Manufacturing technologies of composite parts and subassemblies of automotive vehicles

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Abstract. The article presents a critical analysis of available technologies for the production of automotive components from polymer composites. The advantages and disadvantages of currently used manufacturing technologies are presented. A new technology for the production of vehicle components is proposed by pressing a newly developed powdered epoxy resin. This generates new technological possibilities in the production of vehicle parts and subassemblies.

1. Introduction

The development of vehicle construction is particularly visible in the area of vehicles with alternative drives. We observe the resignation of many companies from the production and use of self-ignition engines for passenger car drives. Other companies present new models of vehicles with hybrid or electric drive. This global trend is caused by the need to reduce the emission of toxic exhaust components into the atmosphere. It is particularly important in large urban centres, where the exhaust gases from vehicles are directed at passersby. New designs require lowering the weight of vehicles. For this reason, it is necessary to use lightweight composite materials for their construction [1, 2]. It is forecasted that the use of polymer composites in the automotive industry may increase up to four times by 2025. It will probably be done by replacing individual structural elements made of classic materials for composite designs. Probably in the future, entire vehicles will produce made of composites. This way of using polymer composites is currently taking place in the construction of a BMW i3 car. The increase in the use of composites for the construction of pressure vessels for compressed natural gas and hydrogen is clearly visible.

With the development and dissemination of CFRP (Carbon Fiber Reinforced Polymer) technology for the production of structural components, the price of composite materials is gradually decreasing, which makes them increasingly attractive to car manufacturers. High potential in the reduction of production costs while maintaining high strength properties of products from CFRP have technologies that enable the manufacture of structural components of vehicles in short technological operations. Interesting in this respect are technologies: High-Pressure Resin Transfer Molding (HP-RTM), Prepreg Compression Molding and Liquid Compression Molding (LCM) [3].

The article presents material requirements and applied technologies for the production of automotive composite parts, as well as the analysis of the possibilities of using new technologies for the production of structural composite elements for the construction of primary structures of vehicles.

2. Material requirements in the production of car parts

In vehicle construction, polymer fibrous composites are increasingly used, as they meet both basic and non-standard material requirements. While maintaining technological requirements, polymer composites with strength parameters higher than those of most commonly used steels can now be obtained. Such exceptional properties are provided by some carbon reinforcement. In the automotive industry, composites with standard carbon reinforcement are used, which are characterized by high durability and lower production costs. These materials have about five times greater specific strength and a specific module than steel and aluminum alloys. This is due to the much lower density of resin and high strength fibers at the same time. Their use makes it possible to reduce the weight of subassembly components and vehicle assemblies by up to 50 – 60 % compared to conventional materials. The occurring anisotropy of the composites is used to obtain more effective structures, e.g. in pulled products (pultrusion). Composites have fatigue strength higher than metal alloys. Usually, fatigue damage is visible much earlier and catastrophic damage can be prevented. Futhermore, autonomous sensors that control the state of the structure can be introduced into the composite structure.

In addition to the required high strength and stiffness of polymer composites, their thermal resistance is also sufficient. Composites based on polyester resins can be used up to a temperature of 120 °C, epoxy resins up to 150 °C, and in case of polyimide resins up to 180 °C. Thermal expansion coefficient α is also acceptable. Depending on the selected matrix of the composite with glass reinforcement, the expansion thermal expansion coefficient α is comparable or higher than steel, and in the case of carbon reinforcement - it is lower. Polymer composites dampen vibration well, whereby vibration damping can be adjusted to the desired level by appropriate selection of composite components and manufacturing technology. Polymer composites also dampen the sound well and at the same time the parts emit less noise. Depending on the design, composite elements do not require corrosion protection. It is possible to apply durable paint coatings or dye in the matrix.

Certain limitations exist in joining of the composite elements. The treatment of composites results in breaking the continuity of the reinforcement, stress concentration near the opening, local delamination of the structure, and then destruction. To avoid this, reduce the number of elements in assemblies by constructing integrated components that maintain the required functionality. Characteristic is the production of composite structures including internal metal inserts embedded in it, which are an integral part of the whole. Proper surface preparation of metal elements ensures the required adhesion. Joining elements is also possible thanks to the gluing technology, which ensures sufficient durability of the joint and at the same time eliminates some of the treatments used in standard joining methods [4-6].

