Materials Science-Poland, Vol. 23, No. 2, 2005

Finite element modelling of the residual stresses in the ceramic-elastomer composites

ANNA BOCZKOWSKA[1*], KATARZYNA KONOPKA[1], KAMIL BABSKI[1], GRZEGORZ KRZESIŃSKI[2], KRZYSZTOF J. KURZYDŁOWSKI[1]

[1]Warsaw University of Technology, Faculty of Materials Science and Engineering, Woloska 141, 02-507 Warsaw, Poland

[2]Warsaw University of Technology, Institute of Aeronautics and Applied Mechanics, Nowowiejska 24, 00-665 Warsaw, Poland

Ceramic-elastomer composites are obtained by the infiltration of porous ceramics by an elastomer prior to the curing reaction at elevated temperatures. Because the elastomer and the ceramic have different expansion coefficients thermal stresses are generated during cooling to ambient temperature. In addition the elastomer contracts as it transforms from a mixture of the substrates in the liquid state to the solid state polymer with a covalently bonded network structure. These two phenomena result in the development of residual stresses in the composite. Residual stresses are of significant concern because they can cause damage in the form of cracks in the ceramic and delamination between the ceramic and the elastomer. They can also have an effect on the mechanical properties of the composite. The aim was to model in 3D space the residual stresses in the composites with two different interpenetrating phases. The Finite Element Method (FEM) was used to calculate the stresses

Key words: *ceramic-elastomer composites; residual stresses; Finite Element Method; infiltration*

1. Introduction

Ceramic-elastomer composites are obtained by infiltrating porous ceramics with urea-urethane elastomers [1]. As a result composites of two interpenetrating phases are obtained [2, 3]. They possess hardness and stiffness of ceramics with the rubbery entropy-elasticity of elastomers. Such composites are distinguished by high compression strength and the ability to achieve large deformations [4–6] as well as the ability to absorb impact energy.

[*]Corresponding author, e-mail: abocz@meil.pw.edu.pl

The infiltration of the ceramic with the elastomer is made before it undergoes its curing reaction. The elastomer is synthesized by a one-shot method. The liquid mixture of the substrates is incorporated into ceramics pores using vacuum pressure at a temperature of 120 °C. Then the addition reaction is conducted at this temperature [7, 8]. Because the thermal expansions of the elastomer and ceramics are different, cooling to ambient temperature results in the buildup of residual stresses in the composite. Additional residual stresses arise due to the elastomer's shrinkage as a consequence of the transformation from the liquid mixture of the substrates to the solid state polymer with a covalently bonded network structure. The adhesion between SiO_2 ceramics and urea-urethane elastomer is fairly good and could be improved by the addition of coupling agents. Good adhesion between the components of the composite is very important from the mechanical point of view [9–11].

The residual stresses developed in the composite by the thermomechanical mismatch between the ceramic and the elastomer during cooling from the fabrication temperature are of significant concern because they can cause damage in the form of ceramics cracks and delaminations between the ceramic and the elastomer as well as affect mechanical properties of the composite [12, 13].

The aim of the studies was to develop a 3D numerical model describing the residual stresses in composites with two different interpenetrating phases. The residual stresses were calculated using the Finite Element Method (FEM). Scanning Electron Microscopy (SEM) was used to determine the microstructure and stereological methods for its quantitative analysis [14].

2. Experimental

Cylindrical porous SiO_2 samples of the diameter of 20 mm and 20 mm high were obtained. The average open porosity measured by the Archimedes method was 40%. The average pore size measured using the mercury porosimeter was 145 μm. The average apparent density of the samples was 1.43 g/cm^3.

Cast segmented polynitrile-urea-urethane elastomer (PNUU) with linear macromolecules structure was used for the infiltration of the SiO_2. It was obtained from 4,4′-diphenylmethane diisocyanate (MDI), ethylene oligoadipate (OAE) and dicyandiamide (DCDA). The PNUU elastomer was synthesized by a one-shot method. Subsequently, the mixture was cast into special moulds with the porous ceramic samples inside and heated to 120 °C. Next the infiltration process was carried out [1]. The elastomer was cured for 10–14 hours at 120 °C. The samples were then cooled to room temperature and conditioned for two weeks.

Observations of the microstructure of the composites were carried out using a scanning electron microscope (SEM) HITACHI S-3500N, equipped with a low -vacuum mode. Quantitative analysis of the microstructure of the composites was carried out using the stereological methods [14]. MicroMeter software was used to

estimate the following parameters: volume fraction of elastomeric phase (V_V) and specific surface of the boundaries of elastomer (S_V). FEM analysis was conducted using the ANSYS software, version 6.1.

3. Results and discussion

Observations of the microstructure of ceramic-elastomer composite were carried out using a scanning electron microcsope. A typical image of the microstructure and its binary form are shown in Fig. 1.

