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Analysis of the cracking process of layered composites with polyester-glass recyclate using dynamic tests

Katarzyna Panasiuk✉, Lesław Kyzioł, Grzegorz Hajdukiewicz

Gdynia Maritime University, Faculty of Marine Engineering, Department of Engineering Sciences
81-87 Morska St., 81-581 Gdynia, Poland
e-mail: {k.panasiuk; l.kyziol; g.hajdukiewicz}@wm.umg.edu.pl
✉ corresponding author

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Abstract

Layered composites are materials that are widely used in industry due to their low manufacturing costs. They are used, among others, as a construction material for the construction of light aircraft, cars, wind turbine blades and the hulls of vessels. The universality of their use has contributed to the formation of a large amount of post-production and post-use waste from these composites. Layered composites, using recycled polyester and glass, or recycled composite waste, may be materials that could be used in the economy. The polyester-glass waste used in the composite was created by crushing and then grinding and sieving to obtain the appropriate granulation. Materials with a waste content of 0%, 10%, 20% and with granulation of this waste of ≤ 1.2 mm were made using the hand lamination method. Test specimens were prepared from the material plates that were obtained in accordance with the PN-EN ISO 179-1: 2010E standard (Plastics – Charpy Impact Assessment – Part 1: Non-instrumental impact test). Impact tests of samples were carried out according to the above-mentioned standards using a Zwick Roell RKP450 swinging hammer. Test bench instrumentation and software enabled the bending forces to be recorded, as well as the deflection of the samples for short time intervals and displacement, so a detailed force-deflection graph could be obtained. During the analysis, the results of the research were focused on describing the kinetics of the process where the samples were destroyed (fracture mechanics), this allowed for the initial determination of the material's resistance to dynamic loads. The results obtained showed that the increase of the recycled content in the produced composite contributed to the lowering of the destructive force threshold in the impact tests, as well as the simultaneous increase of the plasticity of the material. The increase of the sample's deflection with the occurrence of the maximum force resulted in the energy of the elastic state being increased (U_e).

Introduction

Polyester-glass composites are often used in structures that are exposed to dynamic loads with different energies and speeds. They are often used as a construction material for, among others, the construction of light aircraft, gliders, cars, and wind turbine blades (Królikowski, 2012). Designers of flying or floating objects often use these materials to make use of their high values of so-called specific strength and modulus of elasticity (Hyla, 1989). Such elements are exposed, for example, to the impact of hailstones, stones, birds (aircrafts), sea waves and wind. Resistance to dynamic loads (such as impact strength) is very important for their wide application (Barcikowski & Królikowski, 2013).

The value of the force acting under a dynamic load depends on both the mass of the impacting body and its speed when it comes into contact with a given structure, which should absorb the kinetic energy of the body being impacted without destroying it or the occurrence of plastic deformation. In Charpy tests, the kinetic energy of the hammer is used to cause elastic and plastic deformation of the sample. In composites, the share of elastic and plastic deformation is different and depends on a number of factors (e.g. chemical composition, structure, method of manufacture, shape of the samples, presence of stress concentration etc.) (Kyzioł & Szwabowicz, 2018).

The composite materials show high sensitivity to impact loads. These loads, even if they do not lead to the formation of scrap, however, result in the formation of post-impact microcracks in the material, which reduce the strength of the composite. Both the values characterizing its durability and the kinetics of the destruction process change within the material. Knowledge of the effects of the laminate's construction elements on its behavior in the event of a surge load is therefore of major importance in the design and operation of responsible engineering structures (Hyla & Lizurek, 2002). In terms of using these materials for structural elements, it seems insufficient to only determine their material constants in static stretching or bending tests. There is a need to investigate these materials under dynamic loads. Composites have shown that they have limited usability, especially where structures that are made from these materials are subject to fatigue loads (Kwiatkowski & Nabiałek, 2009; Kwiatkowski, 2010).

