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Mechanical and Technological Aspects of Joining Fibrous Composite Hybrids with Metallic Semi-Finished Products

Abstract: The sustainability of transport in the future requires the use of lightweight structures, with composites and steel playing a key role. One of the well-known methods used industrially to join the above-named materials is adhesive bonding. However, the method often fails to satisfy service life and fabrication cost-related requirements assumed at the stage of design, certification and manufacturing. The article discusses mechanical and technological issues concerned with the welding of fibrous composite materials with metallic elements.

Keywords: fibrous composite hybrids, joining of composite and steel

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Introduction

The growing demand for the design and fabrication of lightweight structures entails the challenging development of technologies enabling the joining of dissimilar materials such as metals and fibre-reinforced polymers, also known as composite materials. Both groups of materials are characterised by specific properties which, when combined, make it possible to optimise the weight and the strength of structures used in the transport industry, windfarm power engineering, etc. However, the joining of the two groups of materials requires taking into consideration complex processes at the stage of design, certification and fabrication, necessitated by the adhesive-bonding or bolting together dissimilar elements. Although both technologies are considered to be the most technologically advanced methods of joining metallic and composite materials, they are also characterised by certain disadvantages. Bolting elements together entails damaging the composite structure through drilling, which, in turn, entails the formation of compressive stresses, potentially damaging areas around the opening. On the other hand, adhesive bonding requires the proper penetration of surfaces to be joined, which makes it difficult to perform the non-destructive tests of joints and, consequently, complicates the design of elements in respect of joint strength and long-lasting operation [1,2]. The article presents and innovative method making it possible to join metallic materials and composites illustrated with an example of a metal profile and a hybrid fabric. The joining of the composite structure with metallic fibres enables the making of metal profiles permanently "embedded" in composites, and used subsequently to join the structure with other metallic elements. The metal profile deposition is maintained by the layer of the composite material (joined with the profile).

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The use of joining elements, in particular locally, is a commonly known technology. In such cases, the joining element makes it possible to apply welding technologies in order to join large-sized metallic and composite materials. The use of hybrid fabrics and their integration with composites at the production stage enables the obtainment of a "harmonious" joint (in terms of rigidity) between the base material and the composite. The aforesaid joining elements are used, among other things, in the production of battery housings.

However, presently, the extent of knowledge concerning the joining of hybrid and composite materials with fixed profiles as well as information related to the behaviour of such structures leave much to be desired. Methods applicable in the making of the aforesaid joints are not precisely specified in currently effective DIN, ISO and other standards [3]. The article presents methods used to join hybrid fabrics with fixed metal profiles, discusses results of mechanical tests performed in various configurations as well as presents the current state of the art and the assessment of the future potential and the applicability of such methods in industry.

Methodology – materials and technology

Most well-known methods of joining hybrid fabrics involve the modification of the surface of a metal profile or required the addition of elements such as pins, etc. In turn, in the so-called FAUSST method, hybrid fabrics are joined with metal profiles using the resistance welding process. Figure 1 presents an element composed of two parts, i.e. a metal profile and a hybrid fabric.

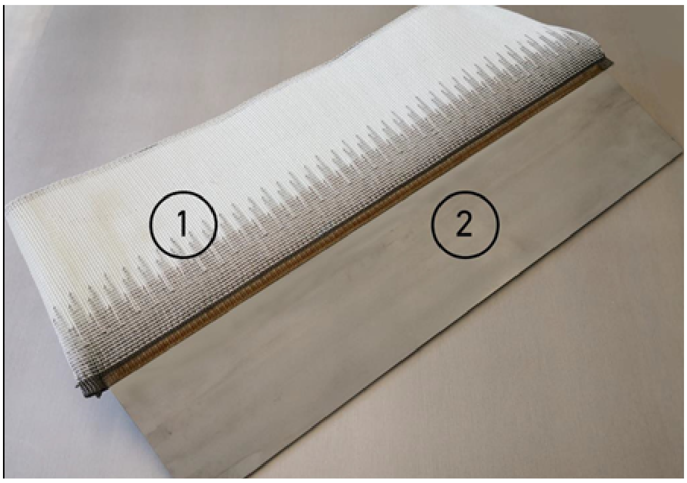


Fig. 1. Element made of the hybrid fabric and the metal profile: 1) one or more layers of the composite material and 2) metal profile

