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Optimal adhesion measuring methods of the glass fibre reinforcement layer

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Abstract. The objective of the current study is to analyse the adhesion processes between the glass fibre reinforcement layer and acrylic sheet to find out the optimal adhesion measuring methods depending on the reinforcement layer concentrations and plastic composite material parameters (dimensions, wall angles, edge radiuses). The experimental tests with different glass fibre reinforcement composition, material heating temperatures and adhesion area variations have been considered. For finding out the optimal adhesion measuring method different well known methods have been tested. For optimal selection of the adhesion area an optimization model have been proposed. Together with the adhesion area optimization an attempt has been made to find out the maximum tensile force, depending on the conditions and material parameters. The FEM simulation has been performed with optimal adhesion area values to verify the prediction accuracy of the surrogate model.

Key words: large composite plastic products, vacuum forming, short glass fibre reinforcement, FEM, adhesion processes.

1. INTRODUCTION

Contemporary enterprises are confronted by challenges arising from continuous innovation, global collaboration and complex risk management. The increasing competitiveness in the global market highlights the importance of rapid product development, design quality management, productivity, optimal price levels, multi-company collaboration and predictability. The manufacturers are under the pressure to maintain their place in the market. To improve their ability to innovate, they have to get products to the market faster than the competitors and reduce errors. The performance of the products and processes is simulated in the computer, to determine if it will perform as desired. Any undesirable conditions are modified, and the new design is simulated again. The manufacturers have also been continuing to improve their product development process, production and product quality management abilities [1–3].

In many industries (whirlpool, portable spa, aerospace, health treatment capsule, plastic boat and car body component building industries) the final product quality depends on composite plastic parts. In those industries the large composite plastic parts are visible and that is why they determine to a large extent the sales success of the final product. It is also very important to reduce the quality defects (in our case the open spaces between the acrylic sheet and the reinforcement layer) in those parts. On the other hand, it is important to manufacture and develop those parts with high productivity. Large parts need more storage and handling spaces and it is very important to organize effectively the whole technology route depending on the manufacturing, lead times, production capacity and market requirements [4–7].

One example of large composite plastic parts is the composite bath-tub (dimensions 2300 mm in length, 900 mm in width and 800 mm in depth). The production of the bath-tub is divided into two main stages. The first stage is vacuum forming of the inner shell of acrylite FF0013 Plexiglas. The second stage is applying the reinforcement layer to the vacuum formed shell. The reinforcement consists of polyester resin with randomly oriented short glass fibres. The reinforcement layer consists of peroxide (0.8%), epoxy resin (64.1%) and glass fibre (35.1%). The reinforcement layer is applied by manual spraying. After manual spraying the layer is rolled and left for drying for a couple of hours. The drying time depends on different parameters like thickness of the layer, peroxide concentrations, room temperature etc. As the thickness of the final layer can vary then it is controlled by the operator [8].

The final shell thickness in different areas may differ significantly in the vacuum forming process, so this has to be taken into account in structural analysis of the product. For modelling and structural analysis of derivative products CAE (HyperWorks) and CAD (Siemens NX) systems are used. A surrogate model has been developed consisting of the FEM and artificial neural network (ANN) to find out the optimal wall thickness distribution for a thermoformed and glass fibre polyester reinforced part [9,10].

There may occur some abnormalities depending on the adhesion between the reinforcement layer and the acrylic Plexiglas. Depending on the vacuum forming temperature, product parameters (wall angle, edge radiuses, etc), reinforcement layer concentration, material thicknesse, glass fibre orientations, concentrations and acrylic type some open spaces between those two layers may be present [11,12]. These open spaces between the layers appear very easily, especially in the corners. Some examples of defective adhesion between the acrylic and the glass fibre reinforcement layer are shown in Fig. 1.

These defects will make the product weak against the loading (pressure and weight). Thus it is very important to control the adhesion processes between the glass fibre reinforcement layer and the plastic shell. In order to achieve an effective control of the adhesion, a proper adhesion measuring method should be developed and improved.