The development of technologies, related to polymer composites (Kwiatkowski & Nabiałek, 2009) that are fiber reinforced, is one of the directions of development that manifests itself in the technical and technological applications of waste materials (Rutecka, Śleziona & Myalski, 2004; Gawdzińska, Nagolska & Kochmańska, 2013; Gawdzińska et al., 2017; Gucma et al., 2015). The conditions necessary for the use of these raw materials are their proper processing. The form of the processed material is decisive for their final use (Rutecka, Kozioł & Śleziona, 2005). There are many methods that are used for recovering glass fibers from waste, which can then be used as full-value components (Habaj, 2008), or to replace part of the reinforcement phase in new composites with waste (Kowalska, Wielgosz & Bartczak, 2002; Asokan, Osmani & Price, 2009). Continuous progress in the recycling of composites and materials (Pickering, 2016), which in the past were considered to be unsuitable for re-use, has encouraged the search for new, and better methods of waste management (Bignozzi, Saccani & Sandrolini, 2000; Błędzki, Gorący & Urbaniak, 2012). Composites with recycled polyester and glass can be used in the production of sports and recreation equipment, such as kayaks, sailboats, motorboats, and yachts. Additionally, it can be used in selected parts of a ship's hull.

This article has presented the influence of the content of polyester-glass recyclate on the properties of the composite. The recyclate studied was glass-polyester waste, which was pre-crushed, and then ground and divided into appropriate fractions. The research materials (composites with different recyclate content) were made using a contact method – manual lamination. Composite materials were made with a waste content of 0%, 10%, 20% and granulation of <1.2 mm. Samples for testing were prepared in accordance with the PN-EN ISO 179-1: 2010E standard (Plastics – Charpy Impact Assessment – Part 1: Non-instrumental impact test). Impact tests on the samples were carried out using the Charpy method with the use of a Zwick Roell type RKP450 swinging hammer. The hammer instrumentation allowed the bending forces to be measured, as well as the deflection of the samples in very small intervals, in order to obtain a force-deflection graph. This graph will then show an illustration of the amount of energy required to destroy the sample in the area of elastic deformation as well as deco-adhesive changes. The testing of materials at high load speeds allows for the determination of not only the impact strength but also the yield and strength characteristics of the material being tested, which are necessary for the strength calculations (Kyzioł, 2018). This article is a continuation of research into the impact tests of composite materials with recycled polyester and glass (Panasiuk & Hajdukiewicz, 2018).

Methodology of the preparation of test samples

The recyclate, which was an addition to the composites, came from a fragment of a ship's hull. The hull fragment was cut into pieces and was pre-crushed with a hammer and then crushed in a crusher. After crushing the sample had a different granulation and was screened on a sieve with a sieve eye diameter of 1.2 mm and 3 mm, in order to obtain a recyclate, which served as a filler to be added to the matrix of the composite (Panasiuk & Hajdukiewicz, 2017).

A rectangular form was used to make the composites; the shape and size of the research material corresponded to the shape of the form. Composite boards were made with the addition of recycled polyester – glass with a content of 10%, 20% and granulation of ≤ 1.2 mm using the contact method – manual lamination; a reinforcement mat with an accidental fiber direction was used as reinforcement (Panasiuk, 2018). Such reinforcement displays comparable strength properties in all directions of the plane of the mat. The basis of the composite was Polimal 1094-AWTP resin (Kyzioł, Panasiuk & Hajdukiewicz, 2018). Detailed analyses were performed on a selection of the appropriate content and granulation. The selected % content and its influence on the material's properties allowed for the determination of further directions of research, i.e. to reduce or increase the recyclate content. The % content of resin, reinforcement and recyclate has been shown in Table 1.

Table 1. % content of reinforcement, resin and recyclate of the tested materials

No.	Sieve [mm]	% content of resin	% content of glass mat	% content of recyclate
1	–	64%	35%	0%
2	1.2	63%	26%	10%
3	1.2	69%	10%	20%

Samples for testing (Figure 1) were prepared in accordance with the PN-EN ISO 179-1: 2010E standard and made using water cutting (which allowed for very high notch shape accuracy).

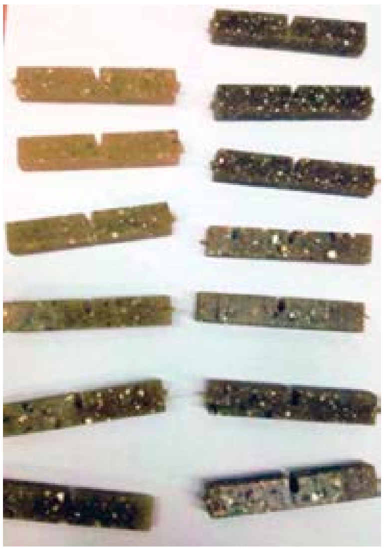

Figure 1. Charpy impact test specimens with 'U' type notch with 10% and 20% recyclate content

Research methodology

The tests used dynamic three-point bending of U-notched specimens. For this purpose, a Charpy type RKP 450 type hammer was used from Zwick Roell (Figure 2), which, thanks to the additional equipment, allowed for not only the impact strength to be determined, but also the changes in the bending force and the accompanying deflection/displacement in very short time intervals. This enabled graphical recording of the course of the changes in energy expenditure during impact bending (Hyla & Lizurek, 2002).

