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Unconventional Methods of Joining Composites and Metals in the Context of Weight Reduction of Car Bodies

Dušan Sabadka[1*], Štefan Kender[1]

[1] Department of Automobile Production, Faculty of Mechanical Engineering, Technical University in Košice, Mäsiarska 74, 040 01 *Košice,* Slovakia

* Corresponding author's e-mail: dusan.sabadka@tuke.sk

ABSTRACT

One of the basic trends in the automotive industry today is to achieve the most acceptable ratio between the total weight of the car to its overall performance and utility properties. Reducing the weight of cars is largely due to the use of new materials, where composite materials offer a wide space for their application. Composite materials have their specific properties which is very beneficial in reducing the total weight. Another advantages is strength, stiffness, low fiber density, the ability to form them into any shape based on the required applications. One of the challenges associated with the use of composite materials is the search for new technological possibilities of joining composite materials with metals. These include technologies as for example riveting, ultrasonic welding, but especially gluing. Bonding is currently one of the most preferred ways of joining composite materials. The paper deals with testing of technology of bonding composite materials with metals used in the manufacture of automobiles and a comparison of individual results obtained from the experiment.

Keywords: weight reduction, carbon fiber, composites, bonded joint.

INTRODUCTION

In the automotive industry and in the construction of means of transport, one of the main trends today is to achieve the most effective ratio of weight and overall performance together with its utility properties [1, 2]. For this reason, selected parts and components of the structure are replaced by other progressive materials, while maintaining or improving the properties and at the same time lower weight. Another challenge in connection with this trend is the search for new possibilities and technologies for joining different types of materials, for which conventional joining technologies such as welding are unsuitable

One of the main current drivers in automotive industry is to reduce environmental impact, particularly emissions. Depending on the range of cars it has been achieved by reducing the amount of materials used and/or by changing the materials themselves. As you can see on Figure 1 the main advantages of reducing the weight of cars include [2]:

- improve fuel efficiency and engine performance by 1.5% and 4.5% respectively,
- reduce collision energy by 4.5%, thus reducing the likelihood of body deformation and passenger injury,
- greater agility results in improved acceleration, better cornering, and reduced braking distance.

According to author [3,4] BIW comprises of three major parts – passenger compartment, cross and side beams, and front and rear structure and contributes around 27–29% of the total vehicle's curb weight. Hence, it is the primary target for vehicle weight reduction by OEMs as you can see on the Figure 2.

With more than 10 times the strength of steel and only about one-quarter of its weight, carbon fiber composites make it possible to reduce vehicle weight dramatically (Fig. 3). Composite materials have their specific properties which is very beneficial in reducing the total weight. The

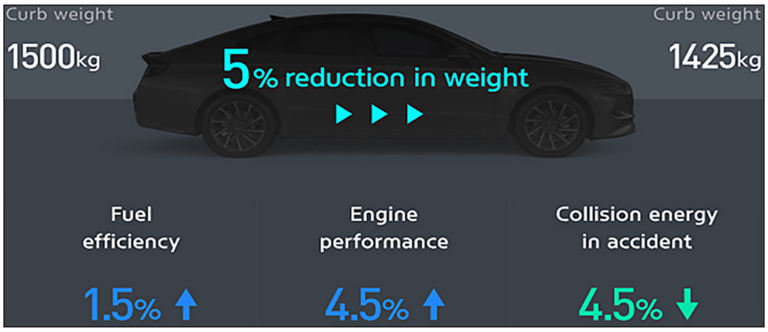

Fig. 1. Reducing vehicle weight

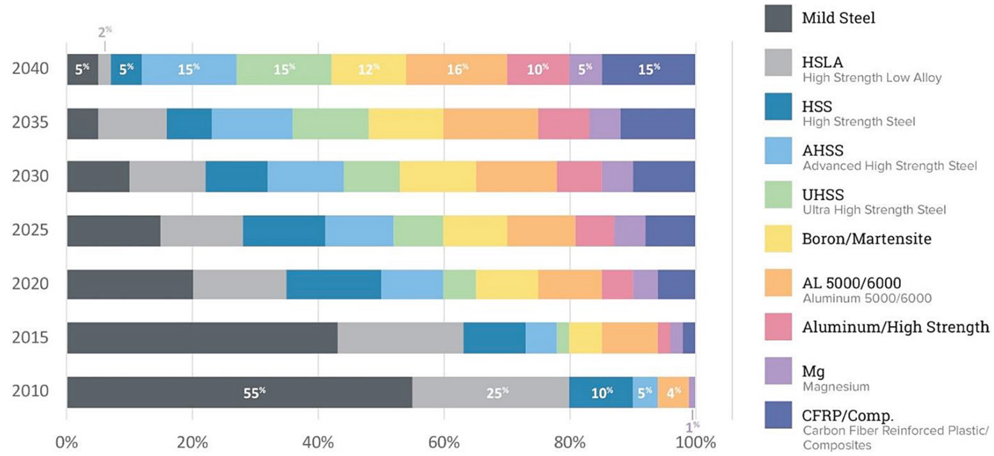

Fig. 2. Materials in BIW [4]

most significant advantage of composite materials with organic matrices is the synergistic combination of the lightweight and conformable formability of the unreinforced resin with the stiffness and strength of the reinforcing fibres [5, 28, 31]. Among the most well-known and most frequently used composite combinations are composites that combine metals, polymers and ceramics. Composites based on organic resins reinforced with different types of fibers are the most widely used composites in industry and automotive production worldwide.

