JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 18 No 3, 03005(5pp) (2026)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 18 № 3, 03005(5cc) (2026)

REGULAR ARTICLE

A Numerical Study of the Elastic Mechanical Properties of Al/SiC Metal Matrix Composite

S. Chouarfia[1,*], L. Sedira[1], K. Meftah[2], W. Kaddouri[2], M. Chitour[3], K. Mansouri[3,4,†]

[1] *Laboratory of Engineering Mechanics LGM, University of Biskra 07000, Algeria*
[2] *Structural Mechanics and Materials Laboratory, University of Batna 2, Algeria*
[3] *University Abbes Laghrour, Mechanical Engineering Department, 40000 Khenchela, Algeria*
[4] *Laboratory of Engineering and Sciences of Advanced Materials (ISMA), Khenchela, 40000 Algeria*

(Received 15 February 2026; revised manuscript received 20 June 2026; published online 26 June 2026)

The traditional analytical homogenization technique, which has been refined over the past century, seeks to elucidate the behavior of heterogeneous materials at a macroscopic level. Numerous factors impact the composite, including the types, sizes, positions, and shapes of the reinforcing materials. The morphology of particles has garnered significant attention in the field of particulate composites; smaller particles exhibit a strong adhesion to the matrix, resulting in a pronounced reinforcing effect. This research examines the elastic properties of 6061 aluminum alloy reinforced with SiC particles. The microstructures are discretized using 4-node quadrilateral membrane finite elements (PFR4M) based on the Plane Fiber Rotation (PFR) formulation. Virtual microstructure images were used to assess the elastic characteristics under unidirectional tensile loading. A parametric study was conducted to investigate the impact of microstructural factors, including particle orientation and shape (square, circular, rhombic, and ellipsoidal). Finally, the validation of the numerical homogenization results was carried out by comparing them with the Voigt–Reuss (VR) bounds and available experimental data, showing good agreement and confirming the reliability of the adopted numerical approach.

Keywords: Particle shape, Particle size, Finite element analysis, Al-SiC, RVE.

DOI: 10.21272/jnep.18(3).03005 PACS number: 81.70. − q

1. INTRODUCTION

The exceptional mechanical properties of heterogeneous materials have resulted in the development of many techniques for their mechanical characterization. The conventional analytical homogenization method, developed over the last century, aims to clarify the behavior of heterogeneous materials on a macroscopic scale. The Voigt and Reuss bounds [1, 2] and the Hashin–Shtrikman bounds [3] are two well-known examples. One big problem with analytical models is that they cannot consider how the shape of particles affects how materials behave mechanically [4]. The finite element method (FEM), on the other hand, has been quite effective at predicting how composites will respond. Homogenization models were among the most important. The Mori–Tanaka (MT) model [5] and other semi-analytical or mean-field homogenization models were among the earliest methods created for linear elasticity. Eshelby's solutions [6], which explain the stress field inside and around ellipsoidal inclusions, provide the basis for these models. Nevertheless, the majority of micromechanical analytical models do not adequately account for the effects of phase morphology and the precise spatial configuration of phases inside the structure.

Recently, stimulated by the progression in computational tools, numerical multiscale strategies have emerged as a powerful tool to research the mechanical behavior of the composites and evaluate their effective properties.

In recent decades, much research has investigated the impact of microstructural factors on the mechanical properties of composites with the finite element method (FEM). For instance, the effect of particle size, shape, and content on the properties of Al 6061/SiC composites was investigated by Paknia *et al.* [7], they found that the tensile characteristics of the MMCs were significantly impacted by particle form, especially at 20% volume percentage. Utilizing FEM to study glass-particle-reinforced composites, Mansouri *et al.*, [8] demonstrated that the mechanical response of thermoplastic matrix composites is influenced by both particle dispersion and shape. Accordingly, Khadraoui *et al.* [9] examined glass-particle-reinforced nylon matrix composites, emphasizing the influence of particle size and shape on their mechanical properties. In their study of square and circular particles in Al–SiC composites, Rivera-Salinas *et al.* [10] focused on the impact of volume fraction and porosity on Young's modulus. Qin et al. [11] investigated how the effect of the shape of silicon carbide (SiC) particles affects the toughness of aluminum composites. Five model composites with spherical, hexagon, square, triangle, and shuttle-shaped particles were used for FEM analyses. Who found that particle shape significantly influences strain fields and residual stresses.