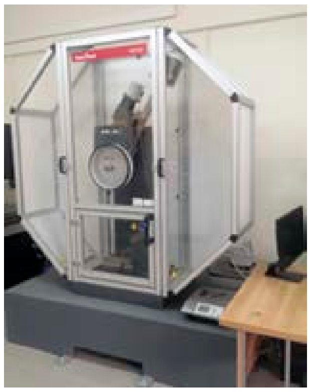

Figure 2. Swinging hammer, model RKP450 from Zwick Roell

Research results

Table 2 has presented the mean of the five values from the results and the tested composite materials, taking into account the percentage and granulation of the recycled material (Panasiuk & Hajdukiewicz, 2018).

Table 2. Results obtained from the impact test of composite materials with different % recyclate content (Panasiuk & Hajdukiewicz, 2018)

Recyclate content	Sieve thickness	F_{max}	f	W	U
%	mm	N	mm	J	kJ/m^2
0	–	1288	0.70	3.11	84.9
10	≤ 1.2	1107	1.12	2.42	59.5
20	≤ 1.2	689	1.16	1.06	31.2

F_{max} – maximum strength, f – deflection, W – work necessary to destroy the sample, U – toughness

Figures 4 to 6 have shown the force-deflection (F–f) diagrams for samples with 0%, 10% and 20% recyclate content and granulation of ≤ 1.2 mm based on the Charpy hammer tests.

Figure 3 has shown a graph of the dependence of the deflection due to the force, for an exemplary composite sample without recycled material, tested with a Charpy hammer. It can be seen from the graph that for a sample of this composite, the maximum force value caused a deflection of $f \cong 0.70$ mm. This was the result corresponding to the averaged result shown in Table 2. After the maximum force was exceeded, until a deflection (total destruction)

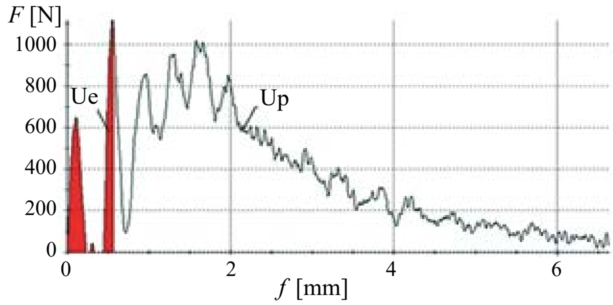

Figure 3. Force-strain diagram *F*(*f*) for samples with 0% recyclate content obtained during dynamic three-point bending on a Charpy type pendulum hammer, where: Ue - operation in the elastic state, Up - work related to the development of defects

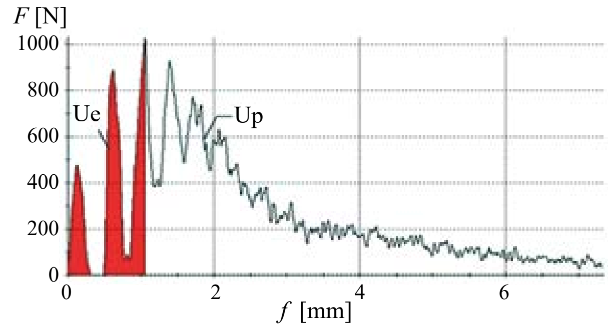

Figure 4. Force-strain diagram *F*(*f*) for a sample with 10% recyclate content and ≤ 1.2 mm granulation, obtained during dynamic three-point bending with a Charpy pendulum type shuttle hammer, where: Ue – operation in the elastic state, Up – work related to the development of defects

of $f \cong 6.50$ mm, a process occurred associated with the development of the destruction of the composite material.

Through analysis of Figure 4, it can be seen that for a material with 10% recyclate content and granulation of ≤ 1.2 mm, obtained a deflection of $f \sim 1.05$ mm for the maximum force, which was an approximate result from the average obtained for this group of samples (Table 2).

