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Analysis of welding and sealing joining methods of single-polymer composite materials in a hot air stream

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Abstract

This article presents joining methods (welding and sealing) of single-polymer composite materials in a hot air stream. The research material was created using the *film-stacking* method, which involves pressing successive fractions of polyethylene terephthalate-modified with glycol (PET-G) at defined technological conditions, such as pressure, temperature, and time. Joining method analysis was carried out based on the tensile test results. Analysis of the obtained results showed that the properties of the overlapped weld joint were the best because they were closest to the original materials. In contrast, PET-G welded joint properties were the worst because the PET-G welded joint does not contain fibers, which enhanced the weld; therefore, the fastest breakage of the material was observed at the welding location. For the overlapped weld, the weld itself is more resistant because the joint surface is influenced by friction forces between joined materials.

Introduction

Dynamically-evolving technologies and the constantly growing needs of various industries have forced the development of new materials that can reduce production costs while improving material properties. Composite materials are currently one of the most popular production materials in the world, and recent years have seen a much wider range of applications for polymer composites. They are used in the automotive industry (body and equipment elements), the railroad industry (interiors, car roofs, cargo tanks), the aviation industry (hulls, fuel tanks, stabilizer tips), and the shipbuilding industry (boats, hulls, superstructures). Modern industries are searching for increasingly suitable construction materials with higher strengths, stiffness, impact strengths, and thermal resistance (Gawdzińska et al., 2018, Krawiec et al., 2020).

Composites consist of at least two phases with different properties, and they are created to obtain more favorable physical, mechanical, and functional properties. A composite is made of a matrix and reinforcement phase, which are called the component phases. As a result of combining these phases, additional properties are obtained that improve upon the properties of the individual components. The composite is an externally monolithic material, but the boundaries between the phases are visible. It is also important that the distribution of the reinforcing phase is as uniform as possible throughout the entire matrix volume. A composite material is a special construction material because its structure – a combination of phases – can affect its mechanical, thermal, or chemical properties (Boczkowska & Krzesiński, 2016). This is done by combining different materials, such as:

- Metals – lightweight, with high resistance to high temperatures, corrosion, and mechanical forces;
- Polymers – lightweight, easy-forming, and inexpensive;
- Ceramic materials – hard, with high abrasion resistance.

Nanocomposites are an interesting class of composites in which one of the phases is on the nanometric scale, allowing the phases to interact at the molecular level. As a result, they exhibit better properties than conventional composites with the same chemical and/or phase composition (Piesowicz et al., 2016).

The task of the matrix is to keep the composite material in a compact form and to tightly bind the composite reinforcement. The role of this part of the composite is to translate external pressures into the reinforcement phase and to protect the strengthening phase against physical damage. This component determines the chemical and thermal properties and also defines the shape of the composite. The function of the reinforcement phase is to correlate with the properties of the matrix and improve the mechanical strength of the composite. Additionally, it improves the abrasion resistance, lowers thermal expansion, and also increases the composite's resistance to thermal shock. For this reason, the reinforcement phase prevents the expansion of cracks in a composite (Boczkowska, 2016; Czarnecka-Komorowska, Sterzyński & Dudkiewicz, 2016).

Single-polymer composites (SPCs) are easily-processable lightweight materials with good mechanical, physical, and functional properties (Gucma et al., 2015). In SPCs, both the matrix and reinforcement phase are made of the same or very similar (compatible) polymeric material. The most important feature is the possibility to easily recycle these materials using simple processing methods. As a result, the production of SPCs provides an alternative to the production of complex composites that are difficult to process (e.g., polyester-glass laminates) (Karger-Kocsis & Bárány, 2014).

Single-polymer composites are environmentally-friendly plastics. Most often, the reinforcing fiber in single polymer composites determines the strength of the SPC. Many factors give polymer fibers an advantage over carbon or glass fibers, including a low density, ease of processing, and compatibility with the polymer matrix (Żenkiewicz et al., 2014). The tensile properties of the fibers are influenced by the spinning process, which can be used to properly orient fibers into polymer chains. An important result of this process is the maintenance of a highly resistant structure to mechanical stresses of a polymer fiber (Bryll et al., 2015). Single-polymer composites are often used for 3D printing because both the matrix and reinforcement are made of the same (or similar) polymeric material, the components of which may only differ in terms of their molecular weight, density, or degree of branching. As a result, there are no problems with discontinuous printing or fiber replacement (Bryll et al., 2018).