Producers of composite elements have at their disposal a large group of polymeric materials, including various types of resins. For larger items, polymer resins are used which, during curing, do not emit volatile products and do not require high external pressure, e.g. pressure. These are polyester, vinyl ester and epoxy resins, and polyimide resins are used if higher thermal resistance is required. Resins are produced in different versions depending on the application of the product, processing methods, etc. Thus, are produce resins with various mechanical properties, different heat and chemical resistance, in the "flame-retardant" version and others. Some technologies (infusions, RTMs) require reduced viscosity resins. Depending on the processing method, resins with the required technological parameters are selected. Resins in liquid form are most often processed. Materials in solid form are more practical, from powder to soft molding, and also with fiber reinforcement. In the automotive industry, pre-impregnates are also often used, which due to the addition of a magnesium compound are pre-cross-linked and can be stored and then processed in the form of high viscosity semi-finished products for a given period of time.

Depending on the requirements of composite products, pre-impregnates can be reinforced with natural or synthetic fibers, organic or inorganic. The most common are glass and carbon fibers, rarely aramid and basalt fibers, and natural fibers are used to reinforce products that complement vehicle equipment, such as shelves and carpets [7-8]. Reinforcements are most often used in the form of semi-finished products: textiles, mats or roving. The highest strengthening effect can be achieved by using continuous filaments, and correspondingly lower, in the case of long, short and powdered staple fibers.

3. Manufacturing methods of vehicles parts from polymer composites

Probably the reason for the lack of widespread use of polymer composites in the construction of cars is the conservative approach of engineers in the design phase of vehicles. Not without significance is the smaller number of plants specializing in the production of composite elements and vehicle subassemblies. A specialized, expensive machine park and specialized engineering staff are required. The relatively low cost of materials and the intensive development of technologies for the production of polymer composites during the last two decades should no longer be an obstacle to their use in vehicles.

There are many methods of manufacturing composite elements with thermoplastic and thermoset matrix. The focus is primarily on structural composite parts with larger dimensions. They are manufactured most often from thermoset matrices. Automotive parts made of plastics generally have a small mass, and many of them have been replaced with parts made of thermoplastics reinforced with chopped glass fibers or others.

The type and quality of the product determine the choice of manufacturing technology, which in turn has a direct impact on the production costs. The broadly understood phase of designing composite parts should, in addition to the factors related to the product, also include the efficiency of the method, energy and media demand, additional operations, the number of production deficiencies, the cost of machinery, equipment and instrumentation, including the nuisance for people and the environment. The typical production volume of truck parts varies from 5,000 up to 20,000 pieces per year. For passenger cars, the scale of production is higher and ranges from 80,000 up to 500,000 parts per year. The total costs of tooling for the production of composite parts are lower than the costs of devices for manufacturing of metal parts, since a pressed product generally requires several operations and various tooling. In the automotive industry, the cost of tooling is important, although due to the large series it is not critical.

Due to the requirements of high strength and durability of elements, in the manufacturing process, an elevated pressure is used to remove excess resin together with the air bubbles enclosed in the space and to shut off the oxygen supply to the surface of the cured product. In manufacturing methods like infusion, cold and hot pressing of liquid resins as well as impregnation in an autoclave, these requirements are met and a relatively large proportion of reinforcement in the composite volume can be obtained. However, only composite parts of the highest accuracy can be obtained with the use of hot pressing of liquid resins and prepregs and the HP-RTM infusion method. The elements are smooth on both sides in the class of smoothness and structure required for automotive components [9-12]. These methods are also characterized by high efficiency. The advantage of using preimpregnants (prepregs) is the "clean" production process. From the supplied prepregs an appropriate product outline is cut out and formed by pressing under appropriate conditions of temperature, pressure and time. Figure 1 schematically shows the usefulness of some technologies for the production of composites in the mass production of vehicles. Two technologies applicable in mass production refer to products reinforced with chopped fibers. These are pressing technologies for thermosetting molding and injection of reinforced thermoplastics. They have been successfully used for several decades to manufacture, among others, parts of engine accessories.

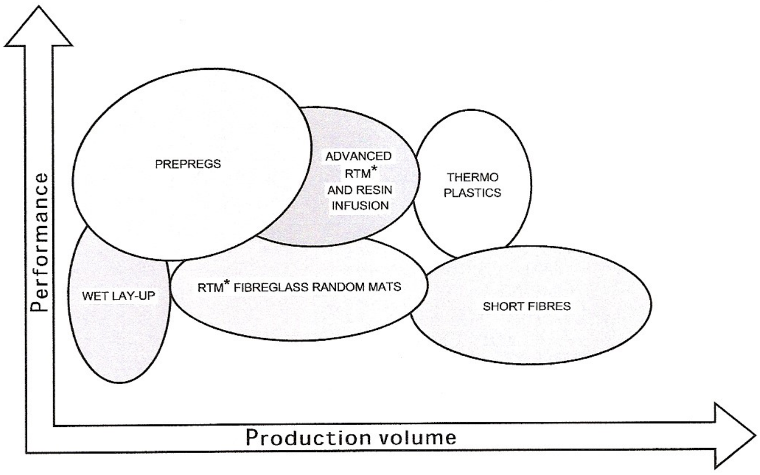

Figure 1. The usefulness of some technologies for the manufacture of products with fiber reinforcement for the production of mass vehicle parts [13].

