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Identification of Factors Affecting the Strength of Joints in Steel-Titanium-Aluminium Composites in Monotonic Peel Tests

Abstract: The paper presents the results of strength tests (ram test) of two types of three-layer material made using the explosion welding technology. Clad materials used in the test differed in the overlay layer (A1050 and A3003). The results were analysed for factors affecting the obtained level of joint strength.

Keywords: explosion welding technology, steel-titanium-aluminium composites

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Introduction

Progress in the electric, metallurgical aviation and chemical industries necessitated a search for new technological solutions involving the use of composite materials characterised by special operational properties [1]. Multilayer composite steel-aluminium materials are used, among other things, in aluminium plants as current connectors or in the shipbuilding industry as structural connectors (used to reduce the weight of ship structures) [2]. In hydrometallurgy, Ti-Cs bimetals are used to make pressure vessels used for the production of nickel in the process of chemical leaching. One of the technological processes enabling the obtainment of a composite characterised by special properties is the explosion welding method. Explosion welding is defined as cold joining, making it possible to join materials characterised by different physicochemical properties using the energy accompanying the detonation of an explosive. The cladding technology is based on two methods used for the joining of metals and their alloys, i.e. an indirect method and a direct method. In the indirect method, energy generated as a result of the combustion of an explosive mixture is transferred from the point of detonation to elements to be joined through an intermediate centre (medium) such as water or an appropriate mechanism. High costs of the indirect method of explosion welding are responsible for the fact that the direct method that has found practical applications [3–5]. In the direct method, an explosive remains in direct contact with elements to be joined and is placed on the surface of an overlay material. The use of the direct explosion welding method involves placing elements to be joined on a previously prepared sand pile. The base material, usually structural steel, remains in direct contact with the substratum. Overlay material is situated at a specific technological

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distance. Afterwards, a high explosive is placed on a flyer plate. The detonation of the explosive creates a shock wave generating a pressure of 10000 MPa [3,6]. The aforesaid pressure makes materials in the contact area behave like liquids, where the joint is formed through atomic bonds. In relation to certain material groups such as aluminium-steel, the excessively high impact force may lead to the formation of refractory intermetallic compounds on the border of the joint. The collision of plates subjected to explosion welding is accompanied by the diffusion of iron (from the base plate) to aluminium. The aforesaid diffusion leads to the formation of hard refractory Fe_xAl_x compounds responsible for the delamination of the joint. Titanium interlayers are used to form a diffusive barrier [7]. In one of his works, J. Banker compared the mechanical properties of the aluminium-titanium-steel and aluminium-steel plated coating after heat treatment. The author revealed that after a 24-hour long heat treatment performed at a temperature of 600°C the aluminium-titanium-steel plated coating was characterised by 70% of peel strength of that of the material not subjected to heat treatment. In turn, after a 24-hour long heat treatment performed at a temperature of 400°C the peel strength of the aluminium-steel plated coating was close to zero. [6].

The work was performed using clad materials made in the ZTW Explomet company. The tests involved the use of clad plates having the identical base material (AISI 1008) and an interlayer made of titanium Grade 1 as well as a different overlay aluminium alloy. The research-related tests involved tests of mechanical properties (peel test) as well as metallographic tests including measurements of wavelength and wave height as well as the EPT parameter.

Material characteristics

The tests presented below aimed to identify the mechanical properties of joints in three-layer metallic composites. All of the test plates were made of the same steel, i.e. steel grade ISI 1008, having a thickness of 38 mm (being the base plate), and of titanium Grade 1 (being the intermediate layer). The overlay layer used in the first of the composites subjected to the tests was aluminium A1050 alloy. In the plates designated as B, the overlay layer was aluminium alloy A3003. The mechanical properties of the above-named alloys are presented in Table 1.

Characteristics of geometric and mechanical parameters of the joints

Joints obtained using the explosion welding technology can be characterised through the determination of their geometric regularities. The joint line was described using primary features including wave amplitude ho and wavelength λ [8]. The above-named properties are related to welding parameters, i.e. the higher the detonation energy, the greater the amplitude of inter-surface waves.