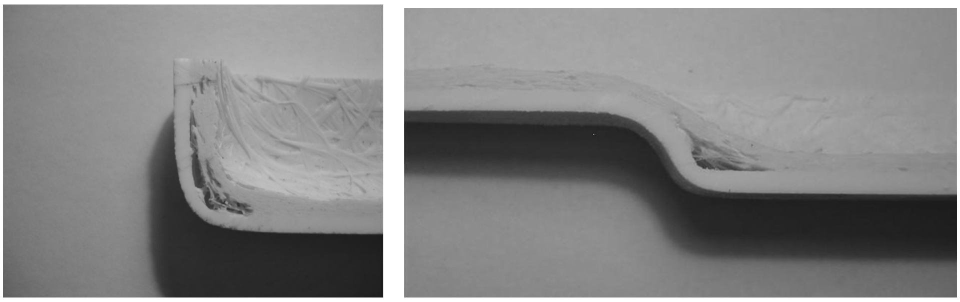


Fig. 1. The samples with defective adhesion in the corner (open space between layers).

2. OPTIMIZATION OF THE ADHESION MEASURING METHOD

Adhesion measuring methods can be divided into two categories: destructive and non-destructive. Usually destructive methods are applied, by which a loading force is applied to the coating in some specified manner and the resulting damage is subsequently observed. Non-destructive methods typically apply a pulse of energy to the coating system and then identify the specific portion of the energy that can be assigned to losses, occurring due to open spaces inside the material. There are many well-known types of the destructive testing methods like the tensile test, peel test, tape peel test, indentation bonding test, self-loading test, scratch test, blister test, beam bending test etc [13–16].

For finding out the optimal adhesion measuring method for the glass fibre reinforcement layer, we have analysed different well-known methods and tried to find out the most effective one, depending on the concrete materials, structure and product shape. After the analysis of different methods, tensile testing was selected. The main issue was to find out the optimal shape for the test part, optimal thickness for the glass fibre reinforcement layer, optimal adhesion area to avoid additional bending and stresses, for getting reliable results.

In the beginning we tried to find out the optimal product shape and adhesion area, depending on the existing conditions and material parameters. The selection of the adhesion area parameters is crucial. On the one hand, when the area is too big then the acrylic material will break down and we can not measure the correct force. On the other hand, when the area is too small then the glass fibre reinforcement layer will be removed too quickly and too low force is measured. Because of that it is important to find out the optimal adhesion area to get reliable measurement data. A sample of the test part is shown in Fig. 2.

Several test were made, but the result was always the same – fracture of the acrylic material. This was caused by too strong connection, too big adhesion area and properties of the materials. One example of the test results with the material breakdown is shown in Fig. 3.

(a) (b)

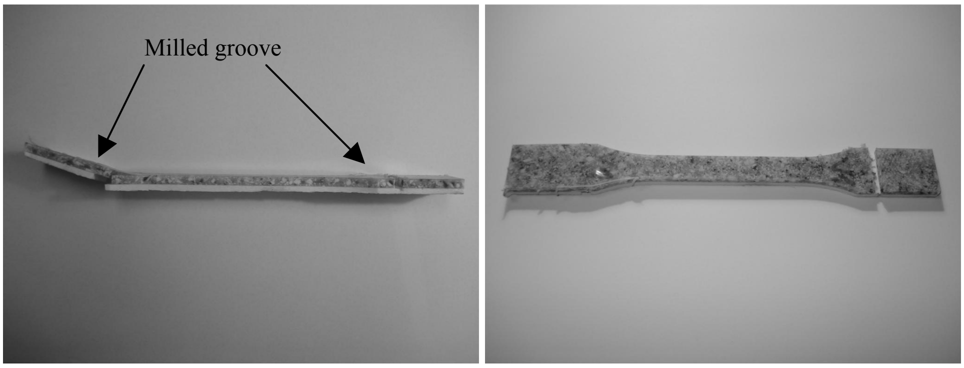


Fig. 2. The side view (a) and top view (b) of the test specimen.

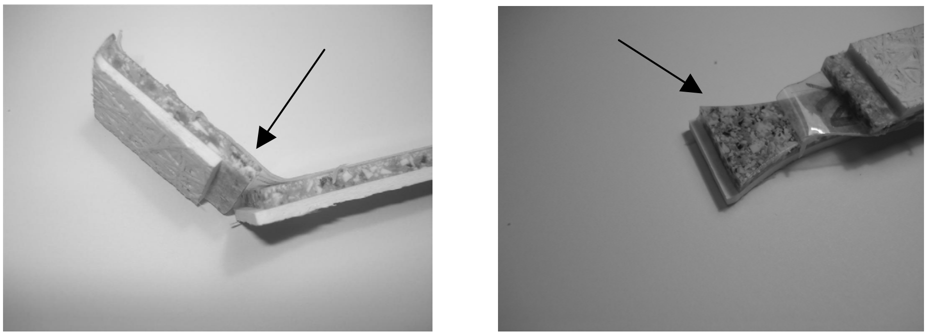


Fig. 3. The acrylic material breakdown.

