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MODELLING OF AGEING AND OPTIMIZATION OF COMPOSITE STRUCTURES

A study of the impact of Short Fibre Reinforced Polymer Composite degradation, based on a PBT matrix, on injection moulded snap geometry is reported. A nonlinear transversely isotropic material, taking into account the material ageing time, along with implemented failure criteria was used. The material direction was assigned separately for each finite element, depending on the result of the simulation of the injection moulding process. In the snap model, three parameters have been defined that could potentially affect the simulation results. These parameters have been used for the Design Of Experiments (DOE). By changing the geometric parameters mentioned above, a full set of tests was performed, which resulted in the formation of assembly forces, pulling forces and the maximum stress in the clip, served as input data for optimization. Based on a series of simulations carried out for the material in an As Received (AR) state and after material ageing, geometry optimization was carried out using the Response Surface Method (RSM). Assuming the same requirements during optimization, two different geometries were obtained, for the AR material, and for the material after ageing, which indicates the necessity to carry out similar studies already in product development in order to avoid costly and time consuming changes of serial production tools. The geometry of the latch after optimization, for the material model after ageing, ensures that the requirements for the assembly and the pull out forces needed for part destruction, posed for such components, will be met, while using the optimum geometry for the AR material does not ensure compliance with the requirements after the ageing process. The presented simulation method, taking into account the degradation of the material, enables the optimization of composite structures including the degradation of the material during the operation, which can contribute to significant savings during the design of components made of short fibres reinforced composites and the validation process.

Keywords: composite ageing, DFSS, FEM, product durability

MODELOWANIE STARZENIA I OPTYMALIZACJA KONSTRUKCJI KOMPOZYTOWYCH

W powyższej publikacji przedstawiono analizę wpływu degradacji kompozytów polimerowych wzmacnianych włóknami krótkimi na bazie polimeru PBT, na geometrię zaczepu wykonanego metodą wtrysku. Do badań symulacyjnych użyto nieliniowego modelu materiałowego transwersyjnie izotropowego, uwzględniającego czas starzenia materiału wraz z zaimplementowanymi kryteriami zniszczenia kompozytu. Model materiałowy został przypisany oddzielnie dla każdego elementu skończonego zależnie od wyniku symulacji wtrysku tworzywa wzmacnianego. W modelu zaczepu zdefiniowano trzy parametry które mogły potencjalnie wpływać na wyniki symulacji, które zostały użyte do zaprojektowania całej serii eksperymentów. Zmieniając wspomniane powyżej parametry geometryczne, przeprowadzono pełny zestaw analiz których wyniki, w postaci sił montażu, sił wyrywania oraz maksymalnych naprężeń w zaczepie, posłużyły nam za dane wejściowe do optymalizacji. Na podstawie szeregu analiz przeprowadzonych dla materiału w stanie nie zdegradowanym (As Received -AR) oraz materiału poddanego starzeniu przeprowadzono optymalizację geometrii zaczepu za pomocą Metody Powierzchni Odpowiedzi (RSM). Zakładając takie same wymagania w trakcie optymalizacji uzyskano dwie różne geometrie, dla materiału AR oraz po starzeniu, co świadczy o konieczności przeprowadzania podobnych analiz już w trakcie projektowania produktu w celu uniknięcia konieczności kosztownych o długotrwałych poprawek narzędzi służących do seryjnej produkcji komponentu. Geometria zaczepu po optymalizacji, dla materiału zdegradowanego, zapewnia nam spełnienie wymagań odnośnie sił montażu i zniszczenia, stawianych takim komponentom, podczas gdy użycie geometrii optymalnej dla materiału AR nie zapewnia spełnienia wymagań po próbach starzeniowych. Zaprezentowana metoda symulacji uwzględniającej degradację tworzywa, umożliwia optymalizację konstrukcji kompozytowej z uwzględnieniem degradacji tworzywa w czasie eksploatacji, co może się przyczynić do znacznych oszczędności w trakcie projektowania i walidacji elementów wykonanych z kompozytów wzmacnianych włóknami krótkimi.