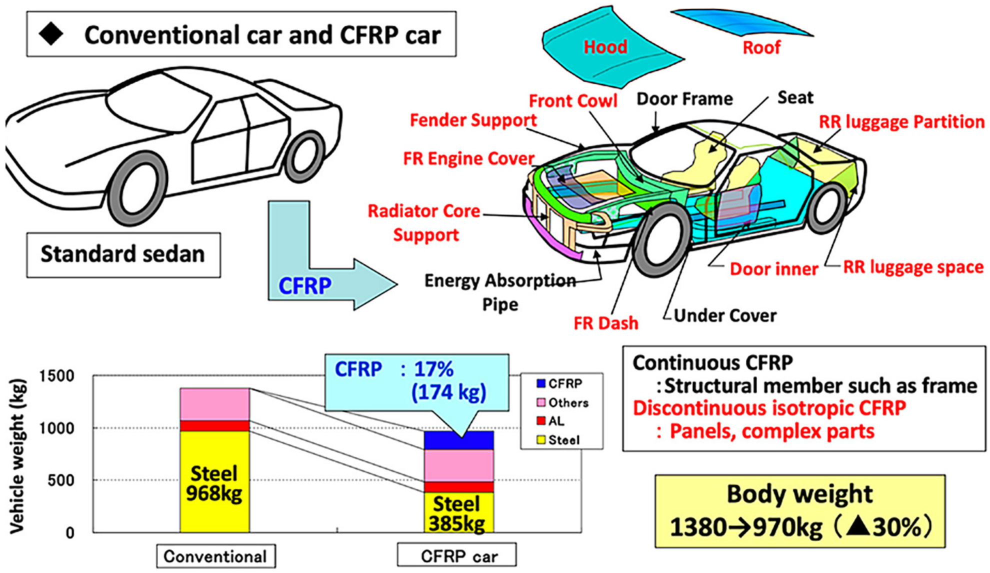

Fig. 3. Reducing weight by composites [5]

Together with the advent of new progressive materials, one of the challenges in the field of automobile construction is their joining. The goal of the research in the contribution is to test the technology of bonding composite materials and various metal materials in combination with different surface treatment of individual samples and, based on the experiment, to choose the optimal combination.

MATERIALS AND METHODOLOGY

Bonded joint technologies

Compared to other conventional technologies for joining materials (for example, welding), bonding does not affect the material being joined. In the publications of several authors [1, 6, 7, 8], when creating a bonded joint, one of the key parameters for creating a solid and prescribed joint is to choose a suitable adhesive according to the properties and type of glued material, because each surface has specific properties, surface structure, different water absorption and gases.

As can be seen in Figure 4, together with riveting technologies, gluing belongs to the most promising methods of joining composites and other types of materials in the constructions of vehicle bodies. In various publications [9, 10, 12], it is stated that the correct selection of a suitable type of adhesive is extremely important for a stressed joint, where the most important parameters of adhesives are shock absorption and sound-insulating properties.

Adhesive bonding is widely used in the automotive industry today. Up to around 100 m of adhesives are used in several car models. Some examples are listed below [11]:

- Jaguar XJ: length of the adhesive bonds is a total of 116 m;
- Jaguar XK: a total of 99 m;
- BMW 5 and 6 series: a total of 15.8 m;
- Audi TT: a total of 97.2 m;
- Mercedes-Benz SL (R231): a total of 76.2 m;
- Mercedes-Benz SLS AMG;

Bonded joints used not only in the automotive industry are technologically implemented in such a way as to meet the required demands on the load characteristics of the joint. According to many authors [13, 14, 15, 16], the implementation and analysis of the results of bonded joint experiments is essential to obtain the development of potential joint damage. According to [1,10], the total load of the bonded joint is a function of its geometry.

Procedure of manufacturing and types of fractures of a bonded joint

When applying and making a suitable glued joint, it is necessary to follow the basic procedures and steps prescribed according to the technical data sheet of the adhesive according to the manufacturer's instructions. According to Bane et al. [9], the basic procedure for production of a glued joint has the following main stages:

- material preparation (processing, cleaning and degreasing of the surface, preparation of adhesion conditions, removal and protection against moisture);
- preparation of glue;

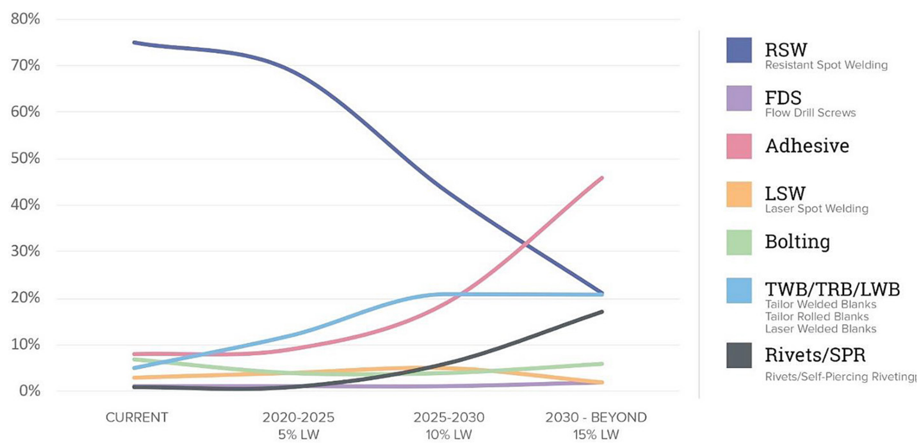

Fig. 4. Evolution of joining technologies in automotive [3, 4]

- application and implementation of the glued joint – application of the glue in the required thickness.

