing reinforcements combined with, for instance, riveted or bolted joints. [2].

Adhesive-bonded joints could be defined as joints involving the use of substances capable of joining materials through the surface joining process. Because of the uniform distribution of stresses in joints, the use of structural adhesives makes it possible to obtain mechanically equivalent (or even “stronger”) mechanical structures. In addition, the application of adhesives reduces fabrication costs as it eliminates the necessity of performing post-weld stress relief annealing.

Advantages resulting from the use of structural adhesive-bonded joints, discussed in publications [1, 4], are, among other things, the following:

- possibility of joining materials characterised by various physical properties,
- eliminating the necessity of making holes in elements to be joined (leading to the weakening of these elements),

inż. Sylwester Chłopek, dr inż. Grzegorz Michta – AGH University of Science and Technology in Kraków; Faculty of Metal Engineering and Industrial Computer Science

- possibility of obtaining tight joints,
- high shear strength (above 15 MPa; in terms of cutting-edge structural adhesives),
- corrosion resistance,
- vibration damping ability.

A particularly important aspect concerning adhesive-bonded joints is adhesion, usually defined as a phenomenon occurring on the boundary of phases (i.e. adhesive-material surface) and consisting in the "tacking" of bodies resulting from interaction occurring between them. The aforementioned mechanism is presented in many various ways, which demonstrates the complexity of the phenomenon [3]. In the adsorptive theory of adhesion, the latter results from the difference of energy states of particles of the material and those of the adhesive, where the primary interaction is of dispersive, dipolar and covalent nature. In turn, the mechanical theory of adhesion states that adhesive, by entering micropores in the surface of a given material, becomes "anchored" in it and, as a result, enables the transfer of loads (after the solidification of the adhesive). According to M. Żenkiewicz, it is recommended that adhesive ability be assessed by measuring the surface wetting angle using goniometer [5] as well as by measuring the roughness of surfaces to be joined using the optical profilometer, the atomic force microscope and the scanning electron microscope.

Related reference publications indicate that the excessive number of pores present on the surface may preclude their filling with adhesive, thus leading to the formation of the so-called boundary layer, characterised by lower strength properties. Because of excessive surface roughness and the presence of high compressive stresses, the total strength of a joint may be reduced by as many as 50% [3]. The above-presented phenomenon is also referred to as the presence of a "notch". In addition, reduced strength properties are also attributable to the insufficient number of surface pores.

The remainder of the article presents test results concerning the roughness of surfaces of materials subjected to adhesive bonding.

Tests

Analysis of the wetting angle and the measurement of free surface energy

Tests concerning the material surface wetting angle were performed using a Kruss DSA25S testing machine, whereas tests results were developed using a dedicated Kruss Advance 1.6.1.0 software programme (Fig. 1).

The tests of the surface wetting angle involved the placement of single drops of the measurement liquid (i.e. water/diiodomethane) of specific volume (2.2 µm ± 0.2 µm) near the edge of a specimen (on the surface of a test material). The