The growing interest of the industry in this type of material makes it necessary to develop new joining methods or to select joining parameters for already-existing methods. Thermoplastics and composites using a thermoplastic matrix are usually joined by sealing and welding with a hot air stream. The aim of this article was to join single-polymer polyester composites using hot air stream techniques and to select the optimal parameters of this process.

Methods of joining thermoplastics (welding and sealing)

The advantages of joining thermoplastics include a high flexibility coefficient, as a result of which small deformations do not damage the material, as is the case with, e.g., steel sheets. This property is exploited in the automotive industry when plastics are used as the car body. In this case, any damage to the material can be easily reversed by welding, fusing, or gluing. By choosing to weld a thermoplastic, a joined material can be regenerated without reducing its strength. When heated, the material changes its consistency to plastic, which can be easily shaped and combined. The type of thermoplastic materials affects the temperature of the process when welding or sealing (Sikora, 1993). The joining of thermoplastics is based on the transfer of heat to the joined material in a technology-dependent manner. Heat is generated inside the material or supplied from the outside. The mechanical properties of the connection depend on the connection technology, but mainly on the temperature and the time range of temperature influence on the connection. The pressure on the connection, temperature, and duration also have an effect. The main problem in joining polyethylene terephthalate is hydrolytic degradation, which occurs very quickly at the temperature required to successfully create joints, i.e. (250°C). At 255°C, the molecular weight may drop by 50% within 20 minutes. For comparison, the same decrease in molecular weight occurs over 18 h at 140°C. The significant decrease in molecular weight leads to the brittleness of the recrystallized matrix phase, which is a natural phenomenon that is very undesirable at PET joints (Karger-Kocsis & Siengchin, 2014; Gawdzińska et al., 2017).

Due to the method of joining composite materials with a thermoplastic matrix, the following types of joints can be distinguished: gluing, welding, and sealing. The first does not fall within the scope of this work and, therefore, will not be presented here.

Joining thermoplastics using the welding method (Figure 1) involves melting and plasticizing welded

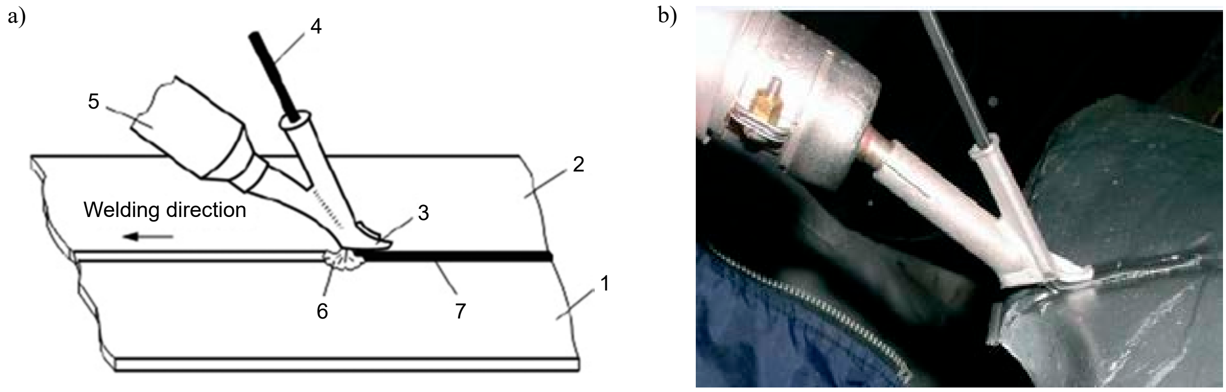

Figure 1. Welding of a thermoplastic using a joint and hot air; a) 1, 2 – welded material, 3 – welding foot, 4 – joint, 5 – heat source, 6 – hot air stream, 7 – ready joint (Klimpel, 2000); b) example of welding (Lepro, 2020)