Joint parameters may also be described using a coefficient related to the number of root

Table 1. Mechanical properties of test materials before welding

Material	Mechanical properties				
	R_{02}, MPa	R_m, MPa	E, MPa	G, MPa	ν, -
AISI 1008	280	340	210000	80000	0.30
Titanium grade 1	215	325	100000	38000	0.37
Aluminium A1050	20	70	69000	25900	0.33
Aluminium A3003	120	130	69000	2590	0.33
R_{02}- yield point, R_m- tensile strength, E- Young ‘s modulus, G – Kirhoff modulus, ν – Poisson ratio					

runs. The coefficient of equivalent penetration thickness (EPT) corresponds to the mean fraction of the root run in relation to the length of the joint line and is expressed using the following dependence:

$$EPT = \frac{\sum A}{L}$$

where $\sum A$ – stands for the sum of areas of all observed penetrations, L – total length of the joint fragment subjected to analysis. Figure 1 presents schematically the individual parameters of the joint. In turn, Figure 2 presents exemplary courses of the joint line.

The strength properties of the joint were determined using a monotonic peel test. The determination of the strength level was based on the value of nominal stress in the joint area. The tests involved cylindrical samples made in accordance with the ABS standard [9], [10]. The shapes and dimensions of the specimens are presented in Figure 3.

The results of metallographic and strength tests are presented in the form of diagrams. Figures 4–6 present the comparison of the geometric parameters of individual joints, whereas Figure 7 presents the results of strength tests.

Analysis of test results

During explosion cladding, welded materials are subjected to dynamic deformation triggered by pressure generated through the combustion

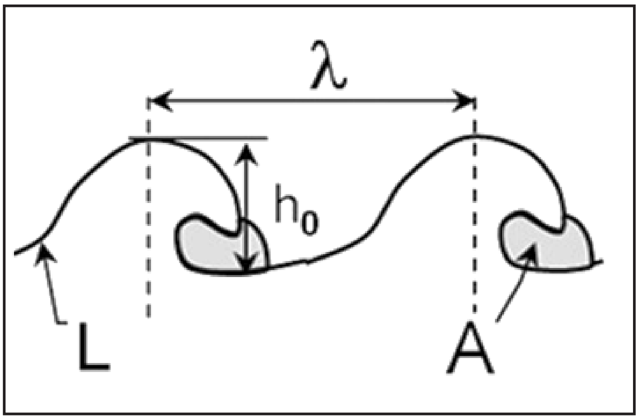

Fig. 1. Geometric parameters of the joint

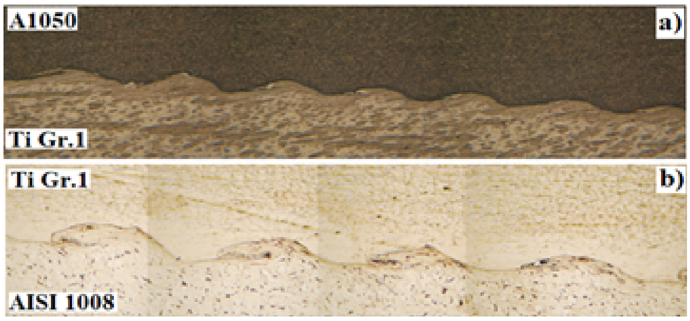

Fig. 2. Geometric parameters of the joint:
a) joint A1050-Ti.Gr.1 and b) joint Ti.Gr.1-AISI 1008

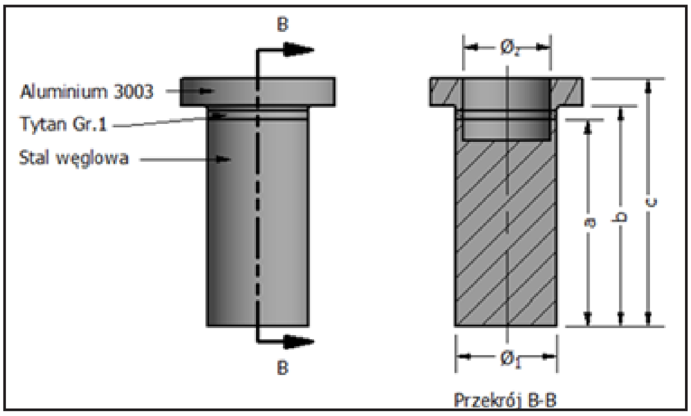

Fig. 3. Shapes and dimensions of the specimens, dimensions a, b and c are related to the thickness of the individual layers of the material

