ESTUDO DA INFLUÊNCIA DE INCLUSÕES ESFÉRICAS EM CARACTERÍSTICAS MECÂNICAS

STUDY OF THE INFLUENCE OF SPHERICAL INCLUSIONS ON MECHANICAL CHARACTERISTICS

ИССЛЕДОВАНИЕ ВЛИЯНИЯ СФЕРИЧЕСКИХ ВКЛЮЧЕНИЙ НА МЕХАНИЧЕСКИЕ ХАРАКТЕРИСТИКИ

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Received 12 June 2020; received in revised form 30 November 2020; accepted 14 December 2020

RESUMO

A relevância do artigo deve-se ao crescimento estável da indústria de compósitos. Devido às suas altas características físicas e mecânicas, os materiais compósitos (MC) desempenham um papel vital em muitas áreas da tecnologia, como indústria aeroespacial, aviação, indústria automotiva, engenharia e instrumentação e a indústria médica. Ao criar os materiais com as características mecânicas e térmicas necessárias, são frequentemente usados vários aditivos e enchimentos que afetam a resistência e a elasticidade das amostras obtidas. Neste artigo, estudamos o efeito de inclusões esféricas em resina epóxi nas propriedades mecânicas do material. Uma estrutura composta de resina epóxi ED-20 com inclusões na forma de partículas esféricas de vidro PBS-50 foi considerada. O tamanho característico das partículas foi de cerca de 50 µm. No âmbito deste estudo, foram produzidos lotes de amostras com o volume característico de inclusões de 5%, 10%, 15% e 20%. Cada lote consistia em 6 amostras do mesmo tipo. Para verificar a distribuição do volume de partículas e estudar as inclusões, a microestrutura da seção delgada da amostra e o pó foram estudadas separadamente. Usando métodos de modelagem do processo, as amostras foram submetidas ao teste de flexão de três pontos. Com base nos resultados de testes mecânicos, foram obtidos o módulo de elasticidade, a resistência à tração e as deformações finais. Como parte do estudo dos materiais, foram realizados os cálculos numéricos usando o software Digimat (MSC Software) para modelar a estrutura e obter propriedades efetivas do material. Também foram realizados os cálculos de tensões usando o método dos elementos finitos em Ansys Workbench. O cálculo foi realizado para o conteúdo volumétrico de inclusões da ordem de 5%, 10%, 15% e 20% e na ausência de inclusões. Os resultados numéricos obtidos foram comparados com o estudo experimental. Com base nos cálculos numéricos, foi obtida a dependência da porcentagem de inclusões na resistência à tração e no módulo de elasticidade.

Palavras-chave: material compósito, inclusão esférica, teste de flexão, proporção de volume, propriedades mecânicas.

ABSTRACT

The relevance of the article is due to the stable growth of the composite industry. Due to its high physical and mechanical characteristics, composite materials (CM) play a vital role in many areas of technology, such as aerospace, aviation, automotive, engineering and instrumentation, and the medical industry. When creating materials with the required mechanical and thermal characteristics, various additives and fillers are often used that affect the strength and elasticity of the samples obtained. In this paper, we study the influence of spherical inclusions in epoxy on the mechanical properties of the material. A composite structure of ED-20 epoxy with

inclusions in the form of spherical particles of PBS-50 glass was considered. The characteristic particle size was about 50 μm . Within the framework of this study, batches of samples with a specific volumetric inclusion content of 5%, 10%, 15%, and 20% were produced. Each batch consisted of 6 samples of the same type. To check the distribution of particle volume and inclusion studies, the microstructure of the thin section of the sample and separately the powder were studied. Using methods of modeling the process, the samples were tested for 3-point bending. Based on the results of mechanical tests, the elastic module, strength limit, and ultimate strains were obtained. As part of the study of materials, numerical calculations were performed using Digimat software (MSC Software) to model the structure and obtain effective material properties, as well as strength analysis using the finite element method in Ansys Workbench. The calculation was carried out for the volumetric content of inclusions of 5%, 10%, 15%, and 20% order and in the absence of inclusions. The obtained numerical results were compared with an experimental study. Based on the numerical calculations, the dependence of the percentage of inclusions on the strength limit and elastic module was obtained.

Keywords: *composite material, spherical inclusion, bend test, volume fraction, mechanical characteristics.*