The impact of particle orientation on the thermo-mechanical characteristics of Al 2080/SiC composites

* Correspondence e-mail: samir.chouarfia@univ-biskra.dz
† mansouri.khelifa@univ-khenchela.dz

Cite this article as: S. Chouarfia, et al., *J. Nano- Electron. Phys.* 18 No 3, 03005 (2026) https://doi.org/10.21272/jnep.18(3).03005

was examined by Hua *et al.* [12] using the Finite Element Method, they showed that the longitudinal elastic modulus in unidirectional alignment was greater than that of random 2D and random 3D orientations. Additionally, Kari *et al.* [13] noted that when compared to RDSF composites, TRSSF composites showed a greater longitudinal elastic modulus.

In this work, the multiphase element approach (MPFE) is applied to predict the mechanical behavior of 6061 aluminum (Al) reinforced with silicon carbide (SiC) particles. The multiphase element method has been the subject of numerous studies [14-17]. The objective of the present study is to investigate the influence of particle orientation and shape on the elastic properties of Al/SiC composites.

To this end, a four-node element, PFR4M, with rotational degrees of freedom, is introduced to predict the elastic response. Various microstructures with different particle shapes and volume fractions ranging from 10 % to 40% are generated. The numerical predictions of the elastic modulus are then compared with available experimental data.

2. METHODS AND MATERIALS

The micromechanical homogenization analysis is performed on metal matrix composites (MMCs), including an aluminum 6061 matrix supplemented with silicon carbide particles. The representative volume element (RVE) measures 50 × 50. The Young's modulus and Poisson's ratio of the matrix and those of the reinforcement are detailed in Table 1.

Table 1 – Matrix and reinforcement properties

Matrix(Al)		Reinforcement(SiC)	
E_m (GPa)	ν_m	E_p (GPa)	ν_p
73.9	0.33	410	0.14

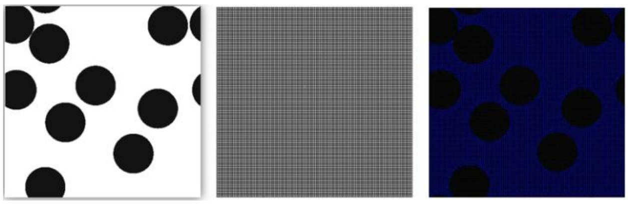
2.1 Finite Element Meshing

After generating the microstructure, a corresponding mesh is constructed. In this study, the Multiphase Element Method (MPFE), initially developed by Lippmann [18], is applied to virtual images of the microstructure. The representative element volume (RVE) of the microstructurein this study is obtained using image processing techniques with Paint Shop Pro 9 software Fig. 1-a. The mechanical behavior at each Gauss point is determined based on the assigned color, where white corresponds to the matrix and black to the particles.

Fig. 1 illustrates the principle of this technique. The finite element grid, implemented using the Zebulon code (Fig. 1b), is superimposed on the virtual microstructure image (Fig. 1a).

The generated meshed microstructure Fig. 1c was used to assign the corresponding phase properties to each integration point of the regular grid, based on the color of the underlying pixels. Several authors have widely used this method for meshing real and virtual images of microstructures with different elements. However, the mesh quality and finite element order closely influence the accuracy of finite element computations. [13].

In the case of linear elasticity, Chouarfia *et al.* [14] utilized the 4-node linear element C2d4, the 8-node quadratic element C2d8, and the PFR4M element for the elastic analysis of date palm fiber-reinforced PVC composite. EL Moumen *et al.* [19] used a mesh of 3D microstructure with quadratic 20-node elements and 27 integration points. In the plasticity domain, Benhizia *et al.* [20] and Khdir *et al.* [21] applied quadratic brick elements.



a b c

Fig. 1 – Multiphase Element Method (MPFE): (a) Representative volume element of the composite, (b) finite element grid, (c) structured grid

2.2 Analytical Models

Understanding the characteristics of each phase, including volume fraction and elastic properties, is essential for predicting the mechanical behavior of composite materials through analytical models. In the literature, several classical analytical homogenization approaches have been proposed. In this study, we focus on the Voigt and Reuss bounds [1, 2].