The thickness of the adhesive layer applied is an important factor that affects the final strength of the bonded joint (Fig. 5). From theoretical knowledge it is possible to determine the optimum thickness of the adhesive layer. This varies between 0.05 mm and 0.25 mm. If too thick a layer of adhesive is applied to the surface, the joint has little strength. Conversely, if a thin layer of adhesive is applied to the surface, then the joint is susceptible to dynamic stresses and is subject to rapid fatigue. [13,17,30]

Author Kelly [18] carried out experimental and numerical studies of the load transfer in hybrid bolt-adhesive composite single-lap joints. He studied how different kinds of adhesives affect the way adhesives and bolts interact. Very stiff adhesives result in joints where the bolts contribute very little to the load transfer. However, adhesives with lower strength and modulus and increased ductility resulted in more flexible joints allowing the bolts to transfer a larger share of the loading [18,19].

Author Hart-Smith in publication [8] mentions that there are two kinds of bonding methods in composite bonded joints, mechanical joint and adhesive bonded joint. In mechanical bonding, the introduction of holes in composites for assembling leads to stress concentrations in the vicinity of the holes. On the other hand, bolts and rivets damage the material around the drilled hole and can greatly affect the overall load-carrying capacity of the structure. According to various authors [8, 20, 21, 22] compared with mechanical joint, the adhesive bonded joint is widely used due to the advantages such as reduction of weight, no stress concentration, and no requirement of drilling.

One of the basic factors that decide when choosing a suitable adhesive for a glued joint is the type of fracture (Fig. 6), which is evaluated during destructive tests together with its resulting strength. [9, 17] And in publications of authors [7, 23, 24, 25] the main failure modes in composite bonded joint include adhesive failure, cohesive failure, matrix failure and mixed failure.

Shear strength test

The significance of the shear strength test is that the tested sample is loaded at a constant speed with a force until the sample is plastically deformed or breaks. The aim of the test is to identify the shear stress of the bond between the adhesives. The required force to break the joint F_{max} is the result of the shear strength test. The test is carried out according to STN 1465. For the experiment, samples were produced according to

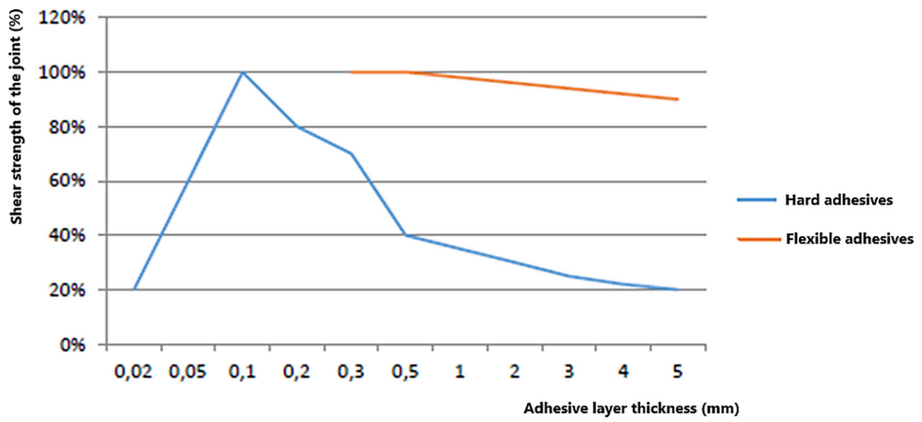

Fig. 5. Dependence of bonded joint strength on adhesive thickness [33]

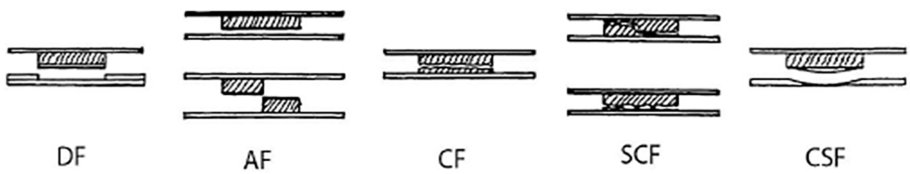

Fig. 6. Basic types of failure of bonded joints: AF – adhesive fracture, CF – cohesive fracture, CSF – failure of one of the adherends, SCF – cohesive fracture at the substrate boundary, DF – delamination of the substrate [14]

the STN 1465 standard, the basic parameters of which are shown in Figure 7. The resulting shear strength is given in MPa [6].

Experimental part

The aim of the experiment is to test several selected samples, where each sample is composed of two components connected by glue. One component is metallic materials, which are most used in automotive manufacturing, and the other is a composite reinforced with carbon fibers. The produced samples were tested with a shear strength test. Table 1 shows the description of individual samples selected for experimental tests – metal materials (galvanized steel, stainless steel, sheet steel and aluminum) and composite material reinforced with carbon fibers. From the point of view of the surface treatment of the samples to which glue was subsequently applied, the surfaces were treated with sandpaper or notches for the experiment.