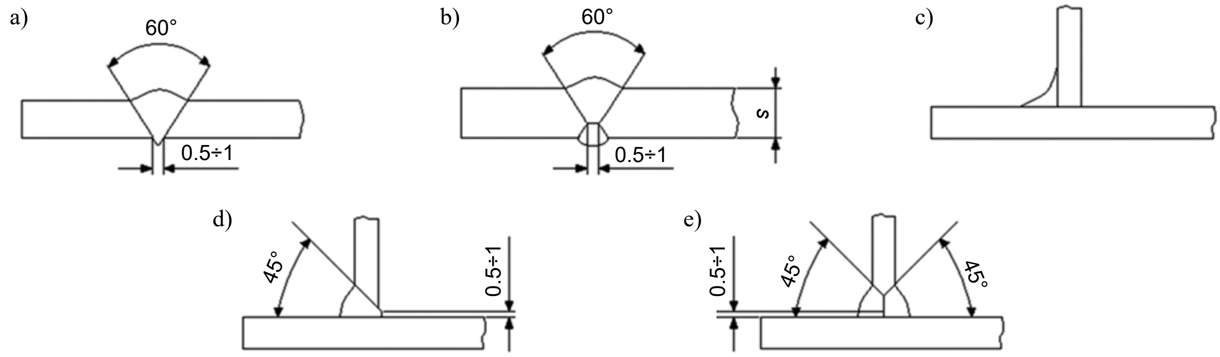

Figure 2. Examples of joints used: a) V-joint, b) X-joint, c) fillet joint, d) HV-joint, e) K-joint (Sikora, 1993)

materials at the point of joining without exerting pressure on the joined elements or adding a welding rod (joint). To create a permanent welded joint, before starting welding, the external surfaces of the welded materials should be prepared, i.e. the material should be degreased (Klimpel, 2000).

The welds shown in Figure 2 are used in thermoplastic welding methods, and the butt joint can be made using a V- or X-joint, a T-joint (a fillet joint), or a K-joint (Sikora, 1993).

Sealing is the process of joining thermoplastic materials, which involves heating a polymeric material to a temperature in the range above the softening point and below the melting point. As a result of this heating, the thermoplastic is in a plastic state. Accordingly, the pressure exerted on the bonding surface causes the diffusion of macromolecules, which creates a permanent bond after cooling. In the welding process, heat can be supplied by various methods, e.g., by friction, electricity, or hot air stream (Klimpel, 2000).

Hot air sealing is a method that combines the internal surfaces of materials by heating them with a hot air stream and pressing them afterward (Figure 3). Most often, joints of this type are made by an overlapping method, and after heating the joined material, it is pressed with a flexible roller, which enables correcting any unevenness of the joint. It is a very quick method of joining, as it allows joining up to 20 m of polyethylene per minute (Józefczyk, 2018).

Figure 3. A device for polymer sealing using a hot air stream by Leister TAPEMAT 50 mm (Heisslufttechnik, 2020)

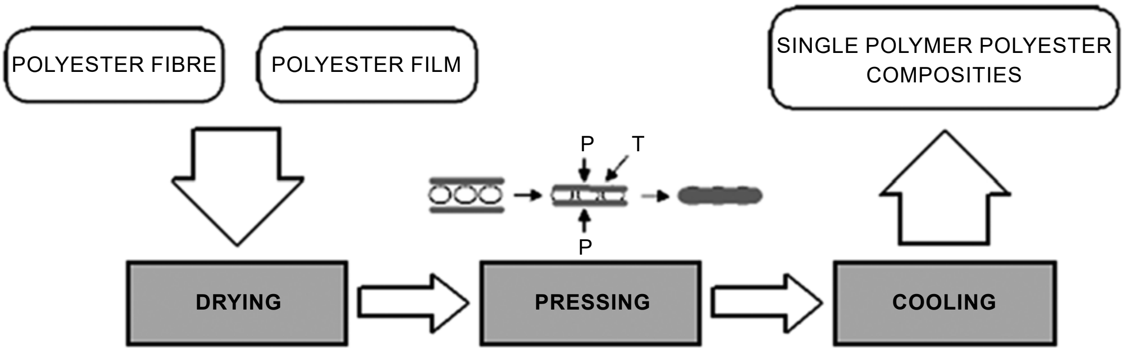

Figure 4. Stages of composites manufacturing using the *film-stacking* method (Bryll, 2017)

Research material and methodology

The plates of single-polymer polyester composites produced by the *film-stacking* method with unordered continuous fibers were used as the research material. The scheme of composite production using this method has been presented in Figure 4.