Słowa kluczowe: starzenie kompozytów, DFSS, optymalizacja konstrukcji, MES, trwałość produktów

INTRODUCTION

Polymer composites reinforced with short glass fibres, commonly known as glass fibres reinforced plastics, are more likely used in engineering material, used in increasingly responsible construction. This is due to many factors, such as the ease of processing, low price, and good strength to weight ratio, etc. Despite the great efforts of manufacturers to produce low-cost materials and a stable polymer matrix, in practice, the unsolved problem of the life prediction of composite components, which during use lose their property as a result of the environmental conditions in which they are utilized. In the automotive industry, for example the manufacture of electrical components, dimensionally stable, and easy for processing, materials from the group of polyesters such as polybutylene terephthalate (PBT) reinforced with glass fibres (GF) are employed widely. This material, however, is susceptible to hydrolysis, a phenomenon which occurs in high humidity and temperatures above the glass transition temperature of the material [1], which often occurs especially for under-the-hood car applications. This causes the need for tool development to predict the durability of such components, also taking into account the dispersion of material properties resulting from the production process and degradation of the material. Computational methods developed so far, used in the analysis of SFRPC components, take into account the influence of the manufacturing process [2, 3], material nonlinearities and asymmetry of tension and compression diagrams [4] but do not take into account the aspect of composite durability and its property changes during the operation. Material models taking into account the material ageing, created mainly for composite laminates, can be used mainly for the calculation of relaxation, creep, and buckling [5, 6]. The combination of these two approaches and the establishment of appropriate procedures for combining the analysis of the injection moulding with non-linear material models taking into account the material degradation [7] allows one to take into account changes in material properties during the operation, and optimization of the structure in accordance with the principles of Design for Six Sigma (DFSS). DFSS is an approach that extends the concept of Six Sigma [8] to improve the design and understand the meticulous design and management processes that support the development of new products and their marketing. Sometimes that is also included in the redesigns of existing solutions so that they might be improved. However, many publications demarcate these processes, giving modifications to existing processes to the approaches of the Define - Measure - Analyze - Improve - Control (DMAIC) and design methodologies for new products, using the approach Define - Measure - Analyze - Design - Optimize - Verify (DMADOV). This methodology divides the process into phase identification (Identify), design (Design), optimize (Optimize) and verification (Verify). Phase includes the identification of defining, measuring, and analysis. Defining, it is to identify and describe the basic requirements of the customer and the purpose of the project. Measurement is required to collect data on the efficiency of the proposed process. The analysis is to understand all the connections and relationships occurring in the process and identify key issues affecting the achievement of the project. The next phase is design, which translates customer needs and expectations of the functional requirements and possible solutions. The selection process allows a progressively narrowing down of the list of solutions until the best choice is found. The next is the optimization which is involved in defining and modelling the final shape of the process on the basis of statistics derived from tests and analysis. The phase of verification confirms |whether the project results will match the expectations of the Customer (CTQ) [8]. The approach to design a DFSS, fulfils a very important role, related to the optimization section. It allows specification of the final product or process, to obtain the product which meets customer requirements. In terms of DFSS several approaches to optimization are used. The method most commonly employed in DFSS is Design of Experiment (DoE). For each plan of the experiment, an appropriate conduct pattern and analysis are chosen. The most commonly utilized are Taguchi Methods for Robust Design, Factorial Methods and Response Surface Methods (RMS) [8] used in this paper.

