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REGULAR ARTICLE

Simulation on the Impact of Pore Dimensions on the Mechanical Properties of Metal Matrix Composites Reinforced with SiC Particles

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This study is designed to examine the effect of pore size on the performance of aluminum matrix composites reinforced with silicon carbide (SiC) particles that contain porosity. To accomplish this, we evaluate both constant and variable pore diameters, assuming a circular shape while preserving the same volume fraction. Finite element analysis is conducted on a square matrix reinforced with nine particles and subject-ed to a tensile test. The simulation utilizes a two-dimensional plane strain model, incorporating square, hexagonal, and random distributions of multiple particles. The findings reveal that, even with the existence of pores, the transfer of stress from the softer matrix to the reinforcement is still effective. Furthermore, it is observed that the composite's properties are increasingly influenced by porosity and pore size, especially as the pore diameter enlarges and the proximity to the particles diminishes.

Keywords: SiC particles, Aluminium matrix, Composite, Porosity, Pore size, Simulation.

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1. INTRODUCTION

Composite materials are identified as polyphase substances that consist of several non-single component elements integrated through composite processes. When compared to traditional materials, composite materials and structures are distinguished by their designability, identity, and reliance on composite technology [1]. Metal matrix composites that are reinforced with particles (MMCp) exhibit significantly superior stiffness and strength relative to the matrix alloys, resulting in their prevalent use in the automotive industry, as well as in aircraft and aerospace constructions [2]. In recent times, silicon-carbide-reinforced composites have gained substantial interest because of their outstanding properties, which include high strength, thermal conductivity, and electrical conductivity. As a significant microstructural property of particle-reinforced composites, porosity plays a vital role in determining the mechanical characteristics of these materials. Because porosity is an inescapable occurrence during the fabrication of silicon-carbide-reinforced composites, it is crucial to analyze the effects of porosity and pore size on the material's properties to optimize its overall performance [3].

This investigation seeks to examine how the characteristics of porosity and pore size impact the efficacy of SiC reinforced aluminum matrix composites that possess porosity. To achieve this goal, we consider both constant and fluctuating pore diameters, assuming a circular geometry while ensuring the volume fraction remains unchanged. Additionally, the secondary goal is to compute the Young's modulus of the composite via finite element analysis in both cases while taking variable and constant diameters.

2. PREVIOUS STUDIES

In a range of discontinuously reinforced metal matrix composites, the failure mechanism of the composite is linked to the initiation and propagation of voids at the interface connecting the matrix and the reinforcement [4]. Numerous researchers have investigated the mechanical characteristics of particle-reinforced composites, emphasizing the influence of porosity on these materials. J.L. Christian *et al.,* [5] indicate that the principal cause of porosity formation is linked to the casting parameters. These parameters consist of the casting route that is applied, the stirring speed and the impeller's position, the volume fraction of the reinforcement material, and the process parameters, which include the duration of holding time. K. Mansouri et al. [6] explore how porosity affects the mechanical properties of Aluminum matrix composites that are reinforced with ceramic particles, concentrating on the optimization of volume fraction and porosity to boost tensile strength, the results revealed that an increase in porosity was associated with a rise in Von Mises stress, while higher volume fractions facilitated improved stress distribution and superior mechanical properties. Tao Zeng [7] and his colleagues examined the fabrication of SiC reinforced aluminum composite foams

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through the method of laser melting deposition (LMD). Their research revealed that an increase in the concentration of SiC nanoparticles led to a decrease in both the porosity and the average pore size of the aluminum foams. According to Xiaohong Xu and others [8], a reduction in SiC particle size significantly boosts the bending strength of porous SiC membrane supports and slightly lowers the firing temperature. This is because smaller SiC particles exhibit a greater specific surface area and higher reactivity. Moreover, the open porosity and the distribution of pore sizes are dependent on the firing temperature, yet they remain relatively unaffected by the size of the SiC particles, as the characteristics related to the pores are mainly governed by the binder. In their study, Yiwu YAN et al. [2] employed the finite element method to examine the influence of particle size on the deformation behavior of SiCp/Al composites. It has been established that a decrease in particle size leads to an increase in both the flow stress and work hardening rate of the composite, assuming a constant volume fraction of the reinforcement. This effect is primarily attributed to the increased strain gradient that develops within the matrix material, which becomes more significant as the particle size diminishes. The study carried out by Yicheng Jin and colleagues [9] examined how the size of preform pores affects the mechanical characteristics and thermal expansion coefficients of the composites. Consequently, a reduction in the size of the preform pores may result in a deterioration of the mechanical and thermal properties of the composites. Mengqin Chen [10] along with colleagues performed an investigation into SiC/Al composites characterized by a considerable volume fraction of SiC particles. They assessed the influence of particle size on the porosity of the preform, with the intention of accurately adjusting the SiC volume fraction to comply with thermal performance criteria for a variety of applications. Furthermore, the preform underwent infiltration with several Al alloys, and the association between porosity and thermal conductivity of SiC/Al was analyzed.