For manufacturing plates with *film-stacking* technology, a film of polyethylene terephthalate modified with glycol (PET-G) and reinforced with 15 wt% polyethylene terephthalate (PET). The basic parameters of the process are presented in Table 1.

Table 1. Parameters of single-polymer composite materials manufactured with the *film-stacking* method

Parameter	Drying	Pressing Stage I	Pressing Stage II	Cooling
Temperature	60°C	234–235°C	234–235°C	to room temperature
Time	over 6 h	15 s	15 s	200 s
Pressure	in vacuum	1.5 MPa	2.0 MPa	–
Others	–	Pressing in air atmosphere		Pressing in air atmosphere

Numerous studies have already analyzed the mechanical properties of recycled films, which were created in a "film-to-film" system (Czarnecka-Komorowska, Wiszumirska & Garbacz, 2018). An exemplary structure of a single-polymer composite material is shown in Figure 5.

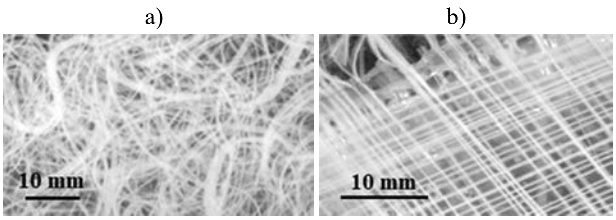

Figure 5. Optical microscope image of an exemplary structure of a single-polymer polyester composite: a) with unordered fibers, and b) without a continuous matrix (Bryll et al., 2015)

The process of joining single-polymer polyester composites using a hot air stream is simple because the method itself, the devices, and their operation are simple. Connections can be made precisely after shaping the material. Obtaining a composite material joint with as few errors as possible requires familiarization with the matrix and reinforcement properties, such as the melting point of the individual phases. So, during the joining process, it is important to focus on (Zhang, Reynolds & Peijs, 2009):

- obtaining a homogeneous material distribution with an approximate thickness, for instance, if it is a board composite;
- avoiding the presence of moisture during joining (chapter: hydrolytic degradation of PET), since moisture causes joint defects such as porosity;
- drying time under a vacuum, which is unique to each polymer material;
- the heat transfer time of the polymeric material, which depends on the thickness of the composite material – the thicker the composite, the longer the heating process. The heating time also depends on the shape, distribution, and type of reinforcement phase, as well as the equipment with which the connection was made, e.g., the heater power or the hot air stream. Excessive reduction of this time by increasing the heating temperature will lead to stress formation that weakens the joint quality;
- the temperature at which the joint is made depends on the matrix material and the reinforcement phase.

The allowable temperature range must be within the so-called "processing window". This means that joining can be completed at the lowest possible temperature in this range, and the composite meets the design requirements. At the moment when the temperature reaches the upper range, the joined material, meeting all the requirements of this connection, cannot be damaged by either thermal or mechanical forces.