АННОТАЦИЯ

Актуальность статьи обусловлена стабильным ростом композитной промышленности. Благодаря высоким физико-механическим характеристикам, композитные материалы (КМ) играют жизненно важную роль во многих областях техники, таких как аэрокосмическая, авиационная техника, автомобильная промышленность, машиностроение и приборостроение, медицинская отрасли. При создании материалов с требуемыми механическими и тепловыми характеристиками часто используются различные добавки и наполнители, влияющие на прочность и упругость полученных образцов. В данной работе исследуется влияние сферических включений в эпоксидной смоле на механические свойства материала. Рассматривалась композитная структура из эпоксидной смолы ЭД-20 с добавленными в нее включениями в виде сферических частиц стекла ПБС-50. Характерный размер частиц составлял порядка 50 мкм. В рамках данного исследования изготавливались партии образцов с характерным объемным содержанием включений равным 5%, 10%, 15% и 20%. Каждая партия состояла из 6 однотипных образцов. Для проверки распределения частиц по объему и исследования включения проводились исследования микроструктуры шлифа образца и отдельно порошка. Используя методы моделирования процесса, образцы испытывались на 3х точечный изгиб. По результатам механических испытаний были получены модуль упругости, предел прочности и предельные деформации. В рамках исследования материалов проводились численные расчеты с использованием программного обеспечения Digimat (MSC Software) для моделирования структуры и получения эффективных свойств материала, а также, проводился прочностной расчет с использованием метода конечных элементов в среде Ansys Workbench. Расчет проводился для объемного содержания включений порядка 5%, 10%, 15% и 20% и при отсутствии включений. Полученные численные результаты сравнивались с экспериментальным исследованием. На основании проведенных численных расчетов была получена зависимость процентного содержания включений от предела прочности и модуля упругости.

Ключевые слова: *композиционный материал, сферическое включение, испытание на изгиб, объемная доля, механические свойства.*

1. INTRODUCTION

The production and use of composite materials (CM) is growing steadily every year. Currently, CMs play a vital role in many areas of technology, such as aerospace, aeronautical engineering, automotive industry, mechanical engineering, and instrumentation, the medical industry and more (Yushkova *et al.*, 2010; Dmitriev *et al.*, 2011; Shershak, 2019; Yu Timkina *et al.*, 2019). The reasons for this rapid growth of the composite industry are low density of products, high physical and mechanical characteristics, resistance to corrosion and aggressive environments, as well as the ability to create

materials with the required mechanical and thermal characteristics (Lakes *et al.*, 2002; Orlov *et al.*, 2001; Jae-soon, 2012). One of the options for obtaining the necessary properties of materials is the use of various additives, for example, the addition of inclusions in the polymer matrix (Trofimov *et al.*, 2017; Wang *et al.*, 2019; Prentkovskis *et al.*, 2012).

The matrix (binding agent) is the most important element of the composite and determines the nature of the change in its properties when exposed to various factors (temperature, chemical resistance, electrical and other properties). A deeper understanding of the

interaction of inclusions and matrix, as well as the influence of the volumetric content of the included particles on the physical and mechanical characteristics, has emerged with the development of nanotechnologies. That is why the study of the mechanical characteristics of CM samples with various fillers and additives is an extremely urgent task (Tagliavia *et al.*, 2010; Tkachev *et al.*, 2018; Xinfeng *et al.*, 2018; Umbetov *et al.*, 2016). At the moment, there are many studies describing the use of inclusions to improve the physical and mechanical characteristics of composites (Odegard *et al.*, 2005; Sanchez-Soto *et al.*, 2007; Vettegren *et al.*, 2007; Song, 2009; Hurang *et al.*, 2010; Markus *et al.*, 2013; Seighalani *et al.*, 2015; Babaytsev *et al.*, 2017; Kenzhaev, 2019; Ryapukhin *et al.*, 2019; Formalev *et al.*, 2019; Jeyaprakash and Devaraju, 2020). However, the addition of particles is nonlinear and depends on many factors, such as the structure of the material from which the inclusions are made, the shape and size of the particles, as well as the volume fraction of inclusions (Markus *et al.*, 2013; Hnatiuk *et al.*, 2019; Jeyaprakash and Devaraju, 2019).

The aim of this work is to prepare and study the mechanical characteristics of glass dispersed and epoxy-filled composites. In this work, we consider the composite structure of the ED-20 epoxy, into which glass particles with a characteristic size of about 50 μm are added. In this paper, five different batches of samples are presented, depending on the volume fraction of inclusions. Each batch consisted of 6 samples of the same type. To check the distribution of particle volume and inclusion studies, the microstructure of the thin section of the sample and separately the powder was studied. Moreover, to study the influence of inclusions (spheres) on the mechanical characteristics of CMs, tests were carried out on samples with three-point bending. As part of the study, a numerical calculation was performed using Digimat MSC Software and Ansys Workbench (Odegard *et al.*, 2005; Lakes *et al.*, 2002; Hurang *et al.*, 2010; Yushkova *et al.*, 2010; Jae-soon, 2012; Xinfeng *et al.*, 2018; Shershak, 2019).

2. MATERIALS AND METHODS

In the study, samples of epoxy with inclusions and pure epoxy were studied. An ED-20 epoxy was used as a matrix, and PBS-50 glass spheres with a characteristic sphere size of about 50 μm were used as inclusions. The volumetric content of inclusions was 5%, 10%, 15% and 20%. The material for the samples in this study was

epoxy composites filled with spherical glass particles with a characteristic size of about 50 μm . The particle-filled polymer composites used in the experiments are batches of samples consisting of five types of volume fraction of the filler: 0%, 5%, 10%, 15%, and 20%. A diagram of the process of manufacturing samples is given in Figure 1. In the framework of this study, samples with a rectangular cross-section of 10 mm x 4 mm and a length of 80 mm were used. Quality control – visual inspection, mixing lasted for 25 minutes, vacuum with degassing was used, cooling took place within 3 hours.