MODELLING

In this work, the effect of the ageing time on the results of the optimization of a latch made of Short Fibre Reinforced Polymer Composite, Polybutylene Terephthalate (PBT) - a polymer-based material, reinforced with 20% glass fibre (PBT GF20). For simulation and optimization, the material model described in detail in an earlier publication the author [6] has been used. This model takes into account:

- Direction of fibre alignment and its impact on the basic properties of materials
- Non-linear elasticity
- Non-symmetrical compression and tension
- Mechanism of failure
- Influence of the time on the above mentioned factors

This model was built on the basis of the following strength tests:

- Transverse and longitudinal tensile tests - stress/ stain behaviour for three different ageing times
- Transverse and longitudinal shear tests - stress/strain behaviour for three different ageing times
- Transverse and longitudinal compressive tests - stress/strain behaviour for three different ageing times

The ageing of the material was carried out through Humidity-Temperature cycling (HT cycling), according to the USCAR standard [9], where high humidity (95%) is accompanied a temperature of 90°C, which is above the glass transition temperature of PBT material (about 70°C). The tests showed the enormous influence of ageing on the mechanical properties of a PBT-GF20 composite. The main changes are:

- Decrease of Young modulus in longitudinal and increase in transverse fibre alignment in tension
- Loss of the viscoelastic properties after HT cycling
- Huge drop in tensile strength for both transverse and longitudinal direction in tension

- Reversal of the anisotropic properties of SFRPC – strain at break in tension
- Increase of the shear modulus and decrease of shear strength
- Decrease of shear strength properties and equalisation of properties for transverse and longitudinal fibre alignment
- Decrease of compressive stress at break and strain at break

The material model taking into account these phenomena was used to analyze the impact of ageing on the latch geometry after optimization. Simulations were performed for As Received (AR) material for the material after 40 HT cycles, each 8 hours long. The arrangement of the reinforcing fibres was defined independently for each finite element, and was imported, from the mould filling analysis done in the Moldflow software, in the form of local coordinate systems, where the first axis coincides with the direction of fibre alignment. Defined in such a way, the strengthening directions allowed the use of stress based failure criteria. A detailed description of calculation procedure and the material model can be found in an earlier authors paper [6]. In the simulations, the parametric model of latch with torsion beam were used (Fig. 1a). Dimensions a, b, and c were selected as the variables used in the subsequent optimization. The assembly process, during which the assembly force needed to close the latch and maximum principal stress were measured (Fig. 1b). Additionally, a simulation with the measurement of pull out force required for joint destruction was done.

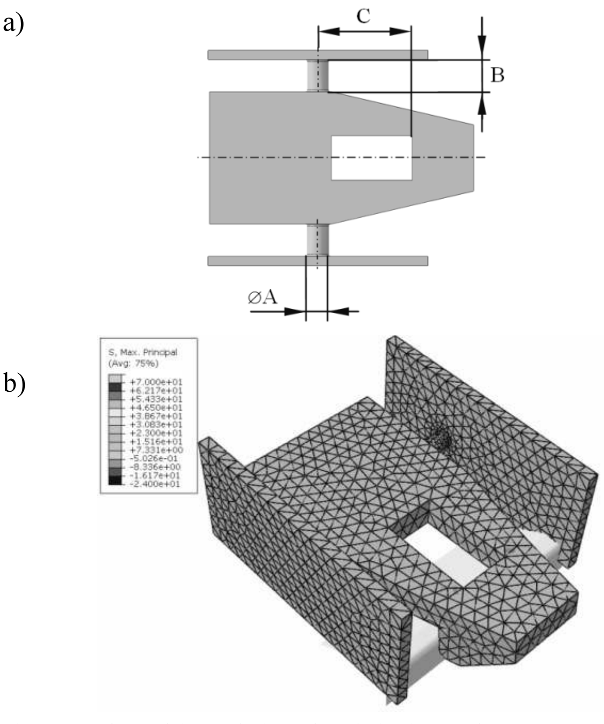

Fig. 1. Latch used in analysis and optimization study. Geometry and parameters used in optimization process (a), Maximum principal stress map during pull out force simulation (b)

Rys. 1. Zatrzask użyty do symulacji oraz optymalizacji. Geometria wraz z parametrami użytymi do optymalizacji (a), Maksymalne naprężenia w kierunku głównym w trakcie symulacji wyrywania (b)