Which are also referred to as first-order bounds, and were the earliest proposed models for isotropic elasticity. They provide the simplest approximation of the effective behavior of composites. The Voigt-Reuss limits can be expressed as follows:

$$E^{Voigt} = pE_i + \left(1-p\right)E_m \tag{2.1}$$

$$E^{Reuss} = \frac{E_i E_m}{\left(1-p\right)E_i + pE_m} \tag{2.2}$$

where E_i and E_m are the elastic properties of the inclusions (i) and the matrix (m). *p* is the volume fraction of the inclusions.

2.3 Finite Element Formulation

The formulation of the PFR4M element is based on the Plane Fiber Rotation (PFR) concept; this concept originates from the Space Fiber Rotational (SFR) rotation concept developed by Ayad et al. [22]. This approach is based

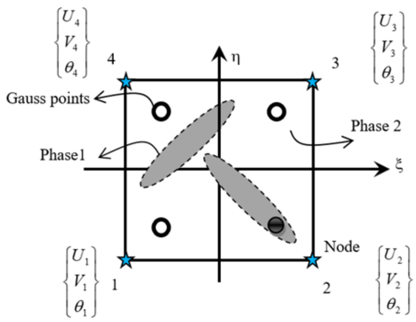


Fig. 2 – Localisation of material phases in the FRQ4M element

on the consideration of virtual rotations of nodal fiber within the element. The principle of the PFR model was discussed in detail in [14].

Fig. 2 shows the interphase treatment and the geometric localization of two or more material phases relative to integration points within the PFR4M element.

3. NUMERICAL RESULTS AND DISCUSSION

This section aims to examine the influence of selected microstructural parameters on the elastic properties of the composite. In particular, we investigate the effects of particle orientation and particle shape on the elastic response of 6061 Aluminum Metal Matrix Composites (MMCs) reinforced with Silicon Carbide particles.

3.1 Effect of Particle Orientation on Elastic Properties as a Function of Volume Fraction

In this section, the influence of particle orientation on the elastic modulus of the 6061 Al/SiC metal matrix composite is investigated. Three particle orientations, horizontal, vertical, and inclined, were considered for both ellipsoidal and rectangular particles with an aspect ratio of 0.6, as illustrated in Fig. 3.

The tensile test is simulated by applying pressure of 1 MPa applied on one side of the representative volume elements (RVE) and simply supporting on the opposite side. A finite element mesh consisting of 40,000 PFR4M elements (Multiphase 4-node quadrilateral elements) was employed to discretize the microstructures

Fig. 4 presents the longitudinal Young's modulus of the composites for different particle volume fractions in the three orientations: horizontal (unidirectional), vertical, and inclined.

The results indicate that Young's modulus increases with higher particle volume fractions. Moreover, in the horizontal orientation, the longitudinal Young's modulus obtained with both rectangular and ellipsoidal particles was greater than that in the vertical and inclined orientations. This behavior can be attributed to the alignment of the particles along the loading direction in the horizontal case. From this study, we can conclude that Young's modulus depends on the orientation of the particles.

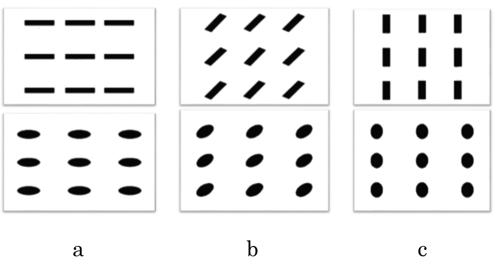


Fig. 3 – Different orientations of particles: a) horizontal direction of ellipsoidal and rectangular shapes, b) inclined direction of ellipsoidal and rectangular shapes, and c) vertical direction of ellipsoidal and rectangular shapes

3.2 Influence of Particle Shapes

This section examines the influence of particle shape on the mechanical behavior of the SiC-reinforced aluminum matrix composite. Four particle geometries, square, circular, rhombic,

