Influence of the inclusion shape on the effective elastic properties of composites

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Abstract. The elastic properties of composites are mainly determined by the characteristics of reinforcing inclusions. This work addresses the dependence of the elastic properties of inclusion-reinforced composites on the inclusion shape. Specifically, ball-shaped, spherical and cubic inclusions are considered.

1. Introduction

Currently, composite materials are widely used in the technology and science. This can be explained by their unique properties, specifically, their ability to withstand simultaneous high-intensity mechanical, physical and thermal loads, while having smaller specific weight as compared to pure metals. In view of this, these materials are of particular importance in the aerospace industry [1].

In aircraft engineering there is a tendency to apply increasingly the carbon-ceramic composites (CMCM). An important feature of this class of composites is a combined matrix composed of a carbon base and inclusions of individual particles that can form one or more ceramic-nature substances. These ceramic inclusions enhance the erosion/oxidation resistance of the composite, while influencing its physical and mechanical properties. In the CMCM fabrication process, as well as during design, development and operation of CMCM-based structures, the influence of these inclusions on the carbon matrix characteristics should be taken into account, particularly, the elastic behavior as being the subject addressed in this paper. For the composite matrix, solution of this problem represents micro-level modeling in terms of building a three-level model of the composite [2].

One of the most widely used and mature methods to introduce ceramic inclusions in a material is the liquid-phase siliconizing that involves formation of particles composed of silicon and silicon carbide. The inclusion shape depends on the specificity of the porousness pattern of the initial carbon-carbon piece, as well as on the siliconizing process mode. Therefore, the inclusion shape can vary widely even for the same material. Thus to build a micro-level model that provides correct representation of the material matrix behavior, it is necessary to investigate the degree and nature of the inclusion shape influence on the matrix effective properties.

There is a number of papers focused on the analytical approaches to investigation of the CMCM elastic behavior on the micro-scale level [3-9]. The advantages of these approaches are the simplicity of relationships and the minimum requirements to the computing capacity. However, these methods have a number of shortcomings, which makes them inapplicable for solving the problem stated above.
The analytical methods are based on assumptions that are often unrealistic for the actual material; moreover, most of these methods don’t take into account the shape of the inclusions. Therefore, this paper focuses on the use of the finite-element method (FEM) implemented using the ANSYS software to investigate the inclusion shape influence on the inclusion-reinforced matrix elastic behavior.

2. Problem definition

As the target of our investigation, we take the 4DL-reinforced ceramic matrix carbon material [7]. As can be seen in Figure 1, the matrix inclusions have various shapes and dimensions. When designing a composite, it is impossible to consider the actual arrangement of the ceramic inclusions in the material; therefore, to simulate the combined matrix behavior, we consider some typical shapes of ceramic inclusions that can be found in the actual composite. For example, the simplest type is a ball-shaped inclusion that consists of silicon carbide (type I) or, mainly, of pure silicon (type II). However, given the specific form of the material’s reinforcing element cross section and the reinforcement pattern, the ceramic inclusions are often polygon-shaped, which can be simulated by a cubic form (type III) when making computations. Since in the carbon matrix, formation of silicon carbide takes place mainly on the surface of the pores that may be inaccessible during the saturation process until the moment of complete saturation, there are also thin-wall shell-shaped inclusions in the composite that can be simulated as a full (type IV) or fragmented (type V) sphere.

![Figure 1. Types of inclusions in the composite material.](image)
to provide their uniform strain states as per [8]. Note that for the problem in this formulation, these volumes are representative in terms of [9] where tension of volumes along three orthogonally-related axes, as well as shear in the planes of supposed orthotropic properties, are considered. The 3D elastic problems were solved by the finite element method in the ANSYS software environment. To determine the effective elastic properties of the combined matrix, the approach described in [10] was applied. The elastic properties of the inclusion materials corresponded to the data given in [11], while those of the matrix – to the results described in [12].

3. Results

Dependencies of effective elasticity modulus $E$ and shear modulus $G$ on conditional reinforcement ratio $\mu$ for the combined matrix with inclusions of different types are shown in Figures 2 and 3, correspondingly.

![Figure 2. The inclusion-reinforced matrix elasticity modulus vs. the inclusion type/volume fraction.](image1)

![Figure 3. The inclusion-reinforced matrix shear modulus vs. the inclusion type/volume fraction.](image2)

Here and elsewhere, the dash-dot single-point curves correspond to the results obtained for the fragmented SiC sphere, while the dash-dot double-point curves – to those obtained for the SiC sphere, the dotted ones – to those obtained for the Si ball, the solid ones – to those obtained for the SiC ball, and the dashed ones – to those obtained for the SiC cube.