3. NUMERICAL SIMULATION

Finite Element Analysis (FEA) has emerged as a prevalent approach for depicting the mechanical behavior of metal matrix composites, particularly those that include aluminum and silicon carbide (SiC). This investigation explores how the volume fraction of SiC particles, the pore distribution and pore size impact the properties of aluminum matrix composites. The model is predicated on the assumption that the SiC particles are completely attached to the matrix, thus averting any interfacial slip or debonding between the particles and the matrix material. This premise is essential for accurately simulating the ideal interaction between the reinforcing particles and the matrix [11]. It is assumed that each element of the composite displays isotropic properties, suggesting that its material characteristics are uniform in all directions. Taking into account the restricted scale of the model, a carefully refined mesh made up of triangular elements was implemented to guarantee high accuracy and convergence in the results. This refinement of the mesh is vital for capturing the detailed interactions that transpire between particles, pores, and the matrix material, thus enabling precise predictions of stress distribution [12]. The composite material underwent a uniform tensile stress (σ) to replicate realistic loading scenarios.

3.1 Composite Properties

The matrix is regarded as having a square configuration [13] with a side length of $l_m = 200$ µm, and simulations were carried out using CASTEM finite element software [14]. Composites that consist of nine SiC particles were represented in three unique packing configurations: square, hexagonal, and random. For the goals of this research, the composite is designed to feature four circular pores (illustrated in Fig. 1 and Fig. 2). These assumptions provide a more thorough perspective on the overall influences of particle layout and pore sizes and distribution on the mechanical behavior of the composite.

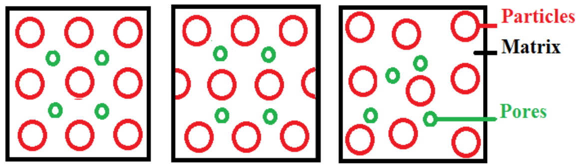

Fig. 1 – Composites with four pores of same diameter

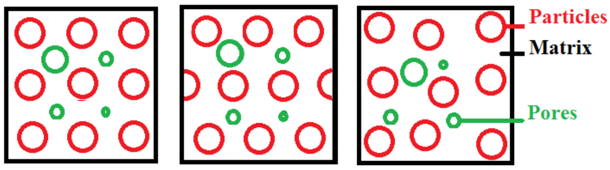

Fig. 2 – Composites with four pores of variable diameter

The following parameters are applied in all computational processes:

Table 1 – Composite properties

Material	E(GPa)	ν	ρ(g/cc)
SiC particles [15]	485	0.2	3.2
Aluminium matrix (Al) [16]	70	0.33	2.7

3.2 Boundary Conditions

The boundary conditions that define the application of tensile stresses to the particulate composite system indicate that at $x = 0$ and $x = l_m$, $U_y = 0$, which signifies that there is no displacement in the y-direction for both the matrix and the particles. In this scenario, the x-axis is aligned with the length direction, and the model exhibits axisymmetry with respect to it [17]. A force of $F_x = 5.65 \times 10^{-8}$ N/µm^2 was applied at the end faces of the matrix, specifically for $x = 0$ and $x = l_m$ [18].

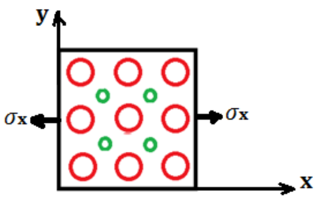

Fig. 3 – Boundary conditions for square arrangement

4. RESULTS AND DISCUSSION

4.1 Pores of Same Size

This section focuses on the analysis of composite materials that contain circular pores, each having an identical radius.

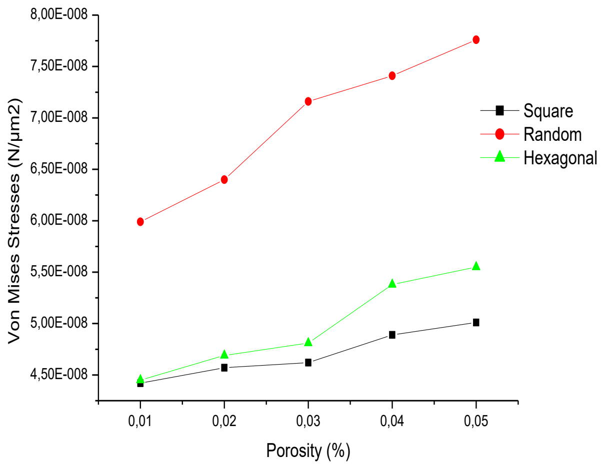

Fig. 4 – Evolution of Von Mises stresses in function of porosity (V_p = 35 %)

Within the composite that contains porosity, it is noted that an increase in porosity leads to a corresponding increase in stresses (Fig. 4). The random distribution illustrates that the stress values are markedly greater in comparison to the square and hexagonal distributions; this can be explained by the presence of pores among the particles, which in turn amplifies the stress concentrations.