In order to find out the optimal adhesion area, several experiments have been performed. One example is shown in Fig. 4a, where the area was still too large and the acrylic material broke down, but the measured force was close to the

(a) (b)

Fig. 4. Cracked acrylic material (a) and optimal cut-outs (b).

optimal one for that adhesion connection and material strength properties. After experimental tests and analysis the optimal cut-out was found (Fig. 4b). The optimization procedure was made by using FEM software ANSYS. The optimal adhesion area was determined and the results were validated with experiments. The first step of the tensile strength FEM simulation is shown in Fig. 5. It can be seen from Fig. 5 that because of the adhesion between the layers, materials will bend only a little and at the corner of the acrylic material there is stress concentration.

The next step of the tensile test simulation is depicted in Fig. 6. The stresses are higher and at the corner the two layers start to withdraw from each other. The final step of the tensile test and a more detailed stress plot are shown in Fig. 7. This was the final step, when the tensile test continued; in the next step the materials were disassembled completely. The experiments with the same adhesion size and material parameters are illustrated in Fig. 8.

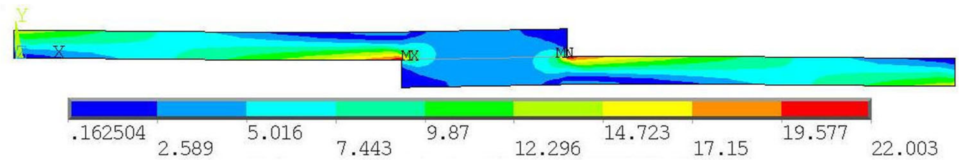
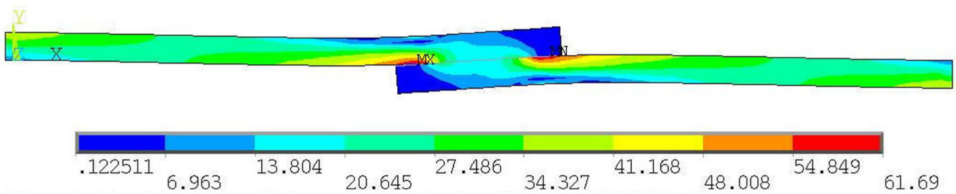


Fig. 5. First step of the loading (equivalent stress plot); stresses are given in MPa.

(a)



(b)

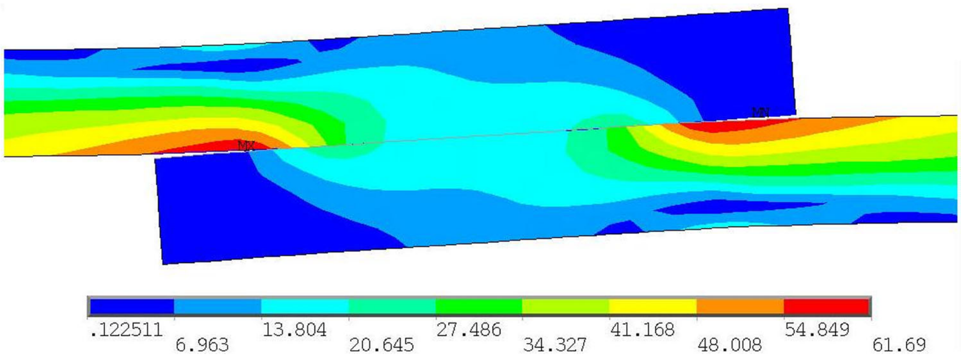
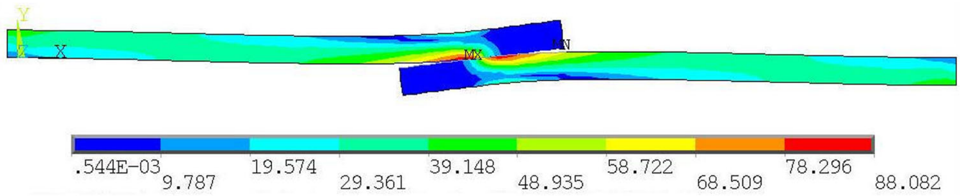


Fig. 6. Second step of the equivalent stress plot (a) and detailed view (b).