To do this, a plate was made, and then samples were cut from it. For each batch of samples, six samples of the same type were produced. Photos of the studied samples are presented in Figure 2. To check the distribution of inclusions by volume, their percentage, as well as confirm the size of the inclusions, we studied the microstructure of the thin section of the sample and separately the powder. The results of microscopy are presented in Figure 3.

To determine the effect of inclusions on the mechanical characteristics of CM, bend tests were performed. The tests were carried out according to standard test procedures on an Instron 5969 universal testing machine with Bluehill software. For each tested batch, a stress-strain curve was constructed (Figure 4). As can be seen from the test results, the presence of inclusion significantly affects the CM mechanical characteristics.

3. RESULTS AND DISCUSSION:

For a more detailed study of the structure under study, a numerical calculation was performed. For this purpose, using the Digimat MF software, a structure with the exact use of matrix and inclusion properties, as well as the distribution of inclusions by volume, were preliminarily modeled. All materials were considered as isotropic linearly elastic materials for spherical inclusion and an epoxy polymer matrix and were presented in Table 1.

For each variant of the volumetric content of inclusions, a calculation and determination of the stress-strain curve of the structure under study were carried out. A representative elementary volume with a volume fraction of inclusions is shown in Figure 5. In a representative fragment, it was assumed that the contact between the particles and the matrix is perfect, there is no slip. The result obtained in the process of this calculation for each case under consideration is presented in Figure 6.

After obtaining the characteristics of the CM, a sample was created similar to the experimental sample in ANSYS Workbench. A three-point bending test process was simulated, where the boundary conditions for a rectangular plate were taken from the condition of free bearing on supports. Of course, the elemental model consisted of 16.469 nodes and 3.200 elements, with an element size of ~ 1 mm (Figure 7a). An example of a strain-stress state of the epoxy plate without inclusion is shown in the figure (Figure 7b).

Thus, based on the numerical calculations, the dependence of the percentage of inclusions on the strength limit and elastic module was obtained. The numerical results obtained are in good agreement with experimental results, which makes it possible to select such a volumetric content of inclusions in order to obtain the necessary physical and mechanical characteristics of the CM. However, in such CMs with a sufficiently large number of inclusions, these particles become stress concentrates and significantly reduce the strength limit and ultimate strains.

The tests performed showed a significant effect of the presence of inclusions of more than 15% on the strength limit and ultimate strain. As part of this study, a numerical analysis of the tested structure was performed using Digimat and Ansys. The results of numerical simulation are in good agreement with the experimental results until the inclusion is equal to 10%. In addition, with an increase in the volumetric content of inclusions, the divergence of the numerical and experimental results begins. This is most likely due to the condition of contact between the inclusions and the matrix and with possible internal defects.

4. CONCLUSIONS:

The mechanical characteristics of glass dispersed and epoxy-filled composites, samples with various inclusions were manufactured. Microscopy and mechanical testing of samples were carried out. Structural studies confirmed the size of the inclusions and their distribution over the sample volume. Based on the results of mechanical tests, the elastic module, strength limit, and ultimate strains were obtained. The tests performed showed a significant influence of the presence of inclusions of more than 15% on the strength limit and ultimate strain. The results of numerical modeling are in good agreement with the experimental results, and with an increase in the volumetric content of inclusions, the divergence of the numerical and experimental

results begins. This is due to the condition of contact between the inclusions and the matrix and with possible internal defects, and therefore requires additional research and more accurate modeling.

5. ACKNOWLEDGMENTS:

The work was carried out with the financial support of the state project of the Ministry of Education and Science on the subject "Theoretical and experimental research in the field of production and processing of promising metal and composite materials based on aluminum and titanium alloys", project code FSFF-2020-0017.

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Table 1. Physical and mechanical characteristics of materials

Characteristics	Unit of measurement	ED-20 epoxy	PBS-50 glass spheres
Young's of elasticity, E	hPa	4.9	7.0
Poisson number, ν	-	0.3	0.2
Density, ρ	kg/m ³	1.25	2200
Heat conductivity factor	W/m.K	0.92	1.15
Bulk modulus	hPa	4.08	3.88
Shear coefficient	hPa	1.88	2.91

Figure 1. The technological scheme of manufacturing a composite

Figure 2. Photographs of test samples from each batch (top-down sample from a batch with inclusions of 15%, 10%, 5%, and pure epoxy)

Figure 3. Microscopy results

Figure 4. Graph of stress-strain curves

Figure 5. Representative elementary volume with a volume fraction of inclusions

Figure 6. Linear stress – strains with the different volume fraction of inclusion obtained using Digimat MF software

Figure 7. Stress-strain state of a finite element model when modeling a bending test