Manufacturing of composite part of samples

Parts of the composite samples measuring 100×25 mm for the experiment were produced at the workplace of the Department of Automotive Production of the Faculty of Mechanical Engineering of the Technical University in Košice, which deals with the production of composite materials and their testing for the automotive industry. Figure 8 shows parts of the process of manufacturing and preparing samples from composites (application of individual layers of carbon fibers, top foil, air extraction and milling of samples). A total of 12 composite samples were produced, each sample has 6 levels of fibers, while the thickness of the sample is 1.6 mm according to STN EN 1465. The material for the matrix was epoxy resin marked 285 (MGS) and hardener 287 (MGS). The ratio of the mix of resin and hardener was 100:20. The technology of making the samples was manual lamination and subsequent suction of air from the mold. After the samples had hardened (24 hours), the necessary parts of the samples with dimensions of 100×25 mm were subsequently milled from the composite board.

The glue used for gluing individual parts of the samples was epoxy resin, which was also used for reinforcing the composite samples. The required glue thickness of 1 mm was ensured by means of delimiting metal components. The final individual samples composed of metal and composite parts and their designation are shown in Table 2.

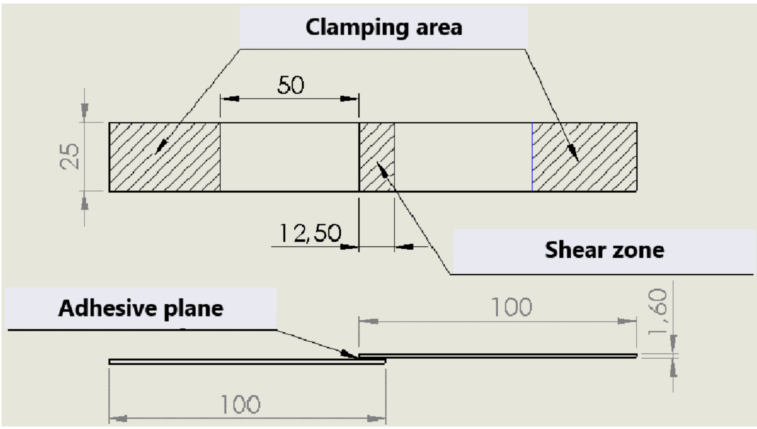

Fig. 7. Dimensions of the individual test sample [26]

Table 1. Material of test samples

Material of sample	Description
Composites – CFRP	Composite samples are made of carbon fibers reinforced with an epoxy matrix – CFRP. The thickness of the material is 1.6 mm
Galvanised sheet	For the production of the samples was used galvanized sheet metal, which is most often used for the production of vehicle body parts, as it has excellent corrosion resistance. The thickness of the material is 1.6 mm
Stainless steel	Cold rolled stainless steel sheet according to STN EN ISO 9446–2, made of steel grade 1,4301+2R according to STN EN 10088–2. The thickness of the material is 1.6 mm
Aluminium	Aluminium sheet EN AW 1050A. Dimensions 100x25mm as prescribed by STN EN 1465
Structural steel	Structural steel is commonly used for structural frames and safety elements of the car body part

Fig. 8. Procedure for preparing composite parts for tested samples

Course and evaluation of the experiment

The shear strength test of glued joints was carried out on the TIRA 2300 axial static tensile testing machine. The entire course of the test was carried out according to the regulations of STN EN 1465 [27]. Individual glued samples were vertically clamped in hydraulic jaws with back pressure in the testing machine (Fig. 9). The samples were clamped between the jaws with special grooved inserts to prevent the sample from slipping during the test. The clamping area of individual samples in the testing machine is shown in Figure 7.

Table 2. Marking of sample composition

Sample designation	Sample composition
P1 – untreated	Composite – galvanized sheet metal
P2 – brushed	
P3 – grooved	
N1 – untreated	Composite – stainless steel
N2 – brushed	
N3 – grooved	
O1 – untreated	Composite – structural steel
O2 – brushed	
O3 – grooved	
H1 – untreated	Composite – aluminum
H2 – brushed	
H3 – grooved	

Temperature conditions during the implementation of the experiment in the laboratory were: at the beginning of the measurement: 20.5°C, at the end of the measurement 20.8°C and relative air humidity 54%. The maximum load force was set at 100kN and the speed of movement of the jaws of the TIRA 2300 machine was 10mm.min-1.

The corresponding maximum force FMAX transmitted through the adhesive surface was measured on each sample during the tensile shear test. According to the formula and the measured forces for individual samples, the maximum contracted shear stress τi of the glued joint was subsequently calculated.