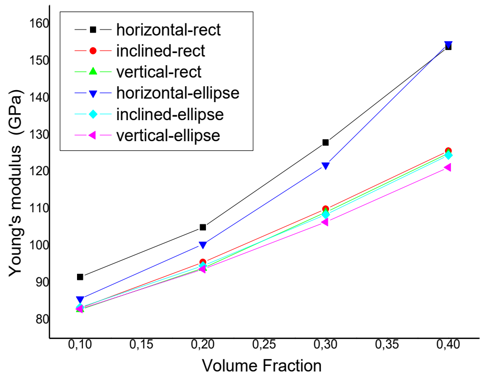


Fig. 4 – Variation of the elastic modulus with different shapes and different orientations of particles

and ellipsoidal, were analyzed at different volume fractions (10%, 20%, 30%, and 40%). As an example, Fig. 5 presents 2D microstructures generated at a 20% volume fraction. The representative volume element is a square domain with dimensions of 50 × 50. A finite element mesh consisting of 40,000 PFR4M elements [14] was employed to discretize the microstructures. The representative volume element was subjected to uniaxial tensile loading in the x-direction, with a prescribed stress of 1 MPa applied on the right boundary. The main parameters, particle volume fraction (V_f), number of particles (N_p), particle length (L_p), area of particles A_p, particle diameter (D_p), fiber aspect ratio $\zeta = 0.6$ are summarized in Table 2.

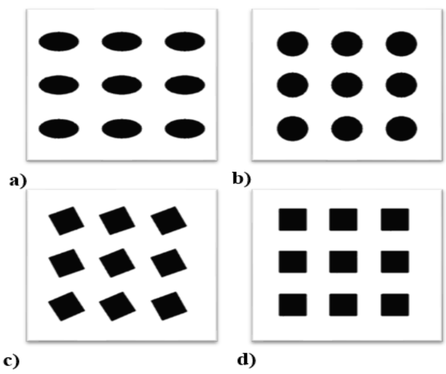


Fig. 5 – Different shapes of the particles in the microstructure for a volume fraction of 20%: a) Ellipse, b) Circle, c) Rhombus, and d) Square

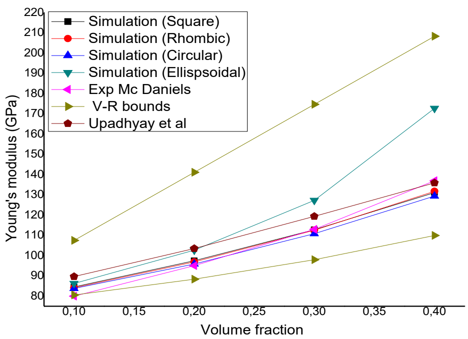


Fig. 6 – Comparison of the Homogenized Young's modulus (E) obtained from the numerical results, experimental data, and the analytical models

Fig. 6 compares the numerical predictions with the Voigt–Reuss bounds and the experimental data reported by McDaniels [23] and Upadhyay *et al.* [24]. The results indicate that the predicted Young's modulus increases with increasing particle volume fraction. At lower volume fractions, the Young's modulus values obtained for the different particle shapes exhibit close agreement. Furthermore, circular particles tend to yield higher modulus values compared to the other shapes. In all cases, the numerical results fall within the Voigt and Reuss bounds.

Table 2 – Calculation of particle length and diameter for different shapes and different volume fractions of particles [8]

<table>
<tr><th>Volume fractions of particles (%)</th><th>Shapes of particles</th><th>Expression of particle size</th><th>Number of particles N_p</th><th>Particles sizes</th></tr>
<tr><td>10</td><td rowspan="4">Circular</td><td rowspan="4">$D_p = \sqrt{4.V_f.VER^2 / \pi.N_p}$</td><td rowspan="4">9</td><td>D_p = 5.947</td></tr>
<tr><td>20</td><td>D_p = 8.410</td></tr>
<tr><td>30</td><td>D_p = 10.306</td></tr>
<tr><td>40</td><td>D_p = 11.894</td></tr>
<tr><td>10</td><td rowspan="4">Square</td><td rowspan="4">$L_p = \sqrt{V_f.VER^2 / N_p}$</td><td rowspan="4">9</td><td>Lp = 5.270</td></tr>
<tr><td>20</td><td>Lp = 7.453</td></tr>
<tr><td>30</td><td>Lp = 9.128</td></tr>
<tr><td>40</td><td>Lp = 10.540</td></tr>
<tr><td>10</td><td rowspan="4">Rhombus</td><td rowspan="4">$L_p = \sqrt{V_f.VER^2 / N_p}$</td><td rowspan="4">9</td><td>Lp = 5.270</td></tr>
<tr><td>20</td><td>Lp = 7.453</td></tr>
<tr><td>30</td><td>Lp= 9.128</td></tr>
<tr><td>40</td><td>Lp = 10.540</td></tr>
<tr><td rowspan="2">10</td><td rowspan="8">Ellipsoidal</td><td rowspan="8">$a = \sqrt{\frac{A_P}{\pi.\zeta}}$
$A_P = \frac{A_{tot}}{N_P}$
$b = \zeta.L$</td><td rowspan="8">9</td><td>a = 3.8382</td></tr>
<tr><td>b = 2.3029</td></tr>
<tr><td rowspan="2">20</td><td>a = 5.4339</td></tr>
<tr><td>b = 3.2603</td></tr>
<tr><td rowspan="2">30</td><td>a = 6.6489</td></tr>
<tr><td>b = 3.9893</td></tr>
<tr><td rowspan="2">40</td><td>a = 7.6775</td></tr>
<tr><td>b = 4.6065</td></tr>
</table>