DFSS OPTIMIZATION

To optimize and investigate the influence of material degradation in the product design, the Response Surface Method (RSM) was used. RSM is a type of optimization that applies an approximation technique to the objective and other functions of an optimization problem[10]. For approximation, it uses a function called a response surface. A response surface is a function (in ex. polynomial) that approximates a problem with design variables and state quantities, using several analysis or experiment results. In general DOE is used for analysis and the last square method is used for function approximation. In the present study, several analyses were done with variable parameters with bounds: A = 2 ± 0,3 [mm]; B = 3 ± 0,4 [mm]; C = 12 ± 2 [mm] for As Received (AR) and after 40 H-T cycling. For optimization, were used the following conditions: The maximum stresses in the principal direction: S_MAX - minimization with the upper limit of 80 MPa; the assembly force: RF_IN - minimization with the upper limit of 18 N, pull out force RF_OUT - maximizing with the lower limit of 100 N. Combining these results and analyzing an optimal solution can be found. As a result of DOE and RSM optimization, we can also get a set of relationships, between the various features of the model (such as forces and stresses) and the specific input parameters. This involves, for example, in determining how big is the impact of changes in the value of dimension A to destructive force, or to determine how a simultaneous change of pair of dimensions, will affect the final product properties. This is highly helpful because in addition to the optimal model, a set of indicators is obtained, which is highly helpful for design changes and designing new products with similar characteristics.

RESULTS AND DISCUSSION

As a result of a series of FE analysis, it was found that for AR samples, increasing A dimension, leads to stress increasing in the torsion beam. However, the increase in the dimensions of B and C is beneficial for reducing stress (Fig. 2). Analysis of the model with the material after ageing showed no statistically significant influence of AB and C on the stress values. This is due to the huge scattering of material properties after H-T ageing which is consistent with observations from laboratory studies.

Factors that have the greatest impact on the assembly forces, are A and C. The Influence of B in the studied range, on the value of the assembly force is negligibly small as seen in the Figure 3.

Along with the ageing time, a decrease in the pull out force, which will affect the final latch geometry, was observed. In the pull out test, the most important are the dimensions A and B. Here, the impact of factor C is negligible, which is consistent with intuition. Nonlinear plots visible in the Figure 4, results from a highly nonlinear material model used in the simulation.

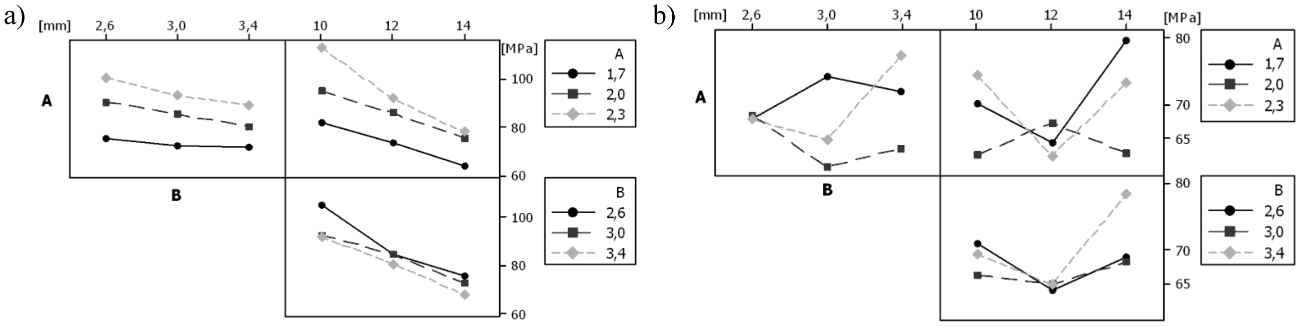

Fig. 2. Interaction plot for S_max for AR (a) and after ageing (b) material

Rys. 2. Wpływ wymiarów A B oraz C na naprężenia S_max dla materiału AR (a) oraz po starzeniu (b)