Sample calculation of the strength of the bonded joint of specimen *N*1:

- Panel width: $b_0 = 25$ mm
- Overlay length: $l_0 = 12.5$ mm
- Test result: $F_{N1\,MAX} = 1600$ N
- Calculation:

$$\tau_{N1} = \frac{F_{N1\,MAX}}{S_0} = 5.12 \text{ MPa} \qquad (1)$$

RESULTS AND DISCUSSION

Achieved results and evaluation

After the experiment, the results were evaluated according to the required parameters. The

Table 3. Measurement results from experimental test

Samples	b_o [mm]	l_o [mm]	S_o [mm^2]	$F_{i\,MAX}$ [N]	τ_i [MPa]
H1	25.00	12.50	312.5	1600.001	5.120002
H2	25.00	12.50	312.5	2985.243	9.552776
H3	25.00	12.50	312.5	2691.830	8.613857
Q1	25.00	12.50	312.5	3354.887	10.73564
Q2	25.00	12.50	312.5	4152.937	13.28941
Q3	25.00	12.50	312.5	4445.952	14.22705
N1	25.00	12.50	312.5	3511.320	11.23600
N2	25.00	12.50	312.5	5022.454	16.07185
N3	25.00	12.50	312.5	3711.428	11.87657
P1	25.00	12.50	312.5	3593.113	11.32516
P2	25.00	12.50	312.5	4896.592	15.66909
P3	25.00	12.50	312.5	5842.738	18.69676

resulting measured values of the experimental test are shown in Table 3. The values of shear stress τ_i were calculated from the measured values of the F_{iMAX} maximum force.

The measured values were entered into the graph in Figure 10, on which it is possible to compare the individual values of the forces that the bonded joint has withstood. The graph in Figure 10

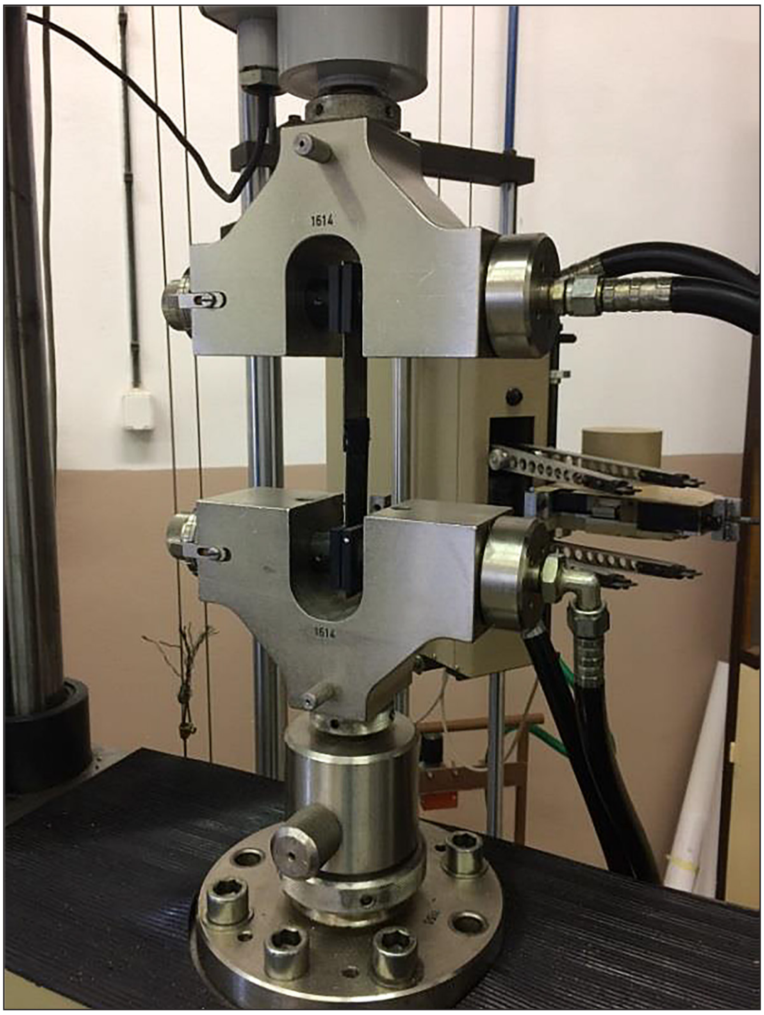

Fig. 9. Clamping the sample into the test machine TIRA test 2300

is presented maximum force as a function of displacement (elongation). The aim of the experiment was to evaluate the maximum force and shear strength parameter. As the weakest samples from the overall results according to the measurements, the bonded samples of the composite with aluminium were evaluated, where it can be seen that total strength of $F_{i\,MAX}$ was the lowest.

In Figure 11, according to the test results, a bar graph has been prepared, where it is possible to see the maximum force required for the deformation of the bonded joint. The highest strength is achieved with samples with a machined surface. For grooved surfaces, samples with structural steel and galvanized sheet showed the best results. For ground surfaces, the best results were obtained with stainless steel and aluminium samples.

The type of fracture is one of the criteria that indicate the quality of the bonded joint. The two most common fracture types were evaluated on the tested samples. It is clear from the results that one type of fracture occurred in all types of samples – adhesive failure (Table 4).

In the following Figures 12 to 15, we can see individual types of fractures that occurred on the surfaces of composite samples or metal samples. The labeling of individual samples in Figures 12–15 and the fracture type are described in more detail in Table 4. It can be seen that the adhesive, in this case the epoxy resin, held better on the composite parts of the test samples. In the case that the metal samples were machined, we can observe a different type of fracture and also a greater shear stress.

