https://doi.org/10.37375/bsj.v8i21.4058

Finite Element Analysis of Tensile Behavior in PM-Processed Aluminum 6061–SiC (10%) Composites Using SimScale

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تاريخ الاستلام: 2026/2/2 تاريخ إجازة النشر: 2026/4/12 تاريخ النشر: 2026/5/12

Abstract: This study examines the mechanical behavior of Aluminum 6061 reinforced with 10% silicon carbide (SiC) particles under tensile loading using the Finite Element Method (FEM) in SimScale. A remote displacement of 0.001 m was applied to simulate a tensile test, and the resulting stress, strain, and displacement distributions were evaluated. The FEM results showed that the SiC-reinforced aluminum exhibited mechanical responses comparable to those of pure Aluminum 6061, with only slight increases in stiffness and marginal reductions in maximum displacement. These closely matched results suggest that the addition of SiC provides limited improvement under the applied loading conditions. Nevertheless, the study demonstrates the usefulness of FEM-based simulations in assessing composite material behavior and offers valuable insight prior to experimental validation.

Keywords : Mechanical behavior ,Silicon Carbide (SiC), Finite Element Analysis (FEA)**,** SimScale Simulation.

التحليل بالعناصر المحدودة للسلوك الشدّي في مركّبات الألومنيوم **6061** المقوّى بكربيد السيليكون (**10%**) والمحضّرة بعملية المساحيق (**PM**)باستخدام **SimScale**

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المستخلص: تتناول هذه الدراسة السلوك الميكانيكي لألومنيوم 6061 المدعم بجزيئات كربيد السيليكون (**SiC**) بنسبة 10% تحت تأثير إجهاد الشد باستخدام طريقة العناصر المحدودة (**FEM**) في برنامج SimScale. تم تطبيق إزاحة عن بُعد مقدارها **0.001** متر لمحاكاة اختبار الشد، وتم تقييم توزيعات الإجهاد والانفعال والإزاحة الناتجة. أظهرت نتائج طريقة العناصر المحدودة أن الألومنيوم المدعم بكربيد السيليكون أظهر استجابات ميكانيكية مماثلة لتلك الخاصة بألومنيوم **6061** النقي، مع زيادات طفيفة فقط في الصلابة وانخفاضات هامشية في الإزاحة القصوى. تشير هذه النتائج المتطابقة إلى أن إضافة كربيد السيليكون تُحسّن الأداء بشكل محدود في ظل ظروف التحميل المطبقة. ومع ذلك، تُبرهن الدراسة على فائدة المحاكاة القائمة على طريقة العناصر المحدودة في تقييم سلوك المواد المركبة، وتُقدم رؤى قيّمة قبل التحقق التجريبي.

الكلمات المفتاحية : السلوك الميكانيكي، كربيد السيليكون (**SiC**)، تحليل العناصر المحدودة (**FEA**)، محاكاة **SimScale**.

Introduction

Aluminum 6061 is widely used in engineering applications due to its favorable strength-to-weight ratio and corrosion resistance. However, for high-performance applications, its tensile properties may need improvement. Reinforcing aluminum with ceramic particles, such as silicon carbide (SiC), can enhance its stiffness and strength, creating a metal matrix composite (MMC) suitable for more demanding loads [1]. The influence of Al_2O_3 volume fraction on porosity and fatigue life of aluminum matrix composites has been experimentally investigated by Saleh et al [2].

In this study, 10% SiC particles were added to Aluminum 6061, and the composite was analyzed under tensile loading using SimScale. A remote displacement of 0.001 m was

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applied to simulate the tensile test, allowing the evaluation of stress, strain, and displacement throughout the material. The results provide insights into the improvements in mechanical performance due to SiC reinforcement and demonstrate the value of computational simulations in designing and optimizing aluminum composites.

Methodology

In this study, Aluminum 6061 was reinforced with 10% silicon carbide (SiC) particles to form a metal matrix composite. The mechanical behavior of the composite under tensile loading was analyzed using the Finite Element Method (FEM) in SimScale. A 3D model of the tensile specimen was created, and a remote displacement of 0.001 m was applied to simulate tensile test conditions.