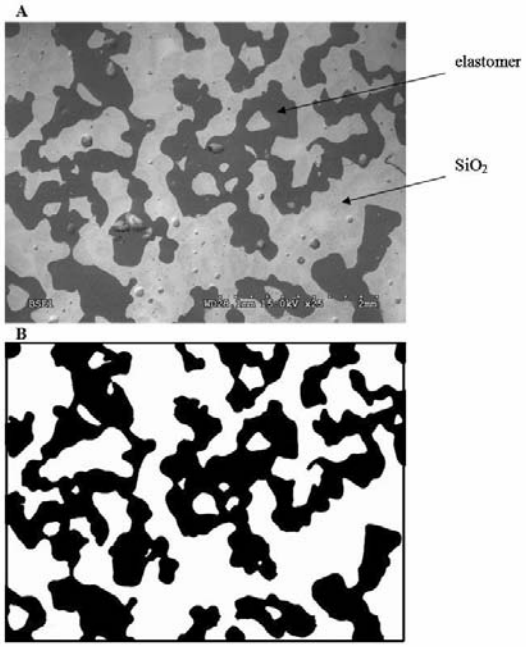

Fig. 1. SEM image of the ceramic-elastomer microstructure (A) and its binary form (B)

It can be seen that the elastomer has infiltrated into the pores of ceramic matrix. Quantitative analysis of the composite's microstructure was carried out to estimate the volume fraction of the elastomeric phase and the specific surface of the boundaries of the elastomer, using stereological methods. The results are shown in Table 1.

Table 1. Results of stereological analysis of ceramic-elastomer composite microstructure

Sample	V_V	S_V [mm^{-1}]
III 29	0.40	3.92
III 37	0.40	4.38
III 41	0.32	3.94
III 33	0.38	4.41

Materials data for the PNUU elastomer and SiO_2 ceramics which were used for the residual stress calculations, are given in table 2. It can be seen that the ceramics and elastomer possess significantly different stiffness and thermal expansion characteristics.

Table 2. Selected properties of PNUU and SiO_2

Properties	PNUU	SiO_2
Elastic modulus, MPa	27	47000
Poissons ratio	0.23	0.49
Thermal expansion coefficient, 1/K	2.1×10^{-4}	0.5×10^{-6}

3-D unit cell Finite Element Models were developed for the ceramic-elastomer composite material. It was assumed that the microstructure presented in Fig. 1 could be described as a composite consisting of a ceramic matrix filled with elastomer particles. The representative unit cell, shown in Fig. 2, is hexahedral and includes the elastomer particles in three corners.

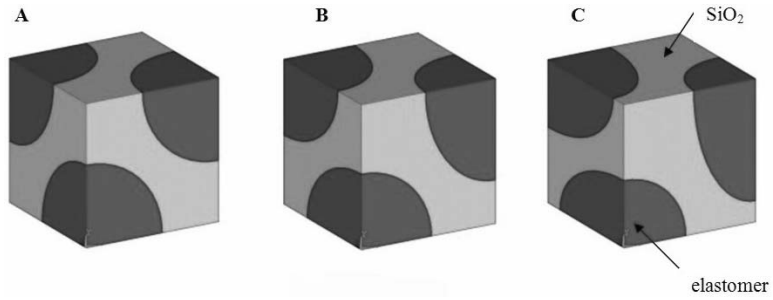

Fig. 2. The 3-D representative unit cell FE models of ceramic-elastomer microstructure: A) model 1, B) model 2, C) model 3

Figure 2 shows that the shape of the particles changes from spherical to ellipsoidal, but the volume fraction of elastomeric phase is constant at 0.40. 3D FE models were chosen for their advantages over axisymmetric and two-dimensional versions. It was assumed that all the particles in each model have the same dimensions and orientation and are uniformly distributed. The ceramic and elastomer are isotropic in stiffness and thermal expansion. Perfect bonding between the ceramic and the elastomer was also assumed. The temperature in the composite was assumed to be homogeneous at all times.

The unit cells were subjected to a thermal load simulating the cooling from the fabrication (120 °C) to room temperature (20 °C). The distributions of principal stresses in the dual phase composite material, obtained by infiltration of the porous skeleton, calculated for each assumed model with the ANSYS 6.1 software, are shown in Figs. 3 and 4.

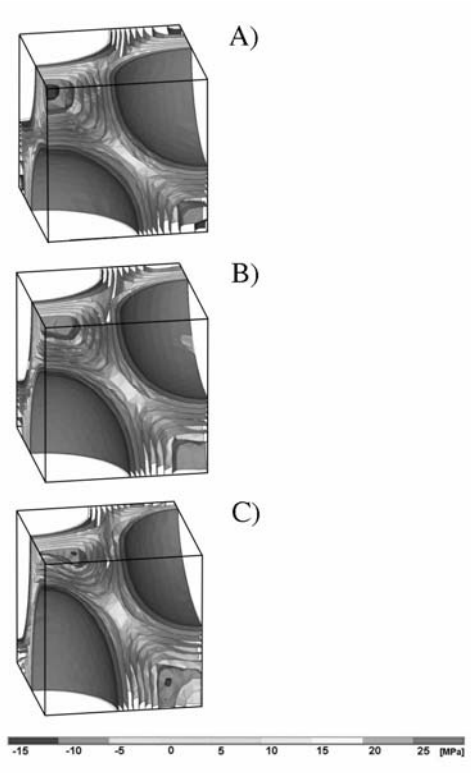

Fig. 3. The maximum principal stresses distribution σ_1 in: A) model 1, B) model 2, C) model 3