Table 4. Final values of the shear strength of the adhesive and the type of fracture

Samples	τ_i [MPa]	Type of material failure
H1	5.120002271	AF (adhesive failure)
H2	9.552776379	AF (adhesive failure)
H3	8.613856779	AF (adhesive failure)
O1	10.7356372	AF (adhesive failure)
O2	13.28939687	SCF (cohesive failure at the substrate boundary)
O3	14.22704594	90% AF, 10% SCF
N1	11.23622492	AF (adhesive failure)
N2	16.07185144	60% AF, 40% SCF
N3	11.87657063	80% AF, 20% SCF
P1	11.325161182	AF (adhesive failure)
P2	15.66909432	40% AF, 60% SCF
P3	18.69676063	90% AF, 10% SCF

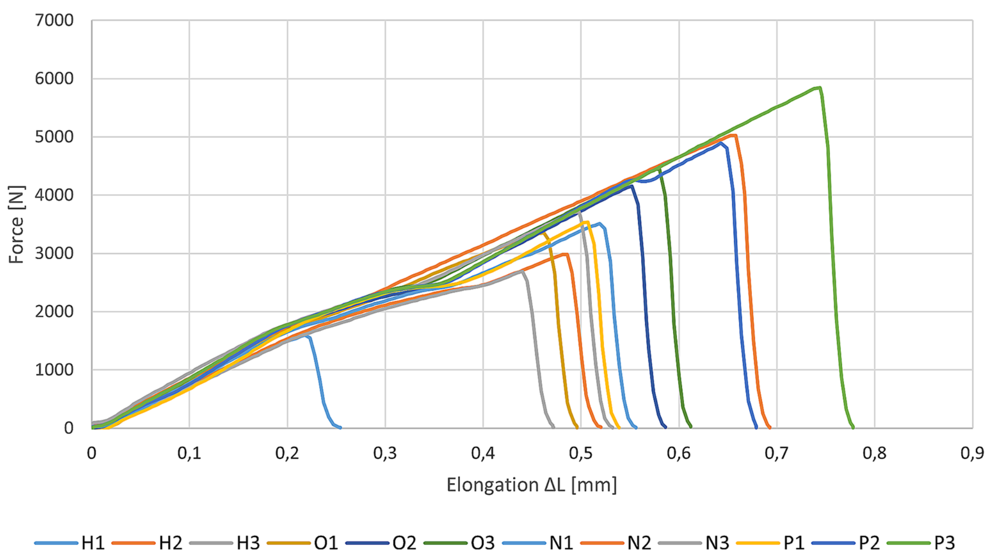

Fig. 10. Deformation curves of samples

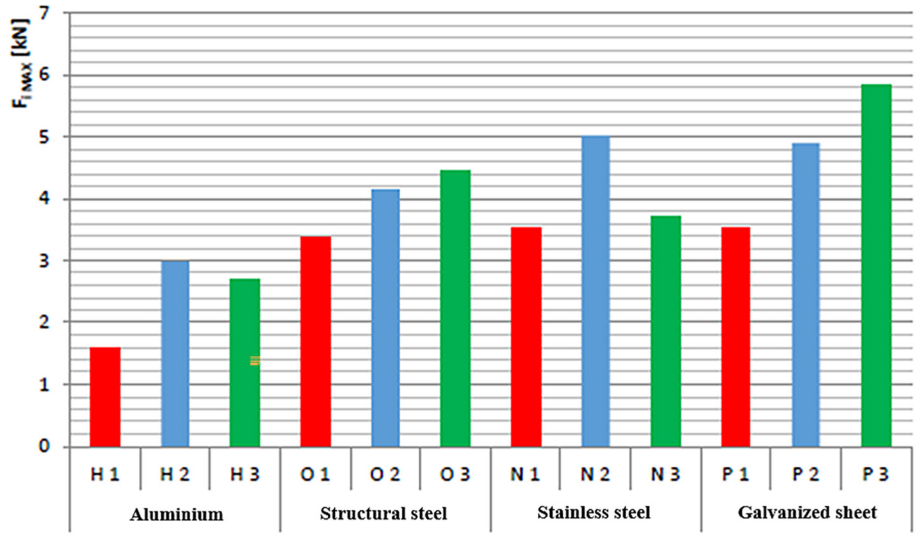

Fig. 11. Results of experiment

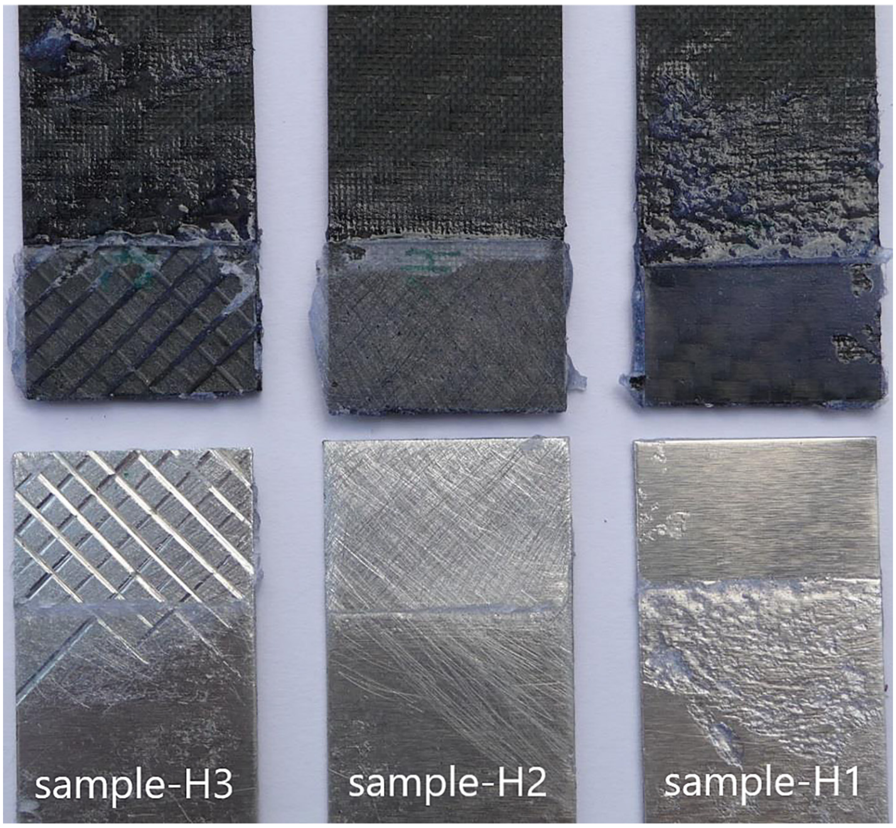

Fig. 12. Aluminium samples

CONCLUSIONS