(a)



(b)

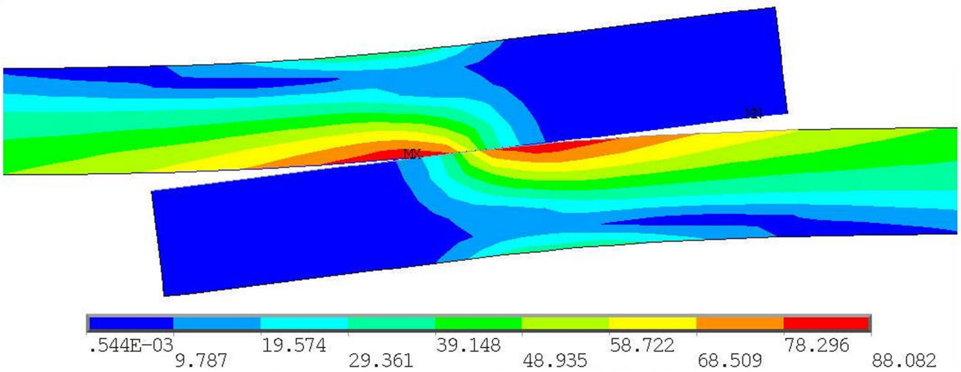


Fig. 7. Final step of the equivalent stress plot (a) and detailed view (b).

(a)

(b)

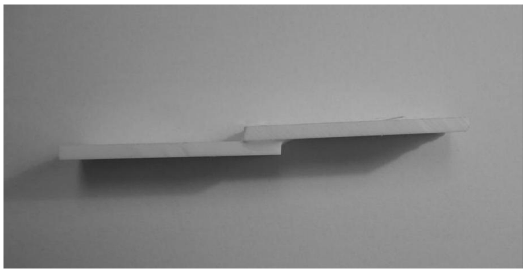


Fig. 8. Material bending before cracking (a) and optimized part (b).

The next constraint in addition to the adhesion area that is to be taken into account, is bending. During the FEM optimization process the optimal size of the adhesion area and need for the additional supporting bars were found out to avoid additional bending. The bending process is shown in Fig. 8a.

(a) (b)

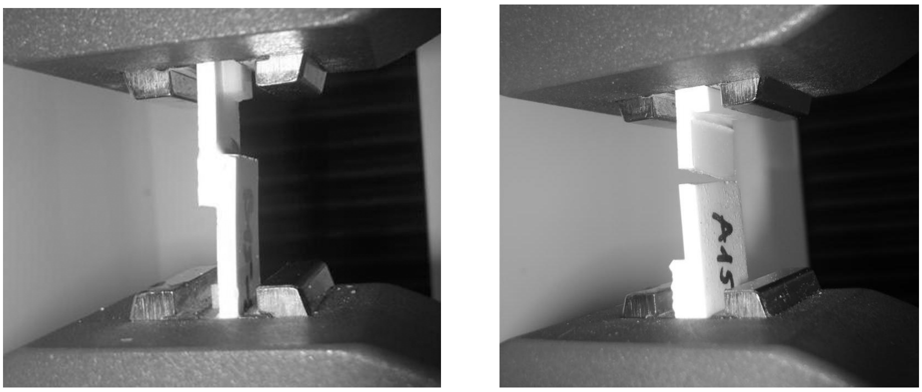


Fig. 9. Additional supporting bars (a) and disjointed part (b).

The problem was that the test material (Acrylite FF0013 Plexiglas) bends near the connection area and after that the acrylic material cracks. To avoid the material bending and additional forces to the materials, the test specimen was optimized. The adhesion area was the same, but the length of the test specimen was shorter. The optimized test specimen is shown in Fig. 8b. Beside the length optimization, supporting bars were added to avoid bending and support the plastic material itself. In Fig. 9a the supporting bars and in Fig. 9b the sample of the final disjointed part are shown. It can be seen that the acrylic material did not crack and the two parts were disjointed perfectly. The optimal size of the adhesion area, obtained from the FEM simulation process, was tested experimentally.

3. ANALYSIS OF THE MEASUREMENT RESULTS

For measuring the glass fibre reinforcement layer and the acrylic sheet adhesion, a number of tests have been performed according to the design of experiments. The ratio of the polyester resin and fibres is kept constant, but the concentration of MEKP is varied from 0.8% up to 2%. Evidently, the ratio of the polyester resin and MEKP has significant influence on the curing time and also on the mechanical properties (e.g. modulus of elasticity, tensile strength) of the composite.