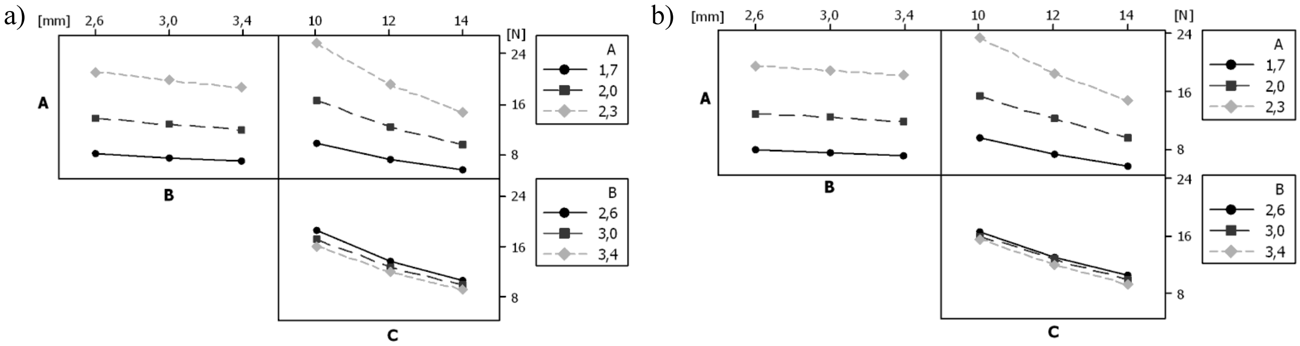

Fig. 3. Interaction plot for RF_IN for AR (a) and after ageing (b) material

Rys. 3. Wpływ wymiarów A B oraz C na siłę montażu RF_IN dla materiału AR (a) oraz po starzeniu (b)

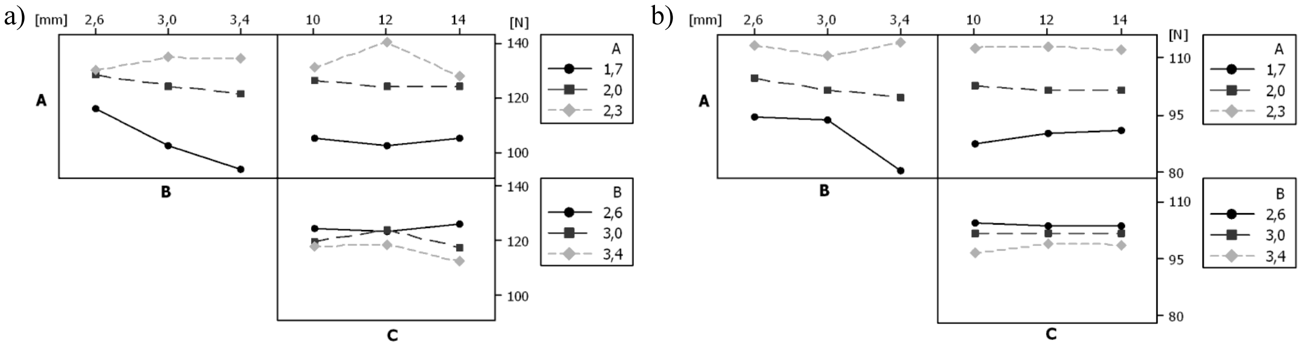

Fig. 4. Interaction plot for RF_OUT for AR (a) and after ageing (b) material

Rys. 4. Wpływ wymiarów A B oraz C na siłę wyrywania RF_OUT dla materiału AR (a) oraz po starzeniu (b)

Two optimizations of the latch were done. The first latch was made of composite material in AR state, while the other, of the material after ageing. Optimization results are shown in Figure 5. During the optimization the conditions described in the previous chapter were adopted, which in the case of the composite can AR have been met, as evidenced by the value of individual desirability (d) values are close to 1, which also implies a high rate of composite desirability (D) talking about the quality of the fulfilment of assumptions, with weights set for specific requirements. In this case the highest priority was set to stress value: S_MAX then pull out force RF_OUT and at the end of the assembly force RF_IN. In the case of material subjected to H-T cycling, it is evident that the established requirements may not be fully met (low value of individual desirability d), which resulted in the low value of composite desirability - D. From the decision of the constructor, and the possibility of design (in ex. the amount of space resulting from the packaging), depends on whether we will optimize the latch with the extended dimension limits, which could increase the value of D and ensure that the requirements will be met.