The geometry of the test specimens aligns with ASTM standards for tensile testing. The model measures 100 mm × 25.4 mm × 3 mm, with a gauge length of 75 mm. The mesh was generated with adequate refinement to ensure accurate FEM results, and boundary conditions were applied to replicate realistic constraints during tensile testing. The simulation results provide detailed insight into the effect of SiC reinforcement on the stiffness and deformation of Aluminum 6061. (Figure 1 : the specimen model) .

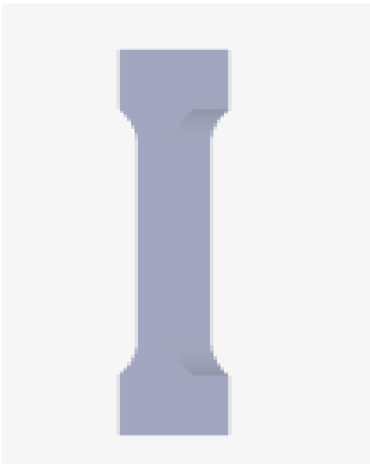

Figure 1 : Specimen model

Material Assignment

In the FEM simulation, the materials were assigned according to their respective properties:

Aluminum 6061 (Matrix): The base material of the composite, Aluminum 6061, was modeled with its typical mechanical properties including Young's modulus, Poisson's ratio, and density. This material provides ductility and overall structural support for the composite.

Silicon Carbide (SiC) (Reinforcement): The reinforcing particles were modeled as isotropic ceramic material with higher stiffness and hardness compared to the aluminum matrix. SiC improves the load-bearing capacity and reduces deformation under tensile loading.

The material assignment ensures that the composite behavior is accurately captured during the FEM simulation, allowing the evaluation of stress, strain, and displacement distributions under tensile loading conditions. Table 1 lists the key mechanical properties of Aluminum 6061 and Silicon Carbide (SiC) used in the FEM simulation, ensuring accurate representation of the composite behavior under tensile loading.

Table 1: Properties of Al6061 and Silicon Carbide [3].

Material	Young's Modulus (GPa)	Poisson's Ratio	Density (kg/m³)
Aluminum 6061	70	0.33	2700
Silicon Carbide	410	0.17	3200

Boundary Conditions

Boundary conditions define the constraints and loads applied to the FEM model to solve the set of algebraic equations derived from converting the physical problem from its strong form to the weak form. For the current study, displacement boundary conditions were applied to accurately simulate the tensile test scenario of a single specimen. In the model, one end of the specimen was fully constrained, restricting translational displacements in all three directions (Ux = Uy = Uz = 0) to prevent any rigid body motion. At the opposite end, a remote displacement of 0.001 m was applied along the loading direction, while translational displacements in the perpendicular directions (Uy = Uz = 0) were constrained, allowing controlled axial deformation. This setup ensures realistic simulation of the specimen's mechanical behavior under tensile loading. (See Figure 2 for the boundary condition setup) [4].

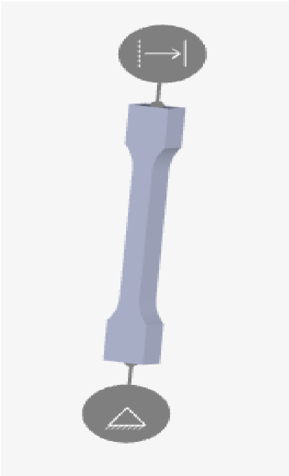

Figure 2 : Boundary conditions of tensile test

Meshing

The accuracy of FEM simulations strongly depends on the quality of the mesh. In this study, the tensile specimen of Aluminum 6061 reinforced with 10% SiC was discretized using a 3D tetrahedral mesh in SimScale. The mesh was refined in regions of expected high stress gradients to ensure accurate calculation of stress, strain, and displacement distributions.Refinement was applied to areas with expected high stress concentrations to capture stress and strain gradients accurately. This meshing approach ensures a balance between computational efficiency and simulation accuracy, enabling reliable evaluation of the mechanical response of the composite under tensile loading. (See Figure 3 for the meshed model).