Table 1 and Fig. 10 illustrate some results of the experiments. These tests were made with different groups of materials. Values, which are shown, are the mean values of different tested groups. Nine different groups of materials and in each group ten specimens were tested. Different parameters were varied: the MEKP concentration, reinforcement layer thickness, acrylic material was heated or not, reinforcement layer was with or without the glass fibres, etc. In Table 1 letter “A” means that the acrylite was not heated, letter “B” means that it was

Table 1. Results of the experiments

Specimen	Thickness, mm	Width, mm	Max force, N	Tensile strength, MPa	Elongation, %
A11-6-3	18	6	486	4.5	7.22
B11-7-3	19	7	554	4.17	14.9
B11K-7-2	18	7	327	3	3.92
B15-7-5	17	7	964	8.1	9.77
A15-9-5	19	9	1013	5.92	9.29
B19-7-4	18	7	1017	8.07	8.46
A19K-6-4	18	6	896	8.29	7.82
B10-6-2	19	6	848	7.44	6.39
A15K-9-3	19	9	1081	6.32	11.3

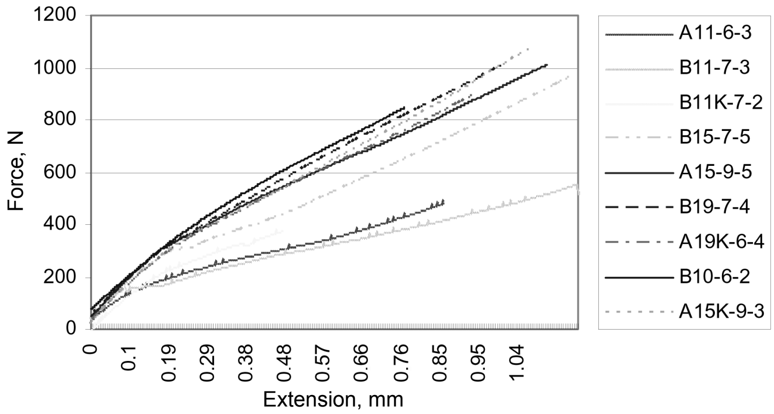


Fig. 10. Force–extension plot.

heated. Numbers behind the letter show the concentration of the peroxide, for instance 10 – 0.8%, 11 – 1.0%, 15 – 1.5%; next numbers show the length of the adhesion area in mm and the number of the sample. The thickness was 1 mm and width was varied. Letter "K" indicates the glass fibres inside the layer.

From the experiments it was found out that the adhesion between the glass fibre reinforcement layer and the acrylic sheet depends on the adhesion area parameters, additional forces and bending, acrylic sheet material conditions (cracks and microdefects), MEKP concentration (better adhesion when the concentration is higher, 1.5 or 2.0%), glass fibre position and orientation in the reinforcement layer (when the glass fibre is close to the acrylic sheet, it makes the adhesion weaker, because the resin and MEKP connection is bad). On the other hand, heating did not remarkably change the adhesion.

Based on experimental data, the relationship between the adhesion area (output) and dimensions, material and loading parameters (inputs) has been established. In the current study, the generalized regression neural networks (NN) are used for the modelling of this relationship. The response surface, constructed by the use of NN, do normally not contain the given response values (similarity with least-squares method in this respect). An approach is proposed, which is based on the use of the MATLAB neural network toolbox. Two-layer network is generated including the radbas neurons in the first and purelin neurons in the second layer. Proceeding from the constructed response surface, the minimal value of the adhesion area has been determined by the use of a genetic algorithm.

4. CONCLUSIONS

The objective of the current study was to analyse the adhesion processes between the glass fibre reinforcement layer and acrylic sheet, and to find out the optimal adhesion measuring methods depending on the reinforcement layer concentrations and plastic composite material parameters (dimensions, wall angles, edge radiuses). For finding out the optimal adhesion measuring method for the glass fibre reinforcement layer, different well-known methods have been analysed and the effective one has been found, depending on the used materials, structure and products shape.

An optimization procedure has been developed for determining the optimal adhesion area. This procedure includes design of the experiment, FEM simulation, response modelling, search for optimal solution and experimental validation of the reliability of the model. A number of tests has been made with different glass fibre reinforcement concentrations, acrylic sheet heating temperatures and adhesion area parameter variations. It was found out that the adhesion between the glass fibre reinforcement layer and the acrylic sheet is sensitive to the MEKP concentrations (better adhesion is obtained when the concentration is higher 1.5% or 2.0%), to glass fibre positions and orientations in the reinforcement layer and less sensitive to temperature changes in the acrylic sheet.