The above-mentioned technologies are mainly used for the production of external sheathing elements. Structural elements are produced from glass or carbon roving by pultrusion technics, while gas tanks (CNG, hydrogen) - by winding methods. Increasingly, in the automotive industry, the technology of reactive injection of epoxy monomers or polyurethane with glass fibers is applied to the production of car body elements (R-RIM and S-RIM methods) [10, 14]. In turn, complementary elements in the construction of vehicles with lower durability requirements are more and more often produced from fibrous composites with a thermoplastic matrix using different plasticizers, mixing and homogenizing devices, and pressing. In this case, it is also possible to manufacture parts from the thermoplastic pre-impregnate [15].

In the automotive industry, RTM and hot pressing technologies have been quite widely used for the production of composite vehicle components. These methods guarantee high quality of both the internal structure and external surfaces of the elements (Figure 2). These methods are particularly useful for producing high-strength structural elements, although they are not free of drawbacks. In the classic RTM method, the technological process is quite slow and complicated, which largely limits its use in mass production [17, 18]. These disadvantages do not include the HP-RTM high-pressure method, which, however, involves high financial costs to purchase the necessary technological equipment. Similarly, the production of composite parts from pre-impregnates requires high financial outlay for technological equipment. In addition, pre-impregnation storage requires appropriate conditions. This significantly limits the use of this method in mass production.

Figure 2. Prefabricated parts of the car body produced in RTM process [16].

4. New technologies for manufacturing of composite vehicle components

Techniques based on the use of powdered epoxy resins can become quite promising methods that are an alternative to the above-mentioned technologies. The company New Era Materials in cooperation with the Technische Universitat Dresden has developed A.S.SET resin powder, which in the temperature range of 80 ÷ 120 °C has a reduced viscosity and perfectly impregnates reinforcing fibers. Above 110 °C the crosslinking process takes place. The crosslinking time of this resin is about 4 minutes and depends on the thickness of the product being manufactured. After curing, the product has thermoset properties and is heat-resistant up to a temperature of 350 °C. The properties of the material make it possible to prepare and start the mass production process of polymer fiber composite components in a short time. Resin A.S. SET can be used in powdered form or in the form of "dry" pre-impregnates. For powdered resins, RPM (Resin Powder Molding) technology was developed, and for the prepregs, TSF (Thermoset Sheet Forming) technology [19, 20].

In both cases, the technological process consists of two stages. In the first stage, a layer of powdered resin is applied to the individual reinforcement layers. The operation can be carried out using powder feeders or powder guns, depending on the size and type of production (Figure 3a, Figure 4). The powder should be applied fairly evenly in an amount ensuring proper impregnation of the reinforcement.

a) b)

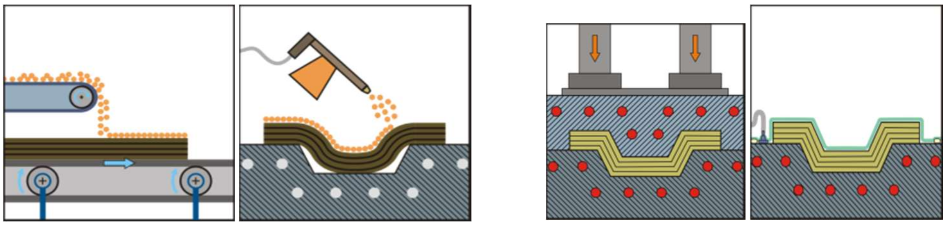

Figure 3. Diagram of the manufacturing process of composite products using the RPM method [20]: a) application of powdered resin, b) hot pressing or vacuum bagging of reinforcement layers.

Figure 4. Applying A.S.SET resin powder on reinforcement [20].

Subsequently, the composite components are preheated to a temperature of approx. 70 °C. Such temperature ensures good adhesion of the powder to be strengthened and facilitates manipulation of the semi-finished product before further processing. The prepared semi-finished products can be stored at room temperature for up to 12 months. During this period, the material is not degraded and the strength parameters are not reduced. In further operations, the semi-finished products may be combined with other pre-prepared semi-finished products or other A.S.SET resin-coated materials, e.g. wooden veneer, balsa.