From the curves shown above it can be seen that the influence of the solid ceramic inclusion does not exceed 10%, which is negligibly small within the reasonable design calculation accuracy. Even less is the difference between the results obtained for the matrix with silicon carbide inclusions and that with pure silicon ones, which can be explained by the fact that both types of inclusions have stiffness two orders of magnitude higher than that of the carbon matrix. The hollow inclusions (type IV and V) have less influence on the matrix properties; however, it is still large enough to be taken into account when estimating the composite characteristics. The fragmented structure of the spherical inclusion reduces considerably the apparent stiffness of the matrix.

The value of Poisson’s ratio $\nu$ of the matrix depends only slightly on the presence of inclusions of types IV and V, while the presence of solid ceramic inclusions results in a considerable reduction of this parameter, which can be seen in Figure 4.
Figure 4. Poisson’s ratio of the reinforced matrix vs. the inclusion type/volume factor.

Generally, the degree of inclusion influence on the composite’s elastic properties was estimated by the relative change in the effective elasticity moduli along X and Y axes and the shear modulus in XZ plane, given the conditional reinforcement ratio of 35%. For the estimation, the 4DL-reinforced elastic model described in [13] was used. The estimation results are shown in Figure 5. It can be seen from the results that the influence of ceramic inclusions in the composite’s elasticity moduli along the reinforcement direction does not exceed 10%, while that on the shear modulus can range to one-and-a-half times, depending significantly on the inclusion type. Consequently, the presence and the shape of ceramic inclusions should be taken into account when making design calculations for the composite elastic properties.

Figure 5. Relative change in the composite effective elastic properties resulting from inclusions in the matrix of the reinforcement factor of 0.35.

As the matrix reinforcement pattern in the composite involves cubic packing of inclusions, it seems reasonable to determine the degree of anisotropy in the resulting matrix material, which is obviously the case, given the random arrangement of ceramic inclusions in the matrix at its larger scales. As the anisotropy measure, relative deviation of the apparent shear modulus value from that obtained by the following well-known formula [14] is taken:

\[
\text{Relative deviation} = \frac{G_{app} - G_{calc}}{G_{calc}} \times 100\%.
\]
\[ G = \frac{E}{2(1+\nu)} \]  \hspace{2cm} (1)

Analysis of the results showed that the larger the conditional reinforcement factor, the greater the deviation from isotropy, with its considerable values of 15-25% obtained for inclusion types I, II and III, while in case of hollow inclusions, this effect is negligibly small. This fact should be taken into account when modeling the characteristics of materials reinforced by discrete randomly-arranged inclusions, as the design case of the symmetry of properties is quite different from that expected in the actual materials. To balance out the effect of inclusion arrangement, stochastic models of materials can be used, as well as larger representative volumes containing multiple randomly-arranged different-type inclusions can be considered. The latter option would make it possible to take into account the presence of ceramic inclusions of various dimensions and configurations in the actual materials.

4. Conclusion

From the results obtained, the following conclusions were derived. Ceramic inclusions of different shapes and dimensions have a considerable impact on the elastic properties of the combined carbon-based matrix, depending on the inclusion type. Introduction of ceramic inclusions in the matrix influences considerably some elastic properties of the composite.

When considering the cubic packing of inclusions, the modeling predicts disturbance of isotropy of the matrix elastic properties, which can be avoided in practice through random arrangement and orientation of ceramic particles. This fact should be taken into account when predicting performance of composite materials under development.

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References

[1] Biksha J 2014 Bulletin of Electronics 1 24–7
[2] Tatarnikov O V 2012 All materials. Encyclopaedic Guide 7 21–6
[3] Shermegor T D 1977 Theory of elasticity for micro-heterogeneous media (Moscow: Nauka). p 400
[4] Hashin Z and Strikman S J. 1962 Mech. Phys. Solids 10 335–43
[5] Eshelby J 1963 Continuous dislocation theory (Moscow: IL) p 248
[6] Skudra A M and Bulavs F Ya 1978 Structural theory of reinforced plastics (Riga: Zinatne) p 192
[7] Tarnopolsky Yu M, Zhigun I G and Polyakov V A 1987 Spatially reinforced composite materials (Moscow: Mashinostroyeniye) p 224
[8] Pobedrya B E 1984 Mechanics of composite materials (Moscow: Publishing House of Moscow State University) p 336
[9] Hashin Z 1962 J. Appl. Mech. 29 pp 143–50
[10] Zarubin V S and Sergeeva E S 2018 Mathematical Models and Computer Simulations 10 pp 288–98
[11] Grigoryev I S and Meylikhov E Z 1991 Physical values (Moscow: Energoatomizdat) p 1232
[12] Vagin V P, Dvoretsky A E, Magnitsky I V et al 2015 Non-destructive testing of composite materials: Collected papers of the 1st distant scientific and technical conference NKKM-2014 (St. Petersburg: Sven) p 228.
[13] Magnitsky I V 2013 New technology In: Proceedings of the Xth All-Russian Conference 2 (M.: RAS) 21–32.
[14] Zarubin V S, Kuvyrkin G N 2008 *Mathematical Models in Continuum Mechanics and Electrodynamics* (Moscow: The Bauman University Publishing House) p 512.