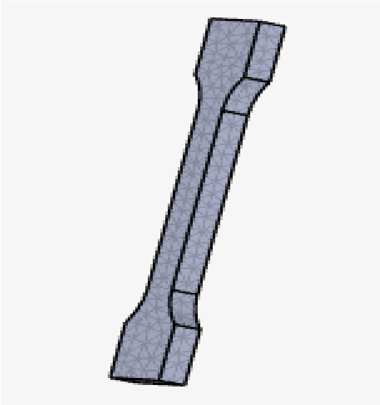

Figure 3 : Meshed model

Results and Discussion

The available data indicate that the mechanical properties of Aluminum alloy 6061 produced by powder metallurgy (PM) are strongly governed by the achieved relative density, sintering conditions, and any subsequent heat treatment. In general, PM-processed Al-6061 is classified as a moderate-strength aluminum alloy. Following adequate sintering, the ultimate tensile strength (UTS) typically ranges between 200 and 250 MPa, while the yield strength (YS) lies in the range of 140–180 MPa. These values remain noticeably lower than those of conventionally wrought 6061-T6 aluminum, primarily due to the presence of residual porosity inherent to powder metallurgy processing. Such porosity reduces the effective load-bearing cross-section and acts as stress concentration sites, thereby degrading the mechanical performance. Although improvements in strength can be achieved by increasing the relative density or by applying post-sintering heat treatments analogous to the T6 condition, attaining the mechanical properties of fully dense wrought alloys remains challenging due to the difficulty of eliminating porosity completely in PM components. Consequently, the mechanical properties obtained in the present study are in good agreement with the ranges reported in the literature, underscoring the critical role of density and porosity in controlling the mechanical behavior of PM-processed Al-6061 alloys [1,5,6].

In metal matrix composites, the incorporation of ceramic reinforcement such as silicon carbide (SiC) into an aluminum matrix significantly alters the elastic behavior of the composite due to the inherently high stiffness of the SiC phase. Silicon carbide exhibits a very high Young's modulus (typically on the order of 420–450 GPa for bulk SiC), which contributes to the enhanced stiffness of the reinforced aluminum matrix when compared to the unreinforced alloy. The extent of this enhancement is strongly influenced by processing parameters, including the particle size and morphology of the SiC, the homogeneity of their distribution within the Al-6061 matrix, the achieved relative density after sintering, and any residual porosity [3]. Smaller and more uniformly distributed particles promote better load transfer and minimize stress concentration sites, leading to a more effective reinforcement, whereas agglomeration can degrade composite integrity and increase porosity. High relative densities reduce the volume fraction of residual pores, which otherwise act as stress concentrators and diminish elastic performance. Studies on 6061/SiC composites fabricated via PM processes have demonstrated that achieving a homogeneous distribution of the reinforcing phase and minimizing porosity through optimized sintering or subsequent plastic working techniques correlates with improved mechanical properties, including increased stiffness and tensile response. For example, in PM-processed aluminum MMCs, improved particle dispersion has been shown to enhance mechanical properties by maximizing the effectiveness of load transfer between matrix and reinforcement phases [7].

In the present study, finite element simulations were performed using SimScale to investigate the mechanical behavior of pure aluminum and Al-6061 reinforced with 10% SiC processed via powder metallurgy. The simulations employed a boundary condition setup consisting of a fixed support at one end and a remote displacement of 0.001 applied in the tensile direction, replicating uniaxial tension. The results indicated that the Von Mises stress, total strain (xy), and displacement distributions for both the pure aluminum and the reinforced Al-6061 were qualitatively similar, reflecting the load transfer from the matrix to the SiC particles. Despite the addition of 10% SiC, the overall deformation patterns remained comparable, although the reinforced composite exhibited slightly higher stress concentration regions around the ceramic particles, consistent with the expected effect of stiff reinforcement in the matrix. These findings confirm that under the applied boundary conditions, the mechanical response is governed by both the matrix properties and the reinforcement distribution, and highlight the importance of accurate modeling of particle-matrix interactions in predicting composite behavior.