In the Figure 5 it is evident that for the material chosen in the state of AR (in the stated limits) the optimum dimensions are: A = 1.76 [mm], B = 2.6 [mm], C = = 13.72 [mm], which correspond to the output values RF_IN = 6.97 [N], RF_OUT = 119.55 [N] and S_MAX = 69.87 [MPa]. For the latch made of the material after ageing, the following dimensions were established: A = = 2.3 [mm], B = 3.08 [mm], C = 14 [mm], which correspond to the output values RF_IN = 14.6 [N], RF_OUT

= 112.42 [N] and S_MAX = 69.91 [MPa]. So we can see that the ageing time significantly influence the geometry of the structure and its operating properties.

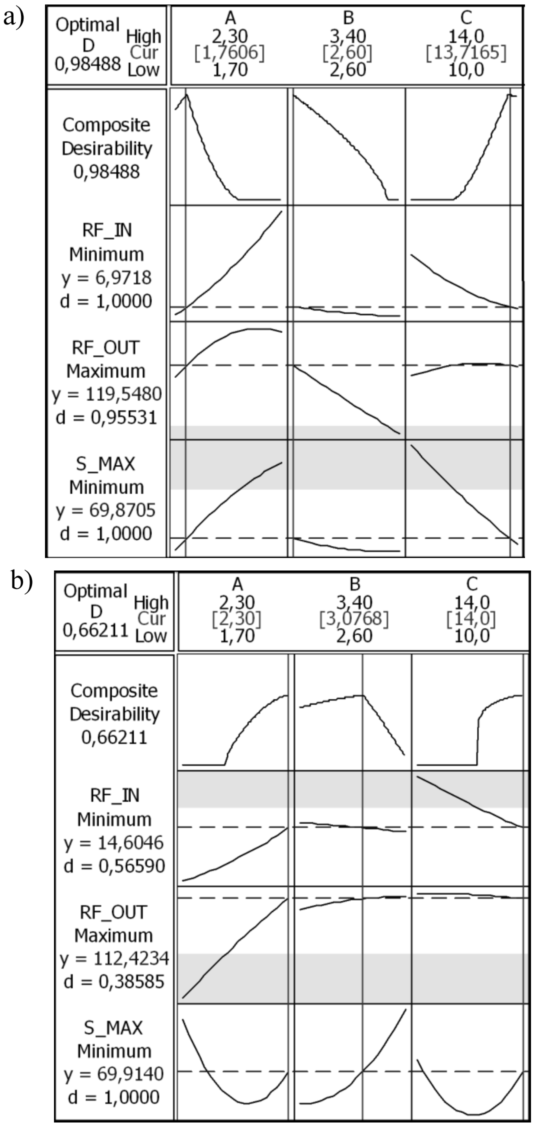

Fig. 5. Response Surface Method optimization results for AR (left) and after ageing (right) material

Rys. 5. Wynik optymalizacji Metodą Powierzchni Odpowiedzi dla materiału AR (lewa strona) oraz materiału po starzeniu (prawa strona)

These factors must be taken into account at the design stage of elements working in hazardous environments.

CONCLUSIONS

In the case of the construction of elements exposed to harmful environmental conditions, optimization of elements made of “fresh” AR materials is not a sufficient approach. It is also reasonable, analyzing and optimizing the part endurance for materials partially degraded. This requires time-consuming material strength testing and the establishment of appropriate material models - taking into account the ageing time. This approach not only shortens the design time, but also allows you to select the design, which apparently is not the best solution but after some operational time can be found as an optimal and the only one meeting the requirements, which can prevent costly modifications of moulding tools for SFRPC components.

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