Currently, the use of bonded joint technology in the automotive industry is widespread. The trend is to apply and use more of these non-invasive joining technologies in the construction of cars, but it is necessary to carefully consider where this type of connection can be used in the construction of a car.

The experimental part of the contribution was focused on testing the combined bonded joint of samples from composite and metal materials through a shear strength test according to the STN EN 1465 standard. Before the test, combinations of selected metal materials with different surface treatments were selected. These materials were subsequently bonded with epoxy resin to the composite samples. After the test was evaluated

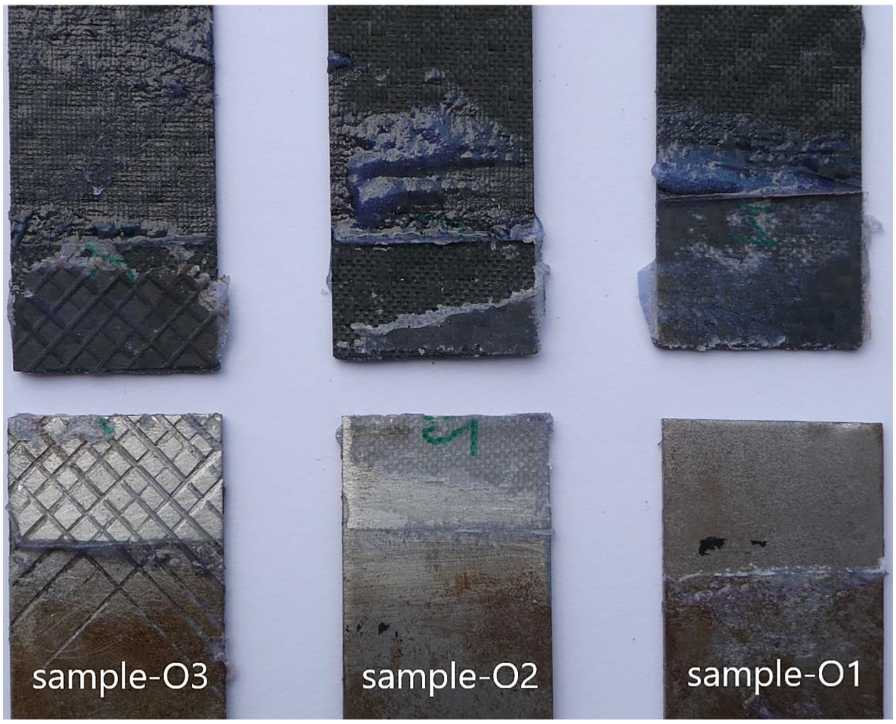

Fig. 13. Strucrutal steel samples

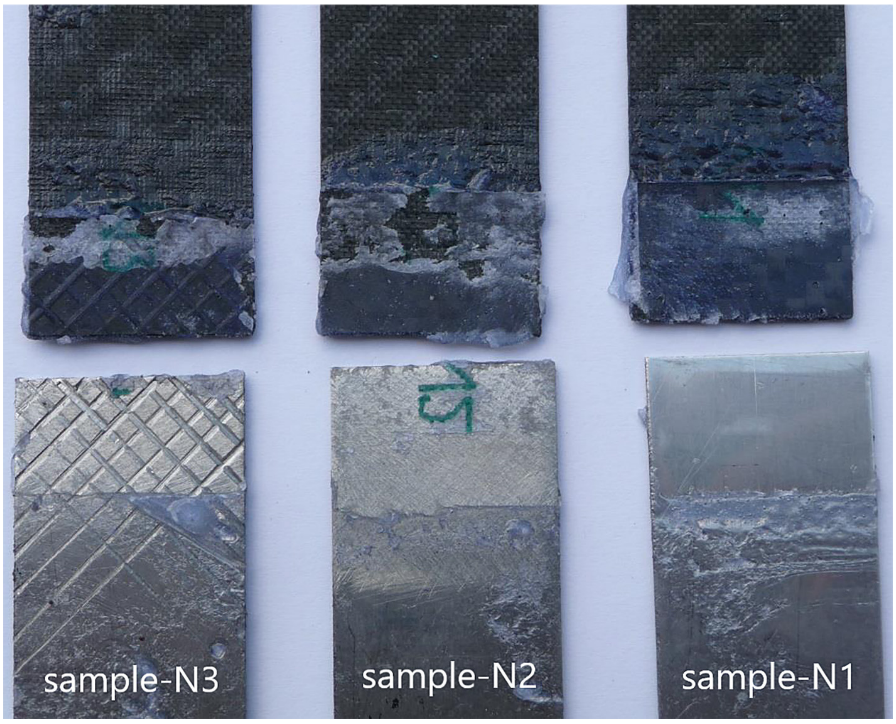

Fig. 14. Stainlees steel sample

the best combination of a composite sample with a metal sample of a certain surface finish.