4. CONCLUSIONS

This paper investigated the influence of particle orientation and shape on the mechanical behaviour of Al 6061/SiC composites. Different volume fractions of particles were used (10%, 20%, 30% and 40%). The numerical results indicate that Young's modulus increases with the volume fraction of particles. Moreover, the findings confirm that the orientation of the particles significantly affects the mechanical behaviour of the composite. Four particle geometries were analysed: circular, square, rhombic, and ellipsoidal. The numerical results were compared with analytical models and experimental data. The results indicated that circular particles yield the highest elastic modulus among the different shapes. Finally, the proposed Multiphase Mesh Technique is highly efficient effective for evaluating the mechanical properties of such materials.

This study also assessed the effectiveness of the PFR4M element in modeling particle-reinforced composites.

REFERENCES

1. W. Voight, *Abhandlung Geselschaft der Wissenschaft zu Gottingen.* **34**, 52 (1987).
2. Reuss, *ZAMM Journal of Applied Mathematics and Mechanics/Zeitschrift für Angewandte Mathematik und Mechanik* **9**, 58 (1929) https://doi.org/10.1002/zamm.19290090104.
3. Z. Hashin, S. Shtrikman, *J. Mech. Phys. Solid.* **11**, 127 (1963) https://doi.org/10.1016/0022-5096(63)90060-7.
4. A. El Moumen, T. Kanit, A. Imad, H. El Minor, *Mech. Mater.* **81**, 105 (2015).
5. T. Mori, K. Tanaka, *Acta Metallurgica* **21**, 571 (1973) https://doi.org/10.1016/0001-6160(73)90064-3.