The results of the experiments can be used as a basis for future glass fibre reinforcement layer and acrylic sheet adhesion optimization processes in the field of manufacturing large composite plastic parts.

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REFERENCES

1. Tang, D. and Qian, X. Product lifecycle management for automotive development focusing on supplier integration. *Computers in Industry*, 2008, **59**, 288–295.
2. Gu, X. and Renaud, J. E. Decision based collaborative optimization. In *Proc. 8th ASCE Speciality Conference on Probabilistic Mechanics and Structural Reliability*. Indiana, 2000.

3. Küttner, R. A Framework of collaborative product and production development system. In *Proc. 3rd International Conference "Industrial Engineering – New Challenges to SME"*. Tallinn, 2002, 34–37.
4. Strong, A. B. *Plastics Materials and Processing*, 2nd ed. Prentice Hall, New Jersey, 2000.
5. Lokensgard, E. and Richardson, T. L. *Industrial Plastics: Theory and Applications*. Delmar Learning, 2003.
6. Sala, G., Landro, L. and Cassago, D. A numerical and experimental approach to optimise sheet stamping technologies: polymers thermoforming. *J. Mater. Design*, 2002, **23**, 21–39.
7. Küttner, R. and Karjust, K. Coordination of complex tasks of engineering product and manufacturing process optimization. *Proc. Estonian Acad. Sci. Eng.*, 2006, **12**, 163–175.
8. Cho, C., Kwahk, S.-Y., Kim, W.-J. and Choi, J.-K. Thermo-viscoelastic-plastic deformation of huge products in thermal process. *J. Achievements Materials Manufact. Eng.*, 2006, **17**, 233–236.
9. Küttner, R., Karjust, K. and Pohlak, M. The design and production technology of large composite plastic products. *Proc. Estonian Acad. Sci. Eng.*, 2007, **13**,117–128.
10. Pohlak, M., Majak, J., Karjust, K. and Küttner, R. Multicriteria optimization of large composite parts. *Composite Structures*, 2010, **92**, 2146–2152.
11. Wrobel, G. and Pawlak, S. Ultrasonic evaluation of the fibre content in glass/epoxy composites. *J. Achievements Materials Manufact. Eng.*, 2006, **18**, 187–190.
12. Fereshteh-Saniee, F., Majzoobi, G. H. and Bahrami, M. An experimental study on the behavior of glass–epoxy composite at low strain rates. *J. Mater. Proc. Technol.*, 2005, **162–163**, 39–45.
13. Lacombe, R. *Adhesion Measurement Methods. Theory and Practice*. Taylor and Francis, 2006.
14. Plonka, R., Mäder, E., Gao, S. L., Bellmann, C., Dutschk, V. and Zhandarov, S. Adhesion of epoxy/glass fibre composites influenced by aging effects on sizings. *Composites, Part A: Applied Science and Manufacturing*, 2004, **35**, 1207–1216.
15. Vas, L. M., Ronkay, F. and Czigány, T. Active fiber length distribution and its application to determine the critical fiber length. *Polymer Testing*, 2009, **28**, 752–759.
16. Kusano, Y., Teodoru, S., Leipold, F., Andersen, T. L., Sørensen, B. F., Rozlosnik, N. and Michelsen, P. K Gliding arc discharge – application for adhesion improvement of fibre reinforced polyester composites. *Surface Coatings Technol.*, 2008, **202**, 5579–5582.

Komposiidi klaaskiud-tugevduskihi nakkuvuse mõõtmise meetodid

Kristo Karjust, Meelis Pohlak ja Jüri Majak

On käsitletud metoodikat komposiidi komponentide akrüülpleksiklaasi ja klaaskiud-tugevduskihi nakkuvuse uurimiseks. On püütud leida optimaalne nakkuvuse uurimise meetod sõltuvalt tugevduskihi komponentidest ja komposiitmaterjali parameetritest. Katsekeha optimaalse nakkuvuse pindala leidmiseks kasutati lõplike elementide meetodit ja tarkvara HyperWorks keskkonda. Optimeerimise meetodi testimiseks teostati eksperimente, muutes klaaskiud-tugevduskihi koostist, komposiitmaterjalide kuumutustemperatuure, kontaktpindala ja katsekehade parameetreid. Analüüsi tulemusena leiti, et nakke suurus on tihedalt seotud MEKP (Methyl Ethyl Ketone Peroxide) kontsentratsiooni ja klaaskiudude orientatsiooniga ning asukohaga tugevduskihis.