In the next stage (Stage 2), prepared semi-finished products with the appropriate geometrical outline are placed in the mold and heated to a temperature of 120 ÷ 140 °C. The heated product is subjected to compression or under pressure (in the case of a vacuum bagging method) to induce subsequent impregnation and crosslinking processes (Figure 3b). In the case of pressing with a hydraulic press, the prepared blank is placed in a heated form, whereas in the case of a membrane press the semi-finished product is heated by means of infrared radiators, and then the pressure is applied by means of a mold or by a silicone diaphragm. Increased temperature and pressure support the process of resin impregnation and curing.

It should be noted that in the RPM processes to remove the product from the mold, there is no need to cool it, which significantly contributes to shortening the production cycle. The indicative process parameters are as follows:

- pressure: up to 40 kPa
- crosslinking temperature: 120 ÷ 140 °C (recommended range)
- pressing time: 4 ÷ 7 min.

The course of viscosity changes for the characteristic temperatures of A.S.SET resin is schematically shown in Figure 5. The processes of transition from solid state to plasticized state in the temperature range 20 ÷ 60 °C can be repeated several times. After heating the resin to a temperature of 110 ÷ 120 °C, the crosslinking process begins and the resin is cured.

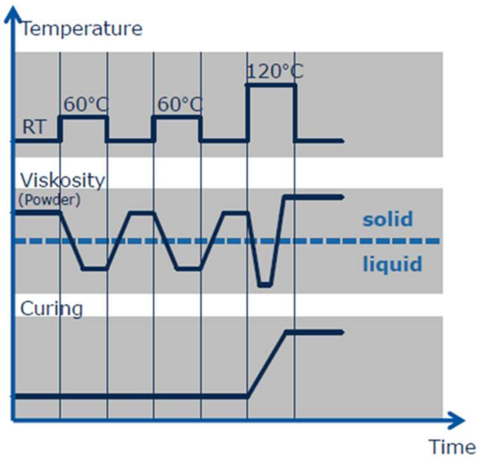

Figure 5. Properties of A.S.SET resin [20].

The development of RPM technology (Resin Powder Molding) is TSF (Thermoset Sheet Forming) technology, which is based on independently manufactured semi-finished products in the form of sheets. The sheets are produced in a continuous pressing process at a temperature not exceeding the temperature of the beginning of crosslinking. Prepared semi-finished products are characterized by high strength parameters. The sheets contain approx. 60 % of the fibres in the form of carbon, aramid or glass fibers (Figure 6). The semi-finished products can be combined in the processing process to the final thickness of the composite resulting from the strength or performance requirements of the parts. The composite product may be made of the same reinforcement (fabric) or in a suitable combination as a hybrid product. The state of aggregation and high quality of semi-finished products allow their easy, long-term storage.

The process of manufacturing composite elements using the TSF method is even less complex than the RPM technology described earlier. It consists of the operation of heating a packet of stacked sheets to a certain temperature, and then pressing them into a mold. The process parameters are each time determined in the tests and are similar to those mentioned for the previous forming method. This technology is schematically shown in Figure 7. This technology allows for a significant shortening of the production process both in the material preparation phase and in the production phase.

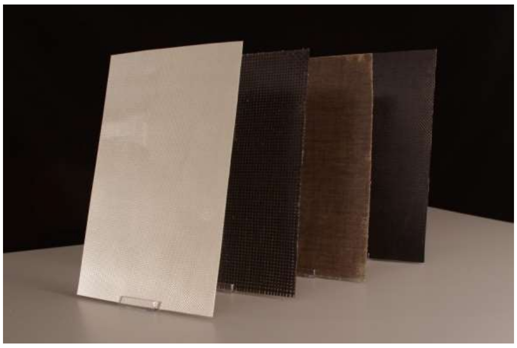

Figure 6. Semi-finished products in the form of A.S.SET Sheets with different types of fabrics [19].

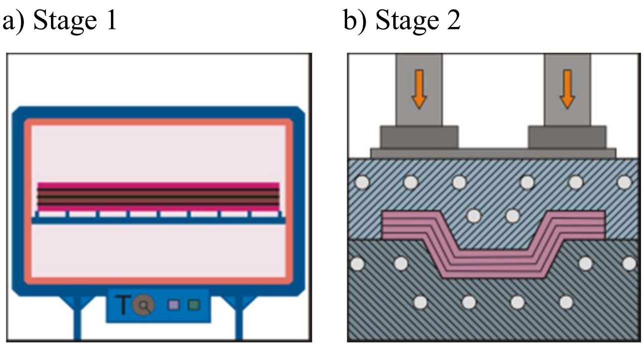

Figure 7. The scheme of the process of manufacturing composite elements using the TSF method [20]:
a) preheating of the stacked sheets,
b) hot pressing of stacked sheets.