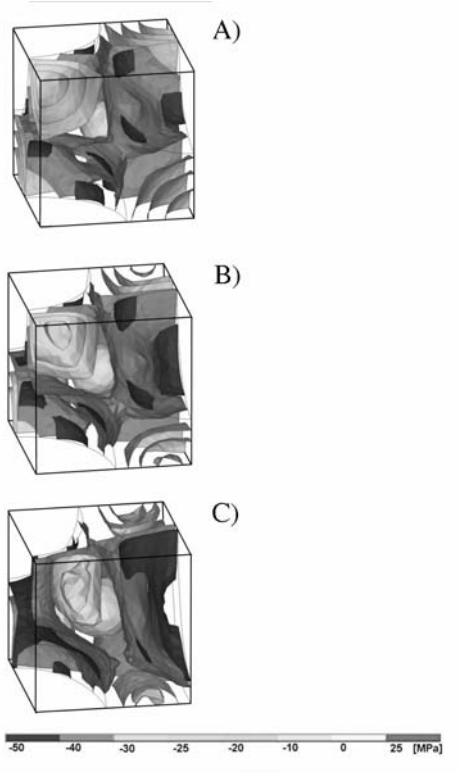

Fig. 4. The minimum principal stresses distribution σ_3 in: A) model 1, B) model 2, C) model 3

4. Conclusions

Residual stresses are often induced in composite materials when they cool from the fabrication temperature to room temperature. This is mainly due to the difference in the coefficients of thermal expansion of the components. The induced stresses were studied using a fully three-dimensional termomechanical model for ceramic-elastomer composites obtained by infiltration of porous ceramics by an elastomer. It was found that elastomeric phase is characterized by an almost uniform tensile stresses. The maximum principal stress distribution σ_1 is weakly dependent on the shape of the elastomeric particles and is more uniform than the minimum principal stresses distribution σ_3. The σ_3 values in the ceramics are mainly compressive. The change of the shape of elastomeric particles from spherical to ellipsoidal leads to a growth of compressive stresses in tangential directions in the ceramic phase which is mechanically advantageous. However, these stresses could also cause debonding between the ceramic and elastomer phases. Further analysis of the results and their interpretation for understanding the mechanical properties of the composites are in progress.

Acknowledgements

The authors thank Professor M. Szafran from Warsaw University of Technology, Faculty of Chemistry for cooperation in the area of porous SiO_2 ceramics. This work was supported by the Polish State Committee for Scientific Research (KBN), Grant No. 3 T08E 00926.

References

[1] SZAFRAN M., BOCZKOWSKA A., KONOPKA K., KURZYDŁOWSKI K., ROKICKI G., BATORSKI K., PL patent No. P.353130 (2002).
[2] KONOPKA K., BOCZKOWSKA A., BATORSKI K., SZAFRAN M., KURZYDŁOWSKI K.J., Mater. Lett., 58 (2004), 3857.
[3] KONOPKA K., BOCZKOWSKA A., SZAFRAN M., KURZYDŁOWSKI K.J., Kompozyty, 7 (2003), 216.
[4] KONOPKA K., BOCZKOWSKA A., BATORSKI K., KURZYDŁOWSKI K.J., SZAFRAN M., Kompozyty, 3 (2002), 108.
[5] BOCZKOWSKA A., KONOPKA K., KURZYDŁOWSKI K.J., 12th Achievements in Mechanical & Materials Engineering, AMME 2003, Zakopane, Conference Proceedings, p. 111.
[6] KONOPKA K., BOCZKOWSKA A., SZAFRAN M., KURZYDŁOWSKI K.J., European Congress and Exhibition on Advanced Materials and Processes Euromat 2003, Lozanna.
[7] PL Patent 148 671 (1990).
[8] PL Patent 150 154 (1991).
[9] BOCZKOWSKA A., KAPUŚCIŃSKI J., LINDEMANN Z., WITEMBERG-PERZYK D., WOJCIECHOWSKI S., *Kompozyty*, II Ed., Oficyna Wydawnicza PW, Warszawa, 2003.
[10] BOCZKOWSKA A., KONOPKA K., KURZYDŁOWSKI K.J., Materiały polimerowe Pomerania-Plast, 2004, Szczecin, Conference Proceedings, 65.
[11] BOCZKOWSKA A., KONOPKA K., SCHMIDT J., KURZYDŁOWSKI K.J., Kompozyty, 9 (2004), 41.
[12] GOLAŃSKI D., Kompozyty, 2 (2002), 5.
[13] CHOO H., BOURKE M.A.M., *Evolution of thermal residual stress in intermetallic matrix composites during heating*; Ceramic Engineering and Science Proc. ACerS, 21 (2000), 627.
[14] KURZYDŁOWSKI K.J., RALPH B., *Quantitative Description of Microstructure of Materials*, CRC Press, Boca Raton, FL, 1995

Received 6 September 2004
Revised 8 October 2004