4.2 Pores of Variable Size

This section discusses the results of the simulation of composite with pores of no constant diameter. We can find that the Von Mises stresses increase as the porosity increases across all three packing; the random arrangement shows a highest value of stresses.

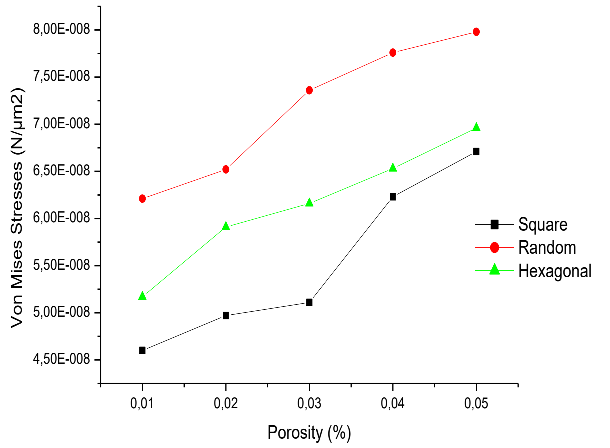

Fig. 5 – Evolution of Von Mises stresses in function of porosity (V_p = 35 %) for variable size of pores

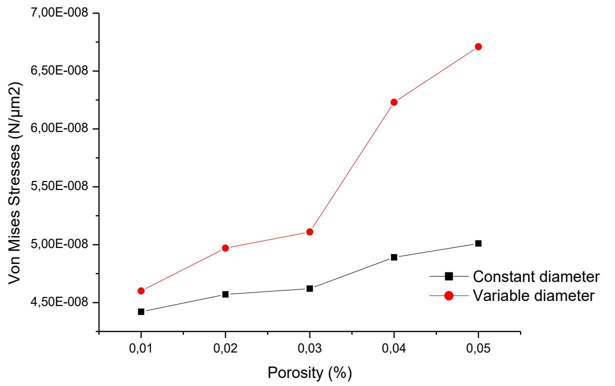

Fig. 6 – Evolution of Von Mises stresses in function of porosity (V_p = 35 %) for square arrangement

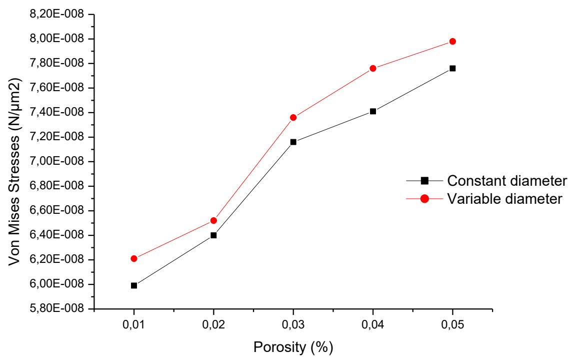

Fig. 7 – Evolution of Von Mises stresses in function of porosity (V_p = 35 %) for random arrangement

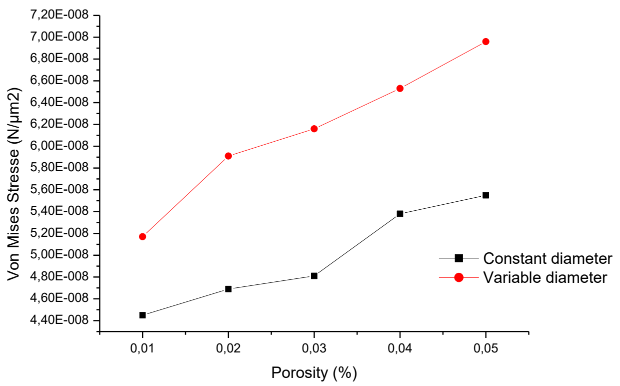

Fig. 8 – Evolution of Von Mises stresses in function of porosity (V_p = 35 %) for hexagonal arrangement

Fig. 6 represents the evolution of V$_{on}$ Mises stresses in function of porosity for square arrangement; it is noted that the stresses are higher in the model with pores of different sizes compared to those where the diameter is constant. This can be explained by the fact that when the size of the voids increases, the discontinuity of the matrix increases which leads to a large stress concentration. The same remark is made in the other two types of random and hexagonal arrangement, respectively (Fig. 7 and Fig. 8).

4.3 Young's Modulus Comparison

Modeling of particles-matrix interaction or pores-matrix interaction at the microscale is usefully in accurately predicting effective properties (e.g., Young's modulus). Two arrangements will be discussed regular (square) and random distribution, and for pores with constant diameter.