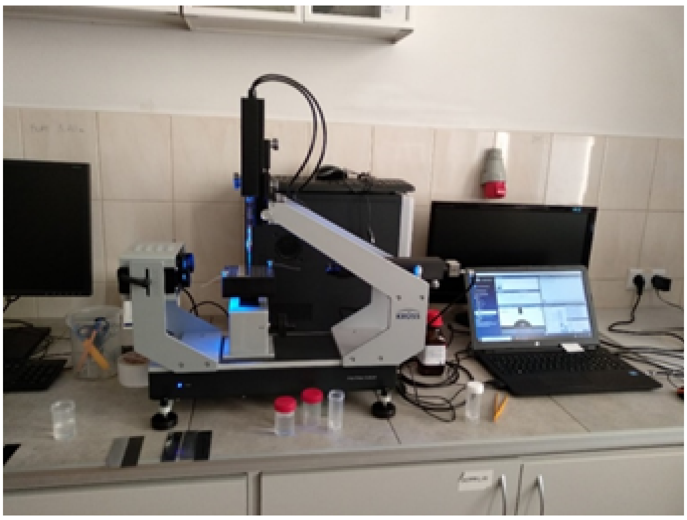

Fig. 1. Equipment used during the tests of the surface wetting angle

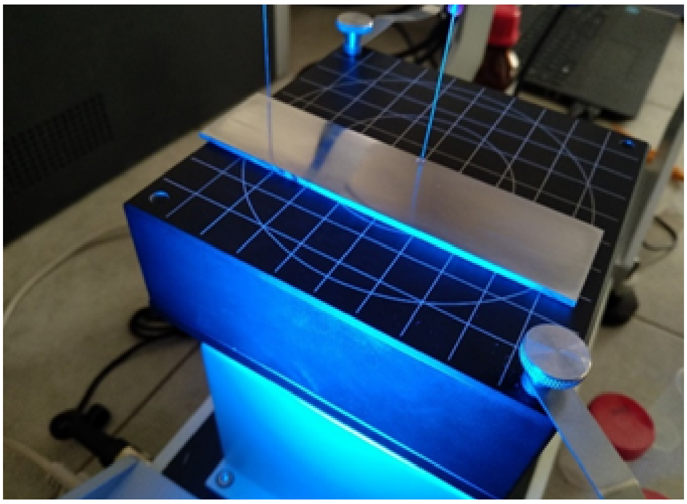

Fig. 2. Application of the measurement liquid on the surface of the test material

material was located in a special container (Fig. 2). The immediate measurement of the two-wall wetting angle (Fig. 3), performed before the spreading of the drop, involved the use of the freeze frame option of a camera.

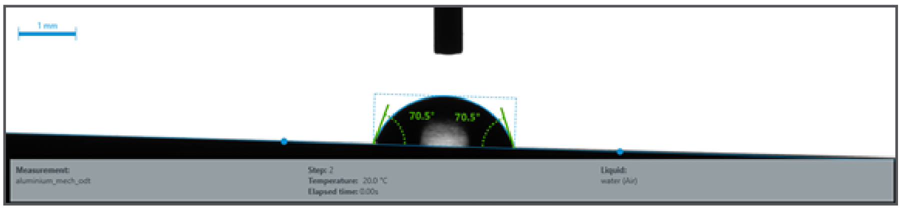

Fig. 3. Measurement of the two-wall wetting angle in relation to the surface of the aluminium alloy subjected to grinding and degreasing

The measurements of the two-wall wetting angle involved the use of flat specimens made in accordance with the ASTM D1002-99 standard. The materials used in the tests included structural steel S335, aluminium alloy AW-7075 (T6) and carbon fibre reinforced polymer (CFRP). During the tests, the above-named materials were characterised by three different surface conditions, i.e.:

- only after degreasing with acetone,
- only after mechanical treatment (grinding with abrasive paper) without degreasing,
- after mechanical treatment and degreasing.

To minimise the effect of drop hysteresis, the surface subjected to mechanical treatment had to (in accordance with publication [2]) be characterised by the average deviation of roughness profile R_a restricted within the range of 0.8 µm to 3.2 µm. Each of the specimens of the material and of the measurement fluids was subjected to a series of five measurements (concerning the surface wetting angle). Afterwards, the software was used to identify average surface energy. The calculation results concerning free surface energy are presented in Table 1.

Knowing that the surface wetting angle measurements were treated as a "tool" enabling the calculation of surface free energy (SFE), to facilitate the identification of differences of surface energy values, the latter were presented in a graphic form (Fig. 4).