The hybrid fabric (Fig. 2) is made of stainless steel fibres based on the glass fibre matrix. The interweaving of two types of fibres leads to the formation of a non-homogenous material containing three areas characterised by various contents of materials, where one area only contains metallic fibres (metallic warp yarn), another area is only composed of glass fibres (glass warp yarn), whereas the area in the middle is the mixture of both. All the above-named areas constitute one material which can be adjusted to any required size.

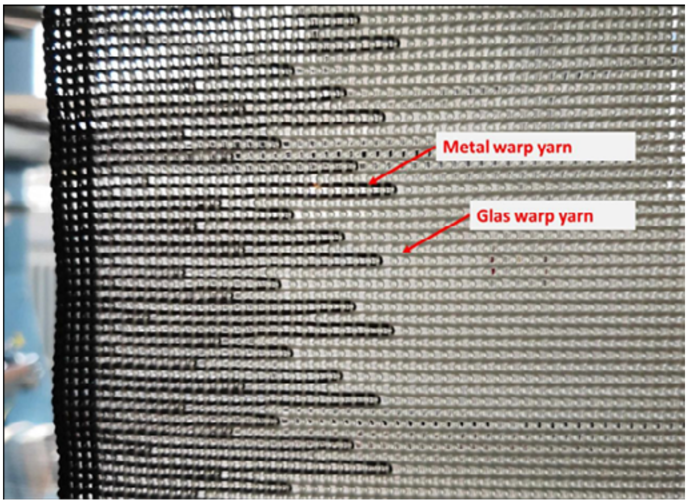


Fig. 2. Hybrid fabric composed of metal warp yarn (i.e. metal fibres) and glass war yarn (i.e. glass fibres)

In the example under discussion, the metal profile made of steel 1.4301 was flat (Fig. 3). One side of the profile was milled to obtain the stepped shape, in order to ensure the smooth transition from the metal to the composite (in terms of rigidity). In addition, the steps facilitated the joining of the FAUSST material with the profile. The elements could be joined using various methods, yet, for the purpose of the article, the fixed system was taken into consideration.

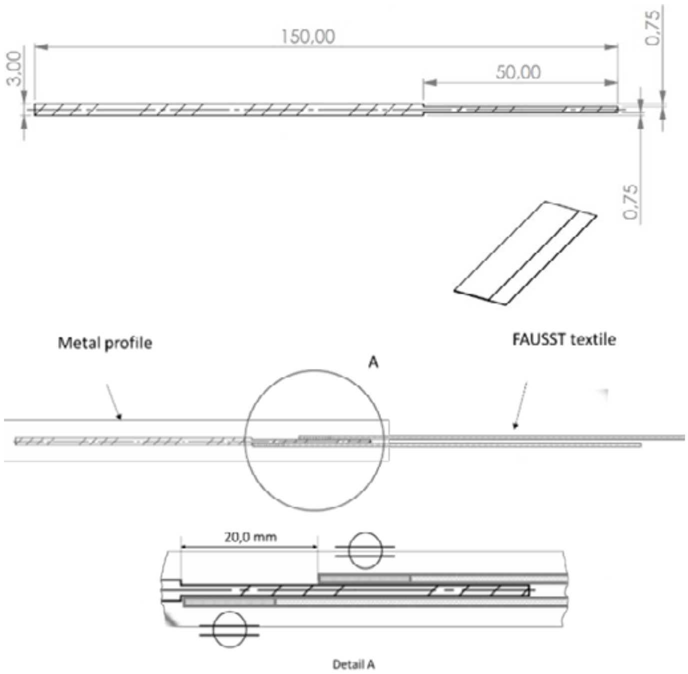


Fig. 3. Configuration of the element joining the FAUSST textile with the hybrid fabric on the metal profile and the milled metal profile for the element joining the FAUSST textile