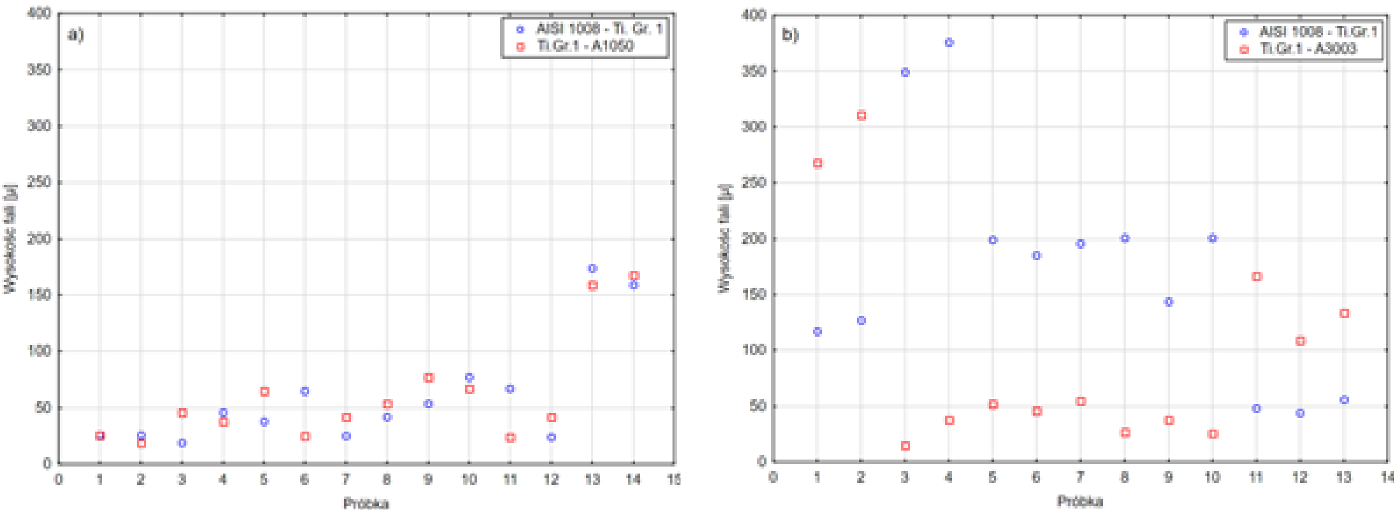

Fig. 4. Mean wave amplitude in the joint in relation to the overlay area: a) A1050 and b) A3003