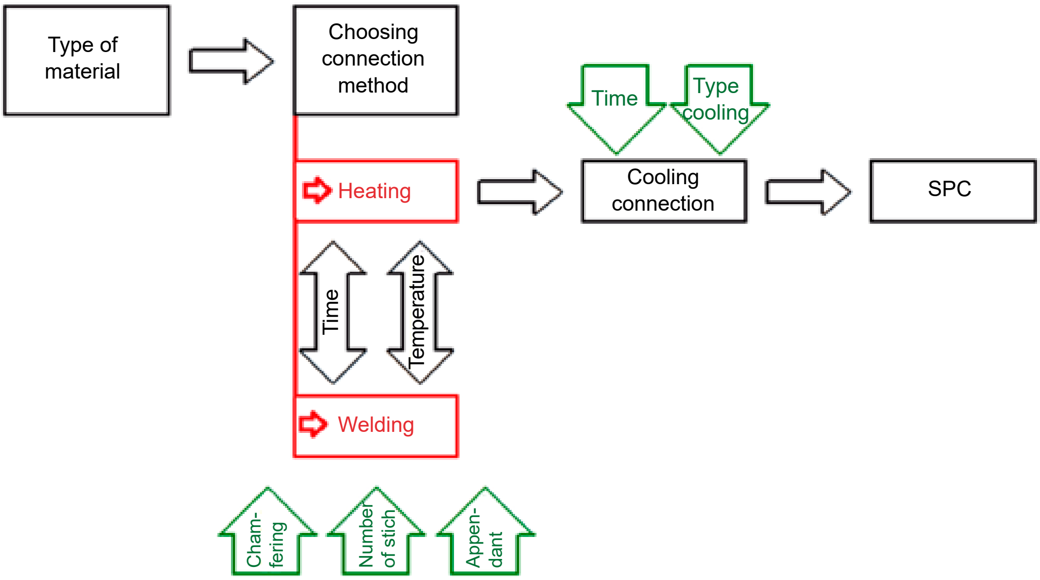

Figure 6. Algorithm of SPC joining process using a hot air stream

a) b)

Figure 7. Exemplary joint preparation: a) welding, b) sealing (Józefczyk, 2018)

The algorithm of the SPC connection process, along with the factors influencing the process, is presented in Figure 6.

This article considers the following joining methods using a hot air stream: sealing (overlapping and butt sealing) and welding (with a PET-G rod and a single-polymer composite rod). The preparation of exemplary joints is presented in Figure 7. For this study, 9 joints were made, and the results were averaged. Plates with a size of 150×100×3 mm were used for the joints. The small thickness of the plate made it possible to perform the weld with the wire-rod method in a hot air stream in one pass, without the need for beveling. Also, sealing took place with a short heating time.

To determine the behavior of the composite during operation, mechanical properties were measured using static load (static tensile) or dynamic load (DMTA) tests (Czarnecka-Komorowska, Sterzyński & Andrzejewski, 2013).

The quality of the joints made (joint strength) was assessed based on a static tensile test. The methods and parameters by which the tensile tests of plastics were carried out are presented in PN-EN ISO 527-1:2000-01 Plastics – Determination of tensile properties – Part 1: General principles. The method used assesses the mechanical properties using a static tensile test where the sample is in the shape of a paddle (the measured part should be 9 ± 3 mm, with a length of 70 or 50 mm).

Research results

We joined single-polymer polyester composites based on a film of polyethylene terephthalate modified with glycol (PET-G), reinforced with high-strength PET fiber. The composites were joined with a hot air stream using two methods – sealing and welding. The joining process was carried out using a STEINEL HL1910E multifunction device.

The temperature range for joining the material by welding was selected experimentally. From 220 to 225°C, when using all compared methods to make joints for single-polymer composites, there was a seriously uneven connection of welds, as well as insufficient welding humps or bad joints. On the other hand, at these temperatures, there were no changes in the joints and no carbonization of the weld. At these temperatures, material swelling was observed at joints; thus, it can be inferred that the temperature of this process is too low to allow a proper joint to be made.

From 230 to 235°C, when using all the compared types of joints for PET-G/15% PET composites, less-frequent uneven joints and swelling of joints were observed. In this temperature range, a change in the structure of the parent material was rare, and an insufficient welding hump did not form.

During the evaluation of joints performed from 240 to 245°C for PET-G/15% PET composites, it was found that occasionally the joint swelled and warped, and the structure of the joint material changed. An uneven connection was not common. It is worth noting that in the given temperature range, an insufficient welding hump did not form.

At a temperature of approx. 250°C, the properties of the joints were significantly reduced, welding humps began to appear, and weld carbonization, joint deformation, and joint structure change were rare. At this temperature, the structure of the original material and swelling also occurred.

Based on this, it can be concluded that the fewest arose during the manufacturing of the joint at the temperature of 235–240°C. No undesirable humps or bad joints formed in this range, and connection defects were rare or occasional. This is the most desirable temperature range, and only joints at this temperature were tested for tensile strength.