Joining the FAUSST hybrid fabric with the metal profile

To obtain the homogenous flow of force between the steel and the composite material, the joint area on the metal element was prepared by machine. The milled step was designed in relation to the material thickness and the structure of the successive layer. In addition, the upward milling process enabled the preparation of the surface for subsequent painting [4].

Composites made of glass fibres are sensitive to high temperature. In thermal joining processes, such as welding, the joint containing metal warp yarn is heated to the melting point of the steel. The heat generated (and flowing) during the process affects glass fibres (glass warp yarn, coated with monosilane). The effect of high temperature (above 180°C) may damage (burn) the aforesaid coating. The quality of the joint between the fibre and the matrix is crucial for the subsequent wetting of the material during the welding process. Damage to the coating leads to the insufficient wetting of the fibre by the matrix and the delamination process (occurring between the fibre and the matrix), adversely affecting mechanical properties. For this reason, during the joining of the above-named materials it is necessary to satisfy strict requirements [5,6,7].

Resistance welding was developed in the electronic industry to join conductors and twisted pairs. The process, classified as the welding method involving the use of pressure affecting the material, involves local resistance heating, where the roller electrode transmits pressure FE and welding current IS to an element subjected to joining. As a result, it is possible to obtain the strong adhesion of the FAUSST textile to the metal surface. The inflow of heat obtained in the above-presented manner reaches a temperature below the melting point of the material made of chromium-nickel steel. As a result, the composite material remains unaffected and