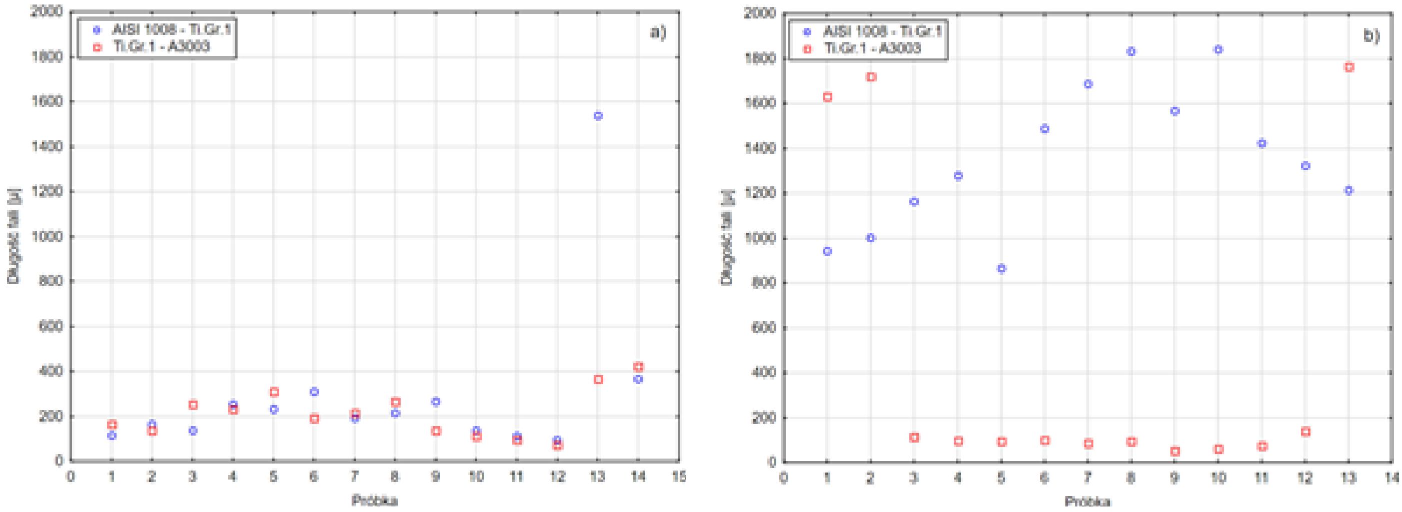

Fig. 5. Mean wavelength in the joint: a) A1050 and b) A3003

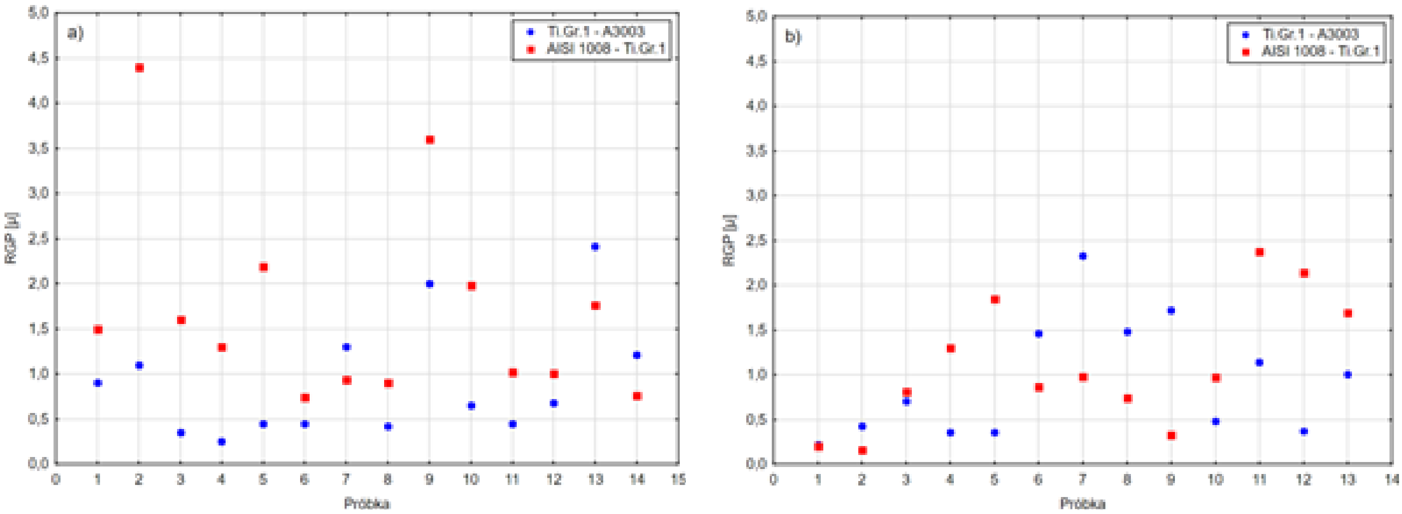

Fig. 6. Values of EPT coefficient: a) A1050 and b) A3003

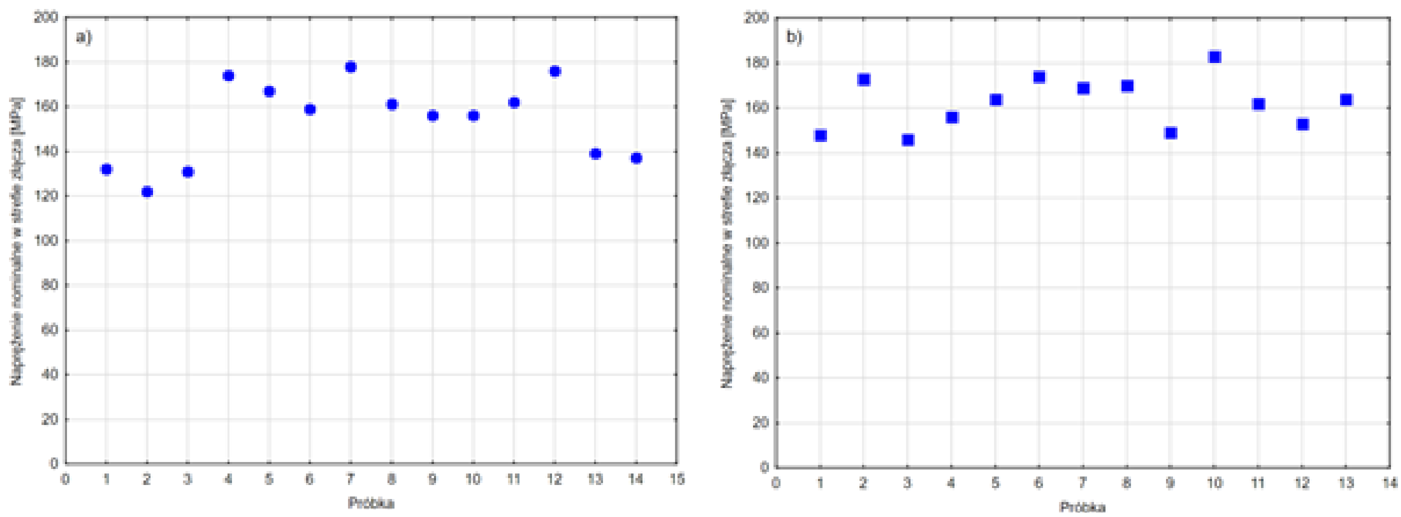

Fig. 7. Maximum peel strength of the joint: a) A1050 and b) A3003

of an explosive mixture. The parameters of the joint, being an intermediate measure of welding process energy, may affect joint strength. The analysis aimed to verify the correlation between the parameters of the joint and peel strength.

The first step involved the comparison of mean values obtained in strength tests in individual groups of materials (Fig. 8). Because of the fact that obtained groups of results did not meet the normal distribution, the analysis involved the Mann-Whitney U test (UMH). The null hypothesis assumed the equality of mean values in both groups.

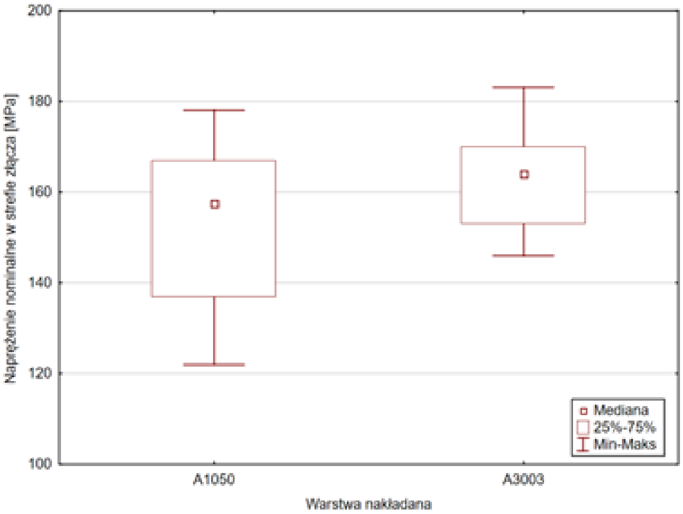

Fig. 8. Comparison of joint strength levels

The level of significance adopted in the UMH test amounted to $a = 0.05$. The obtained probability result $p = 0.29$ revealed that there were no reasons for rejecting the null hypothesis. The graphic interpretation of the test is presented in Figure 9. It should be noted that the multilayer material, where aluminium A 1050 was the overlay layer, was characterised by the greater scatter of results. In all of the cases, the specimen ruptured right next to the aluminium-titanium joint in the overlay material. Because of this, the analysis of the factors affecting the obtained level of strength was limited to the geometric parameters of the titanium-aluminium joints.

Fig. 9. Exemplary specimens after the monotonic peel test

Because of the lack of significant differences as regards the level of strength between the composite with overlay layer A1050 and A3003 in the analysis of the factors affecting strength, the results obtained in relation to both groups were combined. Diagrams of scatter between the level of strength as well as the joint-related amplitude of wave and wavelength are presented in Figure 10. In turn, Figure 11 presents scatter between the nominal stress in the joint area and the coefficient of equivalent penetration thickness.

The identification of the correlation between individual parameters and the strength of the joint involves the application of the Spearman correlation analysis. In relation to various wavelengths and various values of the EPT coefficient amounted to -0.015 and 0.007, indicating the lack of linear correlation. As regards the correlation between strength and the wave amplitude, the correlation coefficient amounted to -0.26, which indicated a week correlation.