Table 1. Results concerning the analysis of wetting angle values and free surface energy

	Measurement liquid	Water		Diiodomethane							
Treatment method	**Type of material**	**Wetting angle [°]**	**Deviation [°]**	**Wetting angle [°]**	**Deviation [°]**	**Value of SFE [mN/m]**	**SFE deviation mN/m]**	**Value of dispersive component [mN/m]**	**Deviation [mN/m]**	**Value of polar component [mN/m]**	**Deviation [mN/m]**
Degreasing	Steel S335	84.72	4.49	44.78	2.08	39.63	2.38	37.13	1.11	2.5	1.27
	Aluminium alloy AW-7075	76.37	1.78	40.37	1.1	44.23	1.24	39.42	0.56	4.81	0.69
	CFRP	105.1	3.3	61.87	2.27	27.61	1.5	27.5	1.3	0.12	0.2
Grinding	Steel S335	65.62	1.43	34.51	0.44	50.96	0.89	42.25	0.2	8.71	0.69
	Aluminium alloy AW-7075	55.26	3.15	25.83	2.3	58.63	2.51	45.85	0.84	12.78	1.67
	CFRP	94.09	0.73	16.44	1.32	48.77	0.35	48.75	0.32	0.03	0.02
Grinding + degreasing	Steel S335	63.05	5.93	40.34	2.3	50.34	4.3	39.44	1.16	10.9	3.13
	Aluminium alloy AW-7075	63.09	4.25	39.64	0.66	50.55	2.54	39.79	0.33	10.75	2.21
	CFRP	91.15	1.8	20.65	0.6	47.82	0.34	47.59	0.18	0.23	0.16

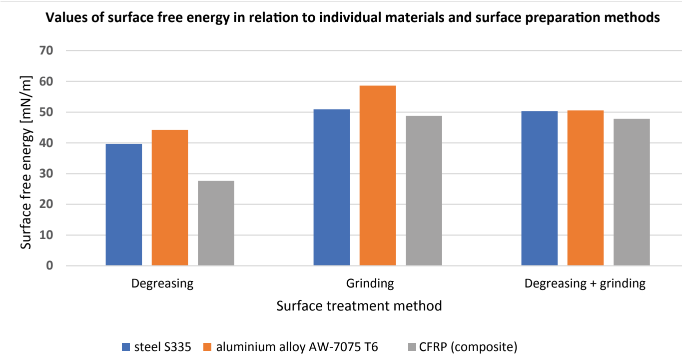

Fig. 4. Graphic presentation of the values of surface free energy in relation to individual materials and surface preparation methods

The bar chart (Fig. 4) revealed that the highest surface energy and potentially high strength properties could be obtained using the mechanical treatment (abrasive paper-based grinding) of the above-named test materials.

Surface roughness measurements

Surface roughness measurements were performed using a Wyko NT3900 optical profilometer (Veeco) along with a dedicated software programme. Figure 5 presents the testing equipment.

The optical profilometer enables fast and non-contact measurements of the geometry and of the topographic features of surfaces (including, among other things, roughness). The operation of the profilometer is based on the interference of visible spectrum, where the light beam is initially split into measurement and reference paths. The reference beam covers a specific (previously known and constant) optical path. In turn, the measurement beam strikes the specimen, is reflected against it and, interfering with the reference beam, is recorded in a detector. The interference light beam contains encoded information about the height of the specimen at a given point. The collection of information concerning subsequent surface measurement points enables the obtainment of information concerning changes of the surface height, which, in turn, makes it possible to determine the roughness of the surface. The performance of the above-named measurements involves the use of a computer.

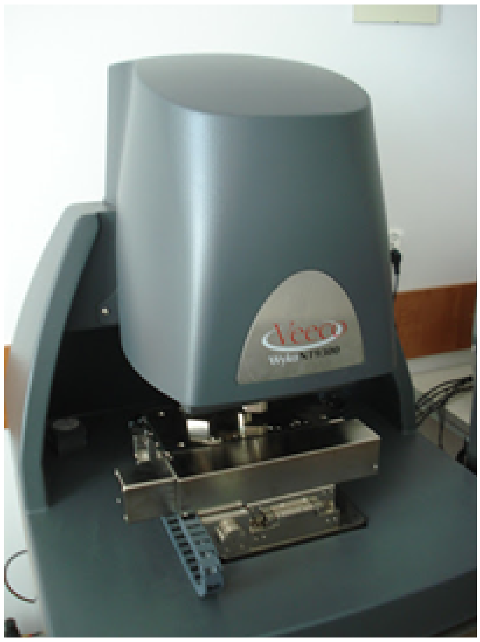

Fig. 5. Optical profilometer (used in, among other things, surface roughness measurements)