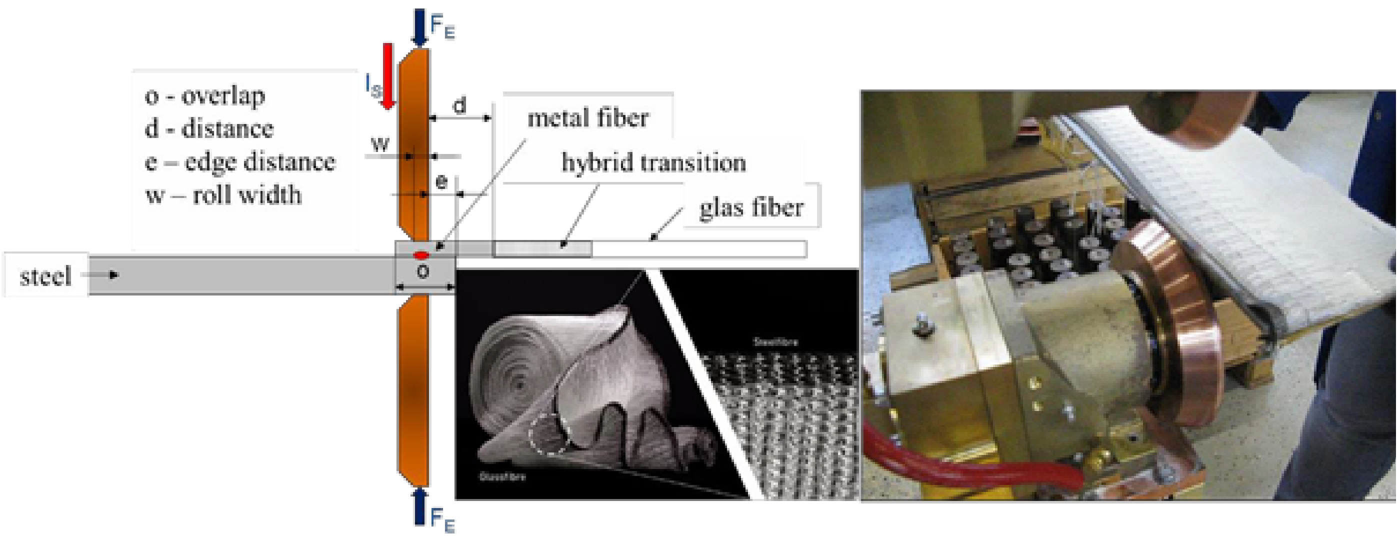


Fig. 4. Joining the metallic and the hybrid elements

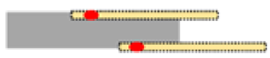
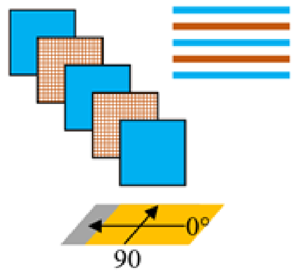
Sketch of joining element	Layers	Orientation
	1. U-E-640g/m² 2. FAUSST-fabric 3. U-E-640g/m² 4. U-E-640g/m² 5. U-E-640g/m² 6. U-E-640g/m² 7. FAUSST-fabric 8. U-E-640g/m²	

Fig. 5. System of the elements of the composite material and of the joining element; all the fibres were placed at an angle of 0°. After solidification, the joining element was fixed to the composite structure. The tests involved the making of several plates having dimensions 500 mm × 500 mm

enables the obtainment of complete mechanical properties of the joint. Figure 4 presents the preparation of components for the production of hybrid elements.

The CuCrZr roller electrodes make it possible to use appropriate current and exert appropriate (pressure) force affecting the joint. The heating of the element, resulting from the exerted pressure and the flow of current, enables the joining of steel fibres with the base material. The welding parameters must be adjusted so that the phenomenon of spatter formation can be avoided. The tests discussed in the article involved the use a DALEX PMS 11-6 welding machine, a DC medium-frequency inverter and a control system (Harms & Wende).

Deposition of the joining element in the composite material

Composite materials are commonly known and used in numerous industrial sectors including, among other things, the maritime industry, transport, the production of renewable energy and other industries. The primary characteristics of such materials and their differentiation results from fibres and polymer systems used in the production process. Basic composites, i.e. glass fibres based on the epoxy matrix, are also known as glass fibre-reinforced polymers (GFRP).

The above-named composite type was used to deposit the joining element in the composite material. The vacuum infusion technology was used to cover several layers with the hybrid fabric of the joining element and, next, to combine with the polymer matrix (EPIKOTE Resin MGS RIMR and EPIKURE curing agent MGS RIMH). The obtained system is presented in Figure 5.

Preparation of specimens and equipment used in tests

The mechanical tests involved the use of two types of specimens (in accordance with the specification of tests concerning composite materials). Specimen no. 1 had dimensions of 500 mm × 270 mm, whereas specimen no. 2 had dimensions of 25 mm × 270 mm. Both (rectangular) specimens were made using water-jet cutting. The specimens and a tensile testing station are presented in Figure 6.

The specimens were subjected to static tests in SLV Halle and SKZ Halle laboratories as well as in the laboratory of Faserinstitut in Bremen. The tests were performed in accordance with the requirements specified in the DIN EN ISO527-4 standard. The processing rate amounted to 2mm/min. The stresses