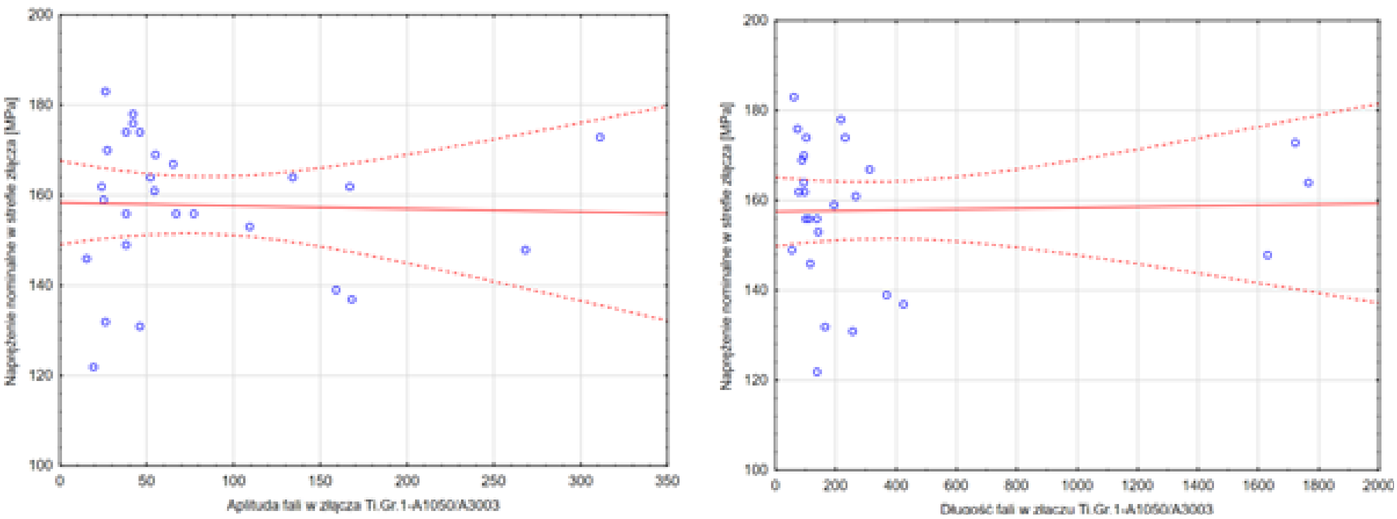

Fig. 10. Ranges of scatter for wave amplitude and wavelength in relation to the strength of the joint

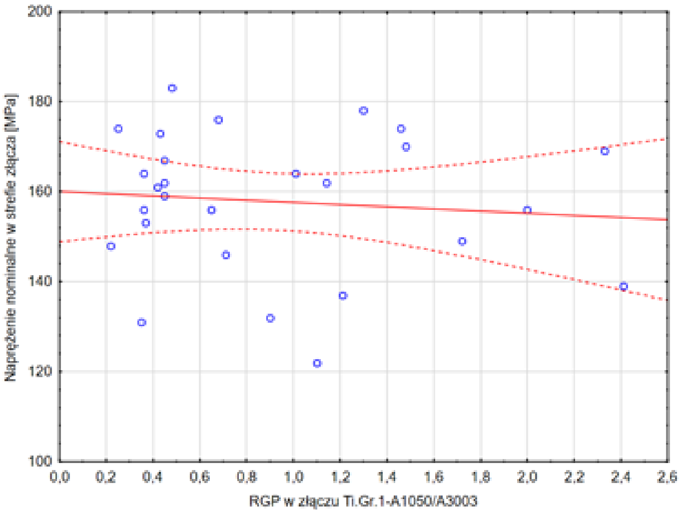

Fig. 11. Exemplary specimens after the monotonic peel test

Summary and concluding remarks

The above-presented tests and analyses enabled the formulation of the following concluding remarks:

- statistical analysis revealed the lack of differences as regards values obtained by the joint in relation to peel strength between multilayer materials and overlay layer A1050 and A3003,
- tests revealed a relatively low correlation between joint line outline parameters and peel strength,
- determination of the correlation between the geometrical features of the joint line and peel strength requires further tests and a larger number of specimens. It is therefore justified to formulate a criterion enabling the association of the parameters of obtained joints with welding process energy,
- further tests and analyses connected with the strength made using the explosion welding technology may find practical applications in FEM-based calculations.

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