Based on the research, analyses, and tests carried out relating to joining single-polymer composites, the most appropriate conditions for joining these materials were established. The ranges of the basic parameters (i.e. temperature, time) are presented in Table 2.

Table 2. Range of basic parameters at sealing and welding of the studied materials

Temperature	Time	Heating speed
235 and 240°C	10 mm/s	Average

Testing the strength properties of the formed joints using static tensile tests

The static tensile test results are shown in Figure 8.

Conclusions

By analyzing the obtained results, it can be concluded that the overlap-welded joint has the best

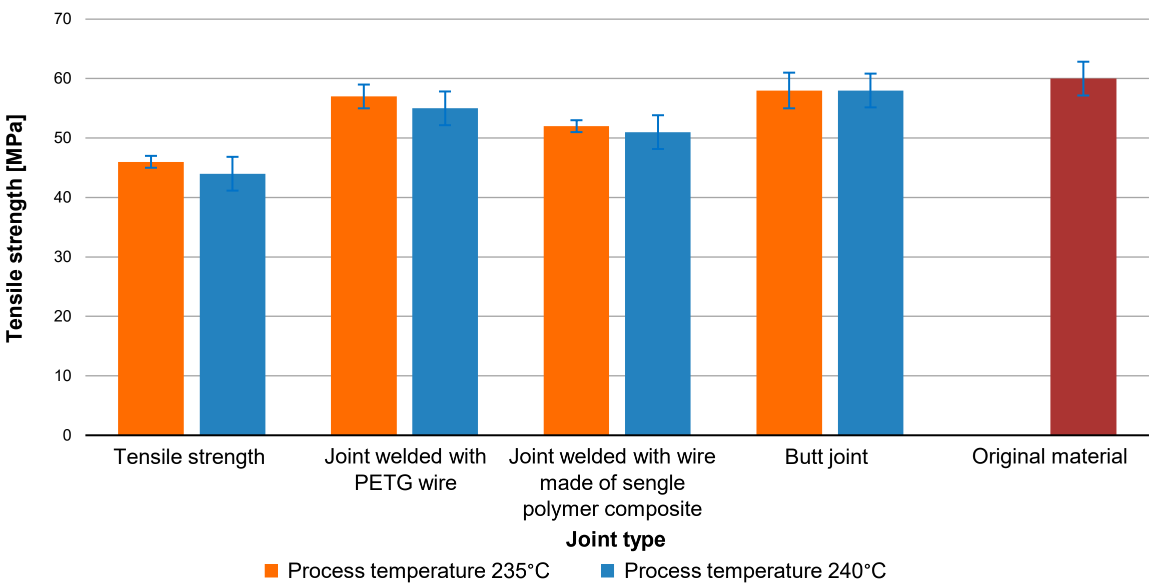

Figure 8. Static tensile test results for the created joints of single-polymer composites

properties, i.e. the closest to the original materials, and PET-G wire-welded joint exhibited the worst properties. This is because the PET-G welded joint does not contain fibers that could also strengthen the weld site; therefore, material tearing occurred fastest at the weld site. In overlap welding, the joining was more durable since the frictional forces between the materials to be joined also acted on the joining surface. In practice, the selection of conditions for joining single-polymer polyester composites is usually done by trial and error, as there is still no complete mathematical description of the relationship between the individual variables of this process, which makes it impossible to use classical methods (Table 3).

Table 3. Disadvantages and advantages of plastic joining methods

Joining method	Advantages	Disadvantages
Welding	The ability to obtain a high-quality joining; the joining takes place relatively quickly and with little material expenditure	The need to carefully prepare the surfaces to be joined to avoid discontinuities in the weld or a lack of fusion, as well as the possibility of burning the material
Sealing	The combination of polymer chains as a result of high temperature and pressure results in the interweaving of these chains and diffusion; after cooling the welded material, the material is permanently joined	Possible air bubbles in the welding area. Materials may move as a result of imprecise machine positioning. There is a need to carefully select the welding parameters of a given material to avoid burning it

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