5. Application of RPM and TSF technology for the production of vehicle components

Currently, works are underway on the application of the aforementioned technologies for the construction of selected elements of vehicle structures. Attempts have been made to produce sections that can be used to build thresholds, posts or stiffening elements of self-supporting bodies of vehicles. Work is also underway on its application for the manufacture of window frames for city buses. Figure 8a shows a fragment of a side post made with RPM technology and in Figure 8b a structural element made with TSF technology. The general construction concept of the composite bus window frame is shown in Figure 9a, and Figure 9b shows the corner of the window frame made with TSF technology.

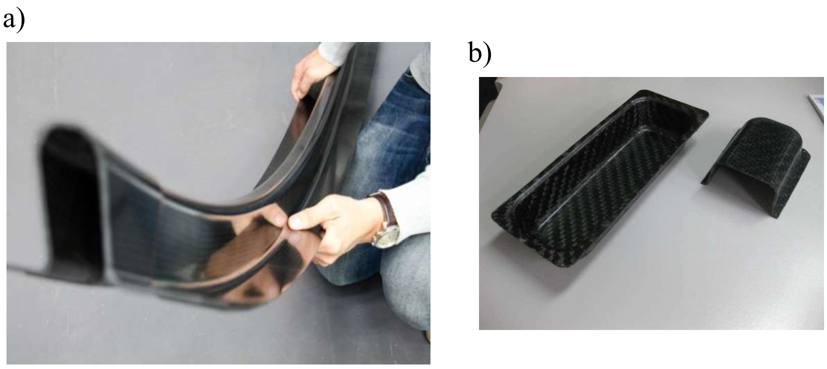

Figure 8. Products made of polymer composites obtained by means of

RPM (a) and TSF method (b) [19, 20].

a) b)

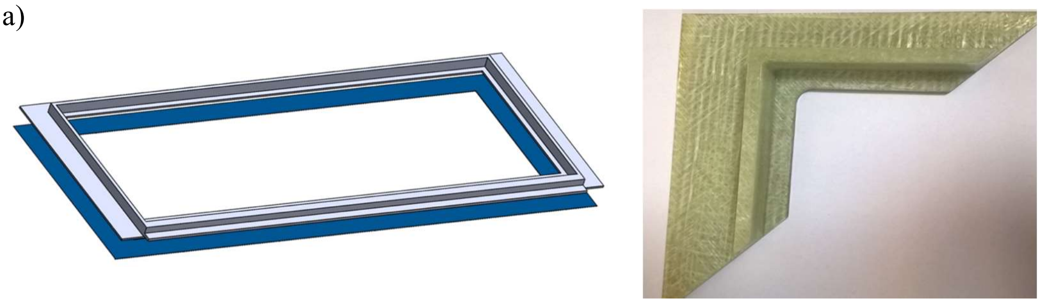

Figure 9. The concept of a composite window frame made with TSF technology (a) and corner of the window frame (b).

6. Summary

One should be aware of the disadvantages and limitations of products and constructions made of polymer composites. If the mass is of no importance, steel and other traditional materials can be successfully used at relatively low material costs and fabrication. Anisotropy and other "special" features of composites are advantages that provide great design flexibility, but on the other hand complicate the design process. Well-known stress analysis tools used for design in the field of isotropy and linear deformability should be extended and take into account the anisotropy of the composites. New, more advanced tools are more difficult to apply and require more knowledge in the field of mechanics and technology for the production of composites. Composites are still considered "materials of the future", and the scale of their economic use is still inadequate to their properties. As a result, products and constructions made of polymer composites are almost always more expensive than from traditional materials. Polymer composites should be used in exchange for "extra" advantages that balance the increase in construction costs.

The RPM and TSF technologies presented in the article are similar to the steel stamping technologies, popular in the automotive industry. Unit times of new technologies are so short that the automotive industry, characterized by high-volume production, can accept them. In one operation, a finished product can be obtained, in particular by eliminating many of the treatments involved in the painting process. The new technology requires attempts to use it to manufacture load-bearing components used in motor vehicles. Comparisons of properties produced with new methods of elements with similar ones made of conventional materials are more advantageous for composite products. Next, it would be necessary to create an analytical tool that could supporting design subassemblies and parts of vehicles. The strength parameters of the connections of elements made with the use of RPM and TSF technology with other load-bearing elements are significant also.

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