6. J.D. Eshelby, *Math. Phys. Sci.* **241**, 376 (1957) https://doi.org/10.1098/rspa.1957.0133.
7. Paknia, A. Pramanik, A.R. Dixit, S. Chattopadhyaya, *J. Mater. Eng. Perform.* **25**, 4444 (2016) https://doi.org/10.1007/s11665-016-2307-x.
8. K. Mansouri, B. Chermime, A. Saoudi, H. Djebaili, A. Litim, Z. Kabouche. *J. Nano- Electron. Phys.* **13** No 6, 06018 (2021) https://doi.org/10.21272/jnep.13(6).06018.
9. F. Khadraoui, K. Mansouri, N. Sid, B. Hannachi, M. Chitour, A. Berkia, B. Rebai, N. Himeur, *J. Nano- Electron. Phys.* **16** No 5, 05029 (2024) https://doi.org/10.21272/jnep.16(5).05029.
10. J.E. Rivera-Salinas, et al. *Metals* **10**, 391 (2020) https://doi.org/10.3390/met10030391.
11. S. Qin, C. Chen, G. Zhang, W. Wang, Z. Wang, *Mater. Sci. Eng.: A* **2**, 272 (1999) https://doi.org/10.1016/S0921-5093(99)00503-1.
12. Y. Hua, L. Gu, *Compos. Part B: Eng.* **45**, 1464 (2013) https://doi.org/10.1016/j.compositesb.2012.09.056.
13. S. Kari, H. Berger, U. Gabbert, *Comput. Mater. Sci.* **39**, 198 (2007) https://doi.org/10.1016/j.commatsci.2006.02.024.
14. S. Chouarfia, L. Sedira, K. Meftah, W. Kaddouri, *Res. Eng. Struct. Mater.* **4**, 1441 (2024) http://dx.doi.org/10.17515/resm2024.342ma0707rs
15. T. Kanit, S. Forest, I. Galliet, V. Mounoury, D. Jeulin, *Int. J. Solids Struct.* **40**, 3647 (2003) https://doi.org/10.1016/S0020-7683(03)00143-4.
16. M.S. Sukiman, T. Kanit, F. N'Guyen, A. Imad, A. El Moumen, F. Erchiqui, *Mech. Mater.* **56**, 107 (2017) https://doi.org/10.1016/j.mechmat.2017.02.002.
17. W. Kaddouri, A. El Moumen, T. Kanit, S. Madani, A. Imad, *Mech. Mater.* **92**, 28 (2016) https://doi.org/10.1016/j.mechmat.2015.08.010.
18. N. Lippmann, Th. Steinkopff, S. Schmauder, P. Gumbsch, *Comput. Mater. Sci.* **9**, 1 (1997).
19. El Moumen, A. Imad, T. Kanit, E. Hilali, H. El Minor, *Compos. Part B: Eng.* **66**, 247 (2014) https://doi.org/10.1016/j.compositesb.2014.05.008.
20. A. Benhizia, T. Kanit, T. Outtas, S. Madani, A. Imad, *Mech. Res. Commun.* **59**, 6 (2014).
21. Y. Khdir, T. Kanit, F. Zaïri, M. Naït-Abdelaziz, *Mater. Sci. Eng.: A* **597**, 324 (2014) https://doi.org/10.1016/j.msea.2013.12.095.
22. R. Ayad. *Contribution to the numerical modeling of solids and structures and the non-newtonian fluids forming process. Application to packaging materials (in French) Certification to conduct research (HDR)* (University of Reims Champagne Ardenne: 2002).
23. D.L. Mc Danels, *Metallurg. Trans. A* **16**, 1105 (1985).
24. Upadhyay, R. Singh, *Modern. Mech. Eng.* 213 (2012) https://doi.org/10.4236/mme.2012.21002.

Чисельне дослідження пружно-механічних властивостей металоматричного композиту Al/SiC

S. Chouarfia[1], L. Sedira[1], K. Meftah[2], W. Kaddouri[2], M. Chitour[3], K. Mansouri[3,4]

[1] *Laboratory of Engineering Mechanics LGM, University of Biskra 07000 Algeria*
[2] *Structural Mechanics and Materials Laboratory, University of Batna 2, Algeria*
[3] *University Abbes Laghrour, Mechanical Engineering Department, 40000 Khenchela, Algeria*
[4] *Laboratory of Engineering and Sciences of Advanced Materials (ISMA), Khenchela, 40000 Algeria*

Традиційний метод аналітичної гомогенізації, який удосконалювався протягом останнього століття, прагне з'ясувати поведінку гетерогенних матеріалів на макроскопічному рівні. На композит впливають численні фактори, включаючи типи, розміри, положення та форми армуючих матеріалів. Морфологія частинок привернула значну увагу в галузі порошкових композитів; менші частинки демонструють сильну адгезію до матриці, що призводить до вираженого армуючого ефекту. Це дослідження вивчає пружні властивості алюмінієвого сплаву 6061, армованого частинками SiC. Мікроструктури дискретизовані за допомогою 4-вузлових чотирикутних мембранних скінченних елементів (PFR4M) на основі формулювання обертання площини волокна (PFR). Віртуальні зображення мікроструктури використовувалися для оцінки пружних характеристик при односпрямованому розтягувальному навантаженні. Було проведено параметричне дослідження для вивчення впливу мікроструктурних факторів, включаючи орієнтацію та форму частинок (квадратна, кругла, ромбічна та еліпсоїдна). Нарешті, було проведено валідацію результатів числової гомогенізації шляхом порівняння їх з межами Фойгта-Ройса (VR) та доступними експериментальними даними, що показало добру узгодженість та підтвердило надійність прийнятого числового підходу.

Ключові слова: Форма частинок, Розмір частинок, Аналіз скінченних елементів, Al-SiC, RVE.