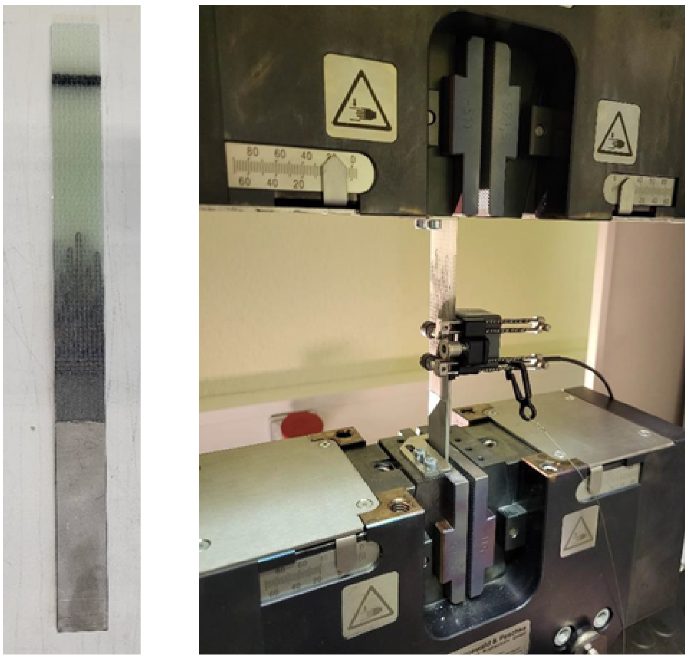


Fig. 6. Specimens having a length of 25 mm (a) and the tensile testing station (b)

were calculated in relation to the nominal cross-section of the metal profile. Dynamic tests were performed in accordance with the requirements of the above-named standards; the frequency amounted to maximum 10 Hz, whereas coefficient R amounted to 0.1. The stresses were calculated in relation to the nominal cross-section of the metal profile.

Test results

Metallographic tests

The resistance welding of the hybrid fabric (in the area of metal fibres) with the fixed metal element made it possible to concentrate and properly coat the metal element with fibres. Because no liquefaction on the surface of materials being joined was observed, their microstructure remained the same in comparison with the base material. In addition, to identify its mechanical properties, the joint was subjected to microscopic observations. To properly assess the quality of the joint it was necessary to make both longitudinal and cross-sections of the specimen containing the joint with the hybrid fabric. Figure 7 presents the results of microscopic metallographic tests (helpful when identifying the distribution of heat in the element).

At the interface it was possible to observe that the materials in the joint area did not melt. Because of various thicknesses of the materials and, consequently, different resistance coefficients, heating took place on the surface of the base material. Single fibres of the hybrid fabric were formed both by force and heating. Diffusion took place at the interface of the materials subjected to welding, which, in turn, resulted in the formation of a strong joint on the surface of the joined elements. The above-presented mechanism, leading to the concentration of fibres through resistance welding, is well-known and thoroughly discussed in related publications.

Mechanical tests

Results of mechanical tests revealed that the tensile strength of the joint was similar to the yield point of the base material. The scatter of results was low in relation to all the specimens subjected to tensile tests; maximum force being F_{max} = 30.0 kN. The primary section of the base material force revealed the effect of a force of 201 MPa (not exceeding a yield point Rp0.2 of 1.4301). The test results are presented in Table 1.

The assessment of the specimen fracture standard specimen revealed that the rupture took place outside the joint area. The joint area itself was characterised by changes in the length and the area reduction of the base material. The test results were repeatable. The average strength amounted to 23.5 kN, with deviations amounting to 4.1 kN and 6.4 kN. Figure 8 presents the curve of displacement force in relation to an elongation of 6.4 mm.