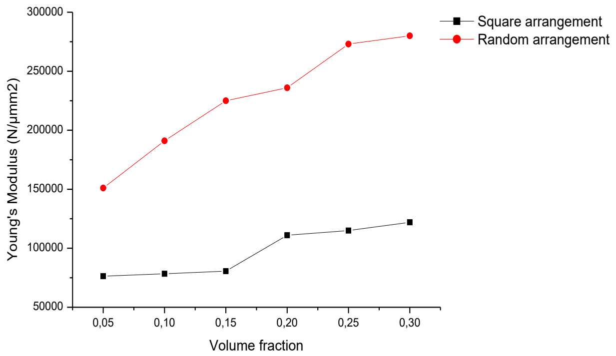

Fig. 9 – Effect of reinforcement content on the elastic modulus of Al/SiC composite without pores

Fig. 9 shows the comparison between bounds on Young's modulus for the Al/SiC composite with data from numerical data obtained in this study for. It can be seen that the Young's modulus evolves almost linearly with the evolution of the volume fraction; we notice that the values of the Young's modulus in the random arrangement are much larger than those in the square arrangement.

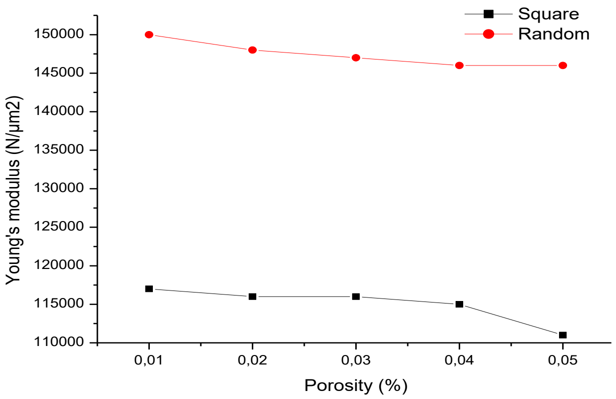

Fig. 10 – Effect of reinforcement content on the elastic modulus of Al-SiC composite with porosity

In Fig. 10, a rise in porosity results in a reduction of Young's modulus. This indicates that a material with higher porosity will exhibit greater flexibility and diminished resistance to deformation compared to one with lower porosity. Pores function as defects, diminishing the contact area between the composite's phases and impairing its capacity to withstand stress. The existence of pores can contribute to a decline in the composite's stiffness, rendering the material more pliable and less capable of resisting deformation. Voids and holes obstruct the uniform distribution of stress within the material, leading to increased deformation and consequently lowering the elastic modulus.

5. CONCLUSION

In the analyzed scenarios that examine the coexistence of pores within the matrix, it was observed that the most significant reduction in the Young's modulus of the composite occurred when a fully dense particle was combined with a porous matrix. Conversely, the least reduction in the elastic modulus of the composite was noted in the case of a porous particle paired with a fully dense matrix. It is evident that, although there are pores present in the composite, the transfer of stress from the soft matrix to the hard particle is effective in all scenarios, with the exception of the situation involving a fully dense circular particle and a porous matrix. In this case, the matrix bears a greater load than the particle. Consequently, the load transfer is diminished, which is manifested as a decrease in the elastic modulus. From the analysis, it can be inferred that the presence of pores with constant and different size disrupts the continuity of the composite, resulting in the elastic relaxation of the matrix. This phenomenon causes the reinforcement particles to experience greater loads, which in turn leads to a decline in their ability to accumulate stress, ultimately resulting in a decrease in the effective elastic modulus of the Al/SiC composite.

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Моделювання впливу розмірів пор на механічні властивості композитів з металевою матрицею, армованих частинками SiC

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Це дослідження розроблено для вивчення впливу розміру пор на характеристики алюмінієво-матричних композитів, армованих частинками карбіду кремнію (SiC), що містять пористість. Для цього ми оцінюємо як постійні, так і змінні діаметри пор, припускаючи круглу форму, зберігаючи при цьому ту саму об'ємну частку. Аналіз методом скінченних елементів проводиться на квадратній матриці, армованій дев'ятьма частинками, та підданій випробуванню на розтяг. Моделювання використовує двовимірну модель плоскої деформації, що включає квадратний, гексагональний та випадковий розподіл кількох частинок. Результати показують, що навіть за наявності пор передача напруження від м'якшої матриці до арматури все ще ефективна. Крім того, спостерігається, що на властивості композиту все більше впливають пористість та розмір пор, особливо зі збільшенням діаметра пор та зменшенням близькості до частинок.

Ключові слова: Частинки SiC, Алюмінієва матриця, Композит, Пористість, Розмір пор, Моделювання.