Roughness measurements involved placing the material specimen on a moving table, above which an optical lens was located. The distance between the lens and the specimen surface was adjusted so that it could be possible to see the spot of light (leaving the lens) on the material and, in addition, so that the image of the illuminated surface could be clearly visible on the monitor (without fogging, shadow, etc.). Similar to the surface wetting angle analysis, roughness parameters concerning steel S335 and aluminium alloy AW-7075 (T6) in the form of flat specimens were only measured in relation to the surfaces subjected to manual mechanical treatment involving the use of abrasive paper having a gradation of 40, 80, 120, 180, 220, 240, 400, 600, 800 and 1000. The test results concerning roughness parameters are presented in Tables 2 and3.

Taking into consideration recommendation related to roughness parameter Ra, restricted within the range of 0.8 μm to 3.2 μm, it appeared that to prepare surfaces characterised by potentially high adhesive properties it was necessary to grind surfaces using abrasive paper, the granularity of which was restricted within the range of 40 to 240 in relation to structural steel S335 and 40 to 120 in relation to aluminium alloy AW-7075 (T6).

Table 2. Surface roughness parameters in relation to structural steel S335

Structural steel S335										
	Abrasive paper gradation									
Parameter	40	80	120	180	220	240	400	600	800	1000
Ra [µm]	1.6	1.29	1.18	1.02	0.97	0.84	0.77	0.69	0.61	0.52
Rt [µm]	19.93	30.99	19.09	16.97	18.3	28.39	11.14	13.55	14.19	15.73
Rq [µm]	2.01	1.6	1.48	1.27	1.18	1.05	0.95	0.89	0.8	0.71
Rz [µm]	15.97	16.46	13.13	12.58	10.49	17.39	9.32	10.67	11.19	10.82

Table 3. Surface roughness parameters in relation to aluminium alloy AW-7075

Aluminium alloy AW-7075 T6										
	Abrasive paper gradation									
Parameter	40	80	120	180	220	240	400	600	800	1000
Ra [µm]	1.25	1.12	0.88	0.69	0.78	0.72	0.48	0.46	0.44	0.41
Rt [µm]	25.66	17.98	18.33	15.22	17.14	22.31	83.21	55.65	19.75	24.34
Rq [µm]	1.49	1.37	0.99	0.88	0.98	0.93	0.64	0.71	0.6	0.63
Rz [µm]	12.83	11.61	10.14	10.23	10.01	12.04	16.4	27.93	11.69	12.81

Strength analysis of dissimilar overlap adhesive-bonded joints

Tests concerning mechanical properties of dissimilar adhesive-bonded joints were performed using an MTS 810 testing machine (Fig. 6). The dimensions of the adhesive-bonded overlap joint (performed in accordance with ASTM D1002-99) were 12.5 mm x 25.4 mm.

Fig. 6. Dissimilar adhesive-bonded joint

The tests of mechanical properties involved two types of overlap adhesive-bonded joints:

- structural steel S335 (thickness: 2.0 mm) – CFRP composite (thickness: 1.5 mm),
- aluminium alloy AW-7075 (T6) (gr. 2.0 mm) – CFRP composite (thickness: 1.5 mm).