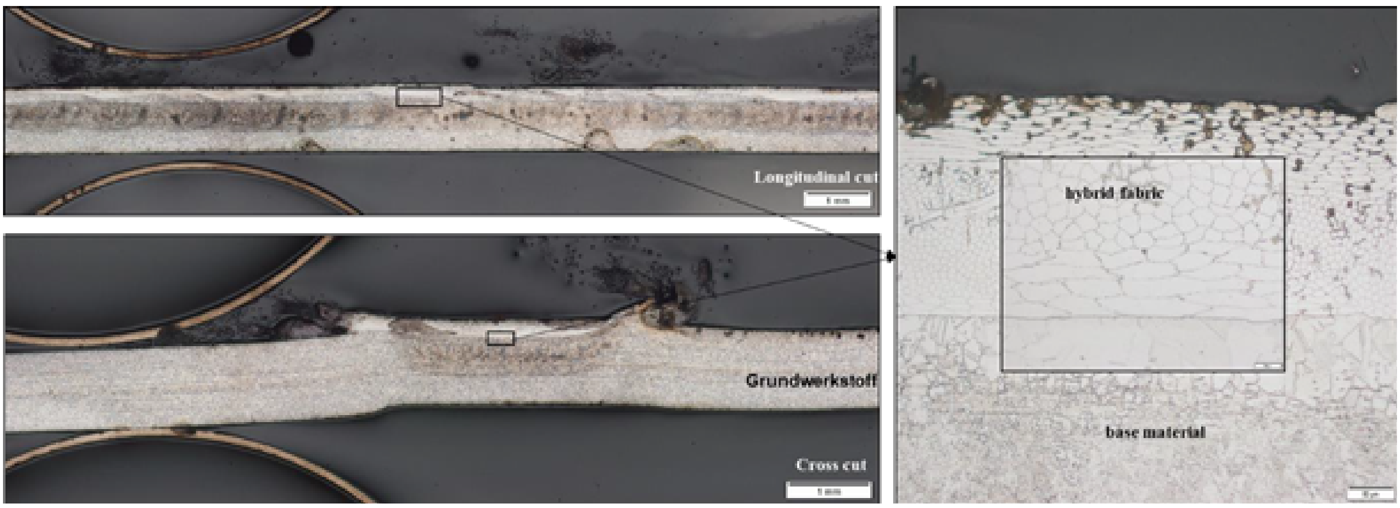


Fig. 7. Longitudinal section and the cross-section of the welded joint of the base material (metal) and the hybrid fabric

Acknowledgements

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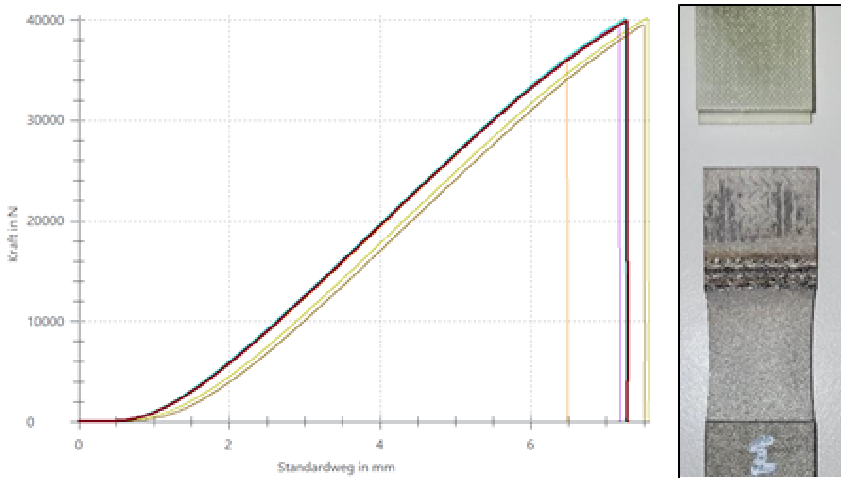

Fig. 8. Curve of displacement force in the tensile tests and the specimen after the rupture

Table 1. Tensile test results

No.	Width [mm]	Thickness [mm]	Area [mm^2]	Force [kN]	Tensile stress [MPa]
1	49.5	3	148.5	27.3	184
2	49.5	3	148.5	24.4	164
3	49.5	3	148.5	20.0	135
4	49.5	3	148.5	19.4	131
5	49.5	3	148.5	20.9	141
6	49.5	3	148.5	20.6	139
7	49.5	3	148.5	21.3	143
8	49.5	3	148.5	27.9	188
9	49.5	3	148.5	29.9	201

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