After F_{max} was exceeded, by a deflection of $f \sim 7.5$ mm under the curve $F(f)$, it could be seen that the field of work Up was related to the development of the defects created in the composite when it was hit by the hammer.

Figure 5, has shown the graph $F(f)$ for a sample with 20% recyclate content and granulation of ≤ 1.2 mm, with the values $f \sim 1.19$ mm at the maximum force corresponding to the average value for this group of materials shown in Table 2. The maximum deflection as a result of work associated with the development of the resulting defects was $f \sim 8.5$ mm and this was higher than the values for the samples with 0% and 10% recyclate content. Figure 6 has shown the scrap samples that were obtained as a result of dynamic bending.

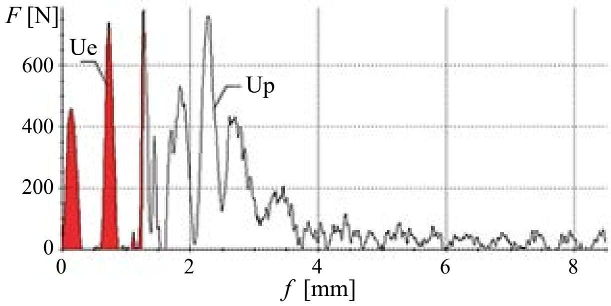

Figure 5. Force-deformation plot *F*(*f*) for a sample with 20% recyclate content, granulation of ≤ 1.2 mm, obtained during dynamic three-point bending with a Charpy pendulum type shuttle hammer, where: Ue - operation in the elastic state, Up - work related to the development of defects

Figure 6. Scrap samples with 10% and 20% recyclate content, obtained as a result of dynamic bending

Conclusions

The results of the impact tests, which were carried out using the Charpy hammer on the samples that were made of composites with different recycled content, have been shown in Table 2. The tests showed that the samples made from composites without any recyclate showed the highest maximum dynamic load force $F_{max} \cong 1300$ N of the three composites tested. This was due to the sample having the largest content of the reinforcement (glass mat) in the material, i.e. with a material that essentially transfers the load. This load corresponded to the deflection (end of the elastic state field (Ue)) equal to $f \cong 0.70$ mm , while the total deflection to destruction (related to the development of the resulting defects – (Up)) was $f \cong 6.50$ mm . The composite without recyclate showed the highest impact strength of $U = 85$ kJ/m^2.

For composites with 10% recyclate and granulation of < 1.2, the maximum dynamic load was F_{max} = 1100 N which was 200 N lower than the strength of the non-recycled material. For this material, the deflection of the samples at the end of the elastic state (Ue) was $f \cong 1.12$ mm. The reduction of the maximum load and the increase in the deflection of the samples for the material with a recycled content of 10%, in relation to the material without recyclate, was due to the fact that there were a larger number of tough and stiff glass fibers in the non-recycled composite. These fibers are a rigid and brittle material, therefore reducing the amount of the fibers and replacing them with recyclate, caused a reduction in the maximum load bearing force of the composite and at the same time caused an increase in the deformation. The total deflection increased to 7.5 mm with the addition of recyclate. The composite with 10% recyclate content had an impact resistance of $U = 60$ kJ/m^2.

Composite samples with 20% recycled content and granulation of < 1.2 mm, that were subjected to impact tests with the Charpy hammer, showed a very large reduction in the maximum dynamic load $F_{max} \cong 690$ N , constituting nearly 50% of the load that was transferred by the material without recyclate. The deflection corresponding to the maximum load was $f \cong 1.16$ mm and it was close to the deflection for the composite with 10% recyclate content. The material with 20% recyclate content showed a further increase in the deflection to destruction value of $f \cong 8.50$ mm. This composite showed the lowest impact strength of $U = 31$ kJ/m^2.

In summary, for a higher percentage of recyclate content in the composite:

- the maximum force in the impact test was lower;
- the deformation at the occurrence of maximum force, assumed a higher value;
- the total strain, combining the work of the elastic state (Up) with the work associated with the development of defects (Ue), was greater.

Further research will be based on the creation of a recycled polyester-glass material, and modifying the amount of reinforcement and recyclate, in favor of increasing the strength properties. This may contribute to the use of these materials in industry, for which it is necessary to develop a complete technology for the production of recycled polyester-glass materials.

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