The surface of the metallic specimens (in the area of adhesion) was subjected to mechanical treatment (grinding) performed using abrasive paper of related gradation. The identified thickness of the adhesive-bonded joint amounted to 0.1 mm with a tolerance of ± 0.1 mm. The adhesive substance was the Loctite® 9466 structural adhesive. The adhesive-bonded joints solidified for an hour at a temperature of approximately 100°C. The solidification process was affected by thermal processing, which increased the cohesive strength of the joint. The solidification process started with the mixing of the two components of the adhesive and finished with the entire loss of adhesive flexibility. As a result, the joint was capable of transferring loads. The solidification process could also take place at room temperature, yet in such a case the time necessary for the solidification of the adhesive-bonded joint would amount to approximately one week. Afterwards, for 8000 hours the adhesive-bonded joints were stored at a temperature of 20°C in a room where humidity amounted to approximately 48%. The results of the mechanical tests of the dissimilar adhesive-bonded joints are presented in Tables 4 and 5.

The adhesive nature of the failure of the adhesive-bonded joints is presented in Figure 7.

Fig. 7. Adhesive nature of the failure of the adhesive-bonded joints – the lack of visible adhesive "particles" on the surface of the composite material

The maximum values obtained in the tests concerning the shear strength of the steel-composite and the aluminium alloy-composite joints and those contained in the technical specification of the adhesive [6] in relation to similar (i.e. steel-steel and aluminium-aluminium) joints amounted to 84% and 93% respectively. The above-presented parameters could be regarded as highly favourable. The standard deviation values exceeding 1 kN entail the necessity of performing further tests concerning the precision of making joints and/or making specimens characterised by different geometry (i.e. only allowing the presence of forces shearing the adhesive). The presence of shear forces is a condition eliminating the effect of joint eccentricity.

Summary

The performance of many tests concerning surface engineering demonstrated the importance of the appropriate preparation of materials before the adhesive bonding process and the subsequent effect of such preparation on the mechanical properties of adhesive-bonded

Table 4. Results of the mechanical tests of the dissimilar adhesive-bonded joints of structural steel S335 and CFRP (composite)

Overlap adhesive-bonded joint: steel S335 – CFRP composite			
Paper gradation	**Average shear force [N]**	**Standard deviation of force *s* [N]**	**Shear strength R_t [MPa]**
40	4633	702	14.4
80	4384	1130	13.6
120	3662	1208	11.4
180	2917	342	6.3
240	2029	101	4.6

Table 5. Results of the mechanical tests of the dissimilar adhesive-bonded joints of aluminium alloy AW-7075 (T6) and CFRP (composite)

Overlap adhesive-bonded joint: aluminium alloy AW-7075 (T6) – CFRP composite			
Paper gradation	**Average shear force [N]**	**Standard deviation of force *s* [N]**	**Shear strength R_t [MPa]**
40	3903	1233	12.1
80	3597	803	11.2
120	3174	932	9.8

joints. The test results also revealed that, in order to prevent the "pressing" of impurities into the material surface, mechanical surface processing (e.g. grinding with abrasive paper or sandblasting) should be preceded by degreasing. In the above-presented tests, the surfaces were prepared by grinding. Some of the specimens used in the tests were additionally subjected to degreasing (before grinding). The tests revealed that mechanical surface processing significantly improved the adhesion ability of the adhesive and, consequently, its shear strength.

Roughness parameter R_a, determined for the various gradation of abrasive paper used in mechanical surface processing made it possible to identify the level of gradation which should be applied when preparing materials and which could help eliminate factors worsening adhesion. The remark formulated above applies to metallic materials, yet composite polymer materials should be subjected to different procedures enhancing adhesion ability (e.g. flame or laser-based method or chemical surface modification). Factors indicating the proper making of overlap adhesive-bonded joints are the dimensional accuracy of test specimens and the tolerance of adhesive layer thickness.

The analysis of the test results concerning mechanical properties revealed that the steel-composite adhesive-bonded joints were characterised by higher shear strength than that of the aluminium alloy-composite joints. Taking into consideration the highest strength of the adhesive-bonded joints, which, according to the technical specification of the adhesive amounted to approximately 17 MPa in relation to the steel-steel adhesive bonded joint (after complete solidification), it could be concluded that the values of the shear strength in relation to the steel-composite adhesive-bonded joint were satisfactory.

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