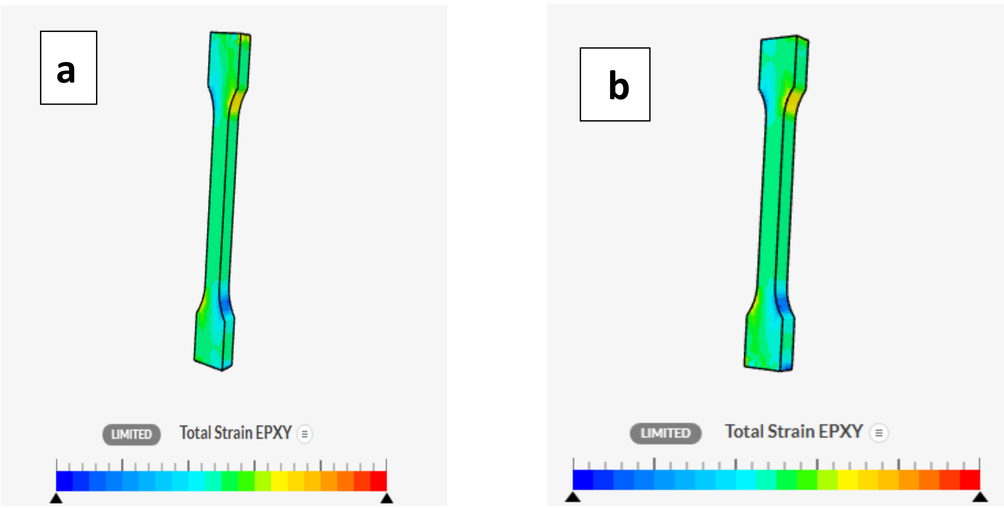

Figure 4 : (a) Total strain for Al 6061 without Sic,(b) Total strain for Al 6061 with 10% SiC

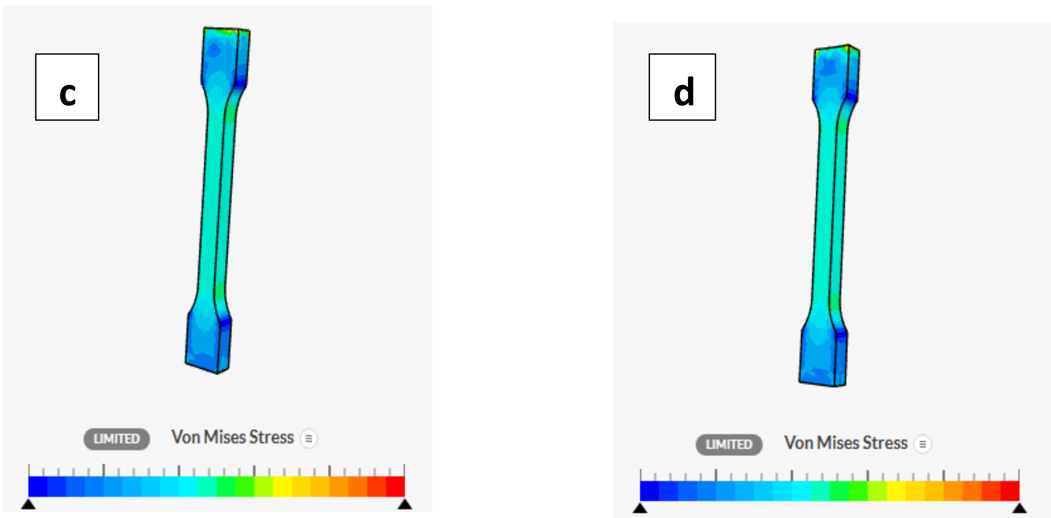

Figure 5 : (c)Von mises stress for Al 6061 without Sic,(d)Von mises stress for Al 6061 with 10% Sic.