The article describes a shear strength test that was performed on a TIRA test 2300 testing machine. There were 12 test samples (4 sample groups, where each sample group contained 3 variants of the bonded joint). The samples were independently tested with the same type of adhesive bond – epoxy resin. The aim of the experiment was to produce parts of composite samples from carbon fibres using hand lamination technology with vacuum bagging suction and subsequently to identify the best combination of bonded joint between

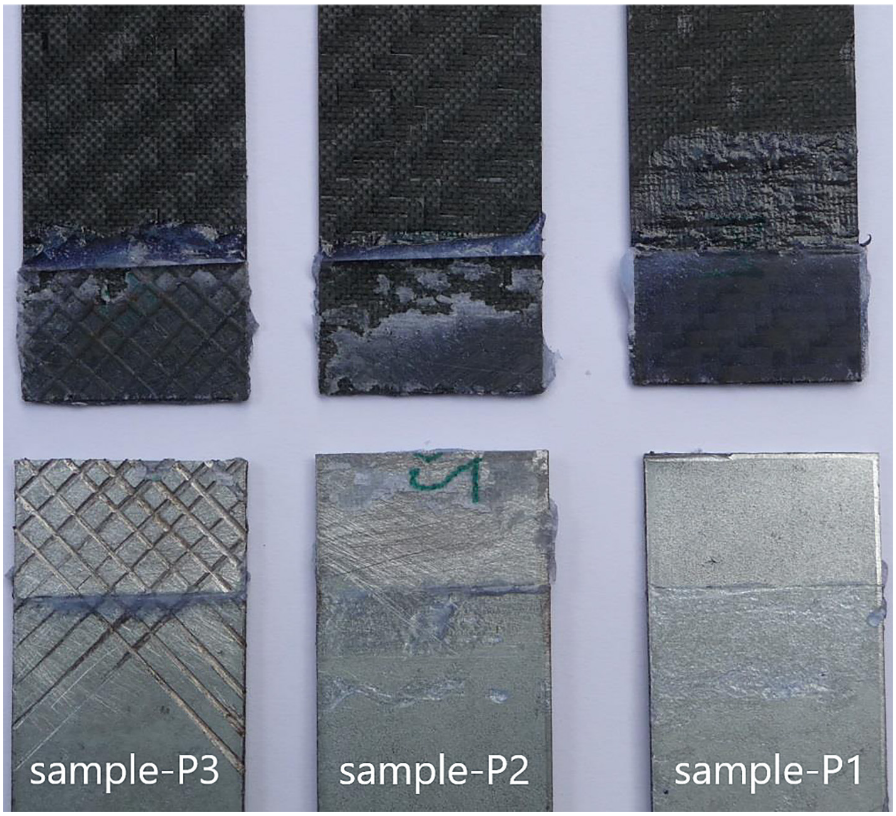

Fig. 15. Galvanized sheet sample

composite and metal materials. Analysis of the shear strength test identified that the best combination of bonded joint is composite material and galvanized sheet. This combination shows the highest values of the indices of maximum shear stress – 18.69676 MPa and maximum force – 5842 N for grooved processed samples. The worst results in terms of the mentioned parameters of the maximum shear stress values – 5.120002 MPa and the maximum force of 1600 N were identified for the combination of the bonded joint in shear of the composite sample with the aluminium sample.

One of the evaluated criteria of the experiment was also the type of fracture after breaking the glued joint. From the point of view of the type of fracture, cohesive fracture and adhesive fracture at the substrate boundary occurred most often on broken samples, while adhesive fracture occurred in all samples. It can be concluded that the epoxy resin as an adhesive held better on the composite parts of the tested samples, which results from its primary use. In the case of metal parts of the samples that have been surface treated, it is possible to observe another, or a combination of fractures and also greater shear stress. It follows that samples whose metal surfaces were treated with sandpaper (samples O2, N2, P2) or by grooving (samples O3 and P3) showed higher strength and shear stress.

From the point of view of objectivity, it is possible to state that more reliable and relevant conclusions can be reached by testing several variants of bonded joints, and it is also recommended to test the use of other types of resin-based adhesives.

Some of the samples in pictures 12 to 15 have a different overlap length, which was created when gluing individual parts of the sample. These sample defects arose during the gluing process, where due to the consistency of the used mixed glue-resin, there was a slight shift and thus also a deviation of the originally planned overlap of 12.5 mm. Overall, however, this did not significantly affect the results in terms of comprehensive evaluation.

In order to obtain more relevant and meaningful results, it is advisable to continue the experiments, testing the joints for brittleness and impact strength tests, which could then be compared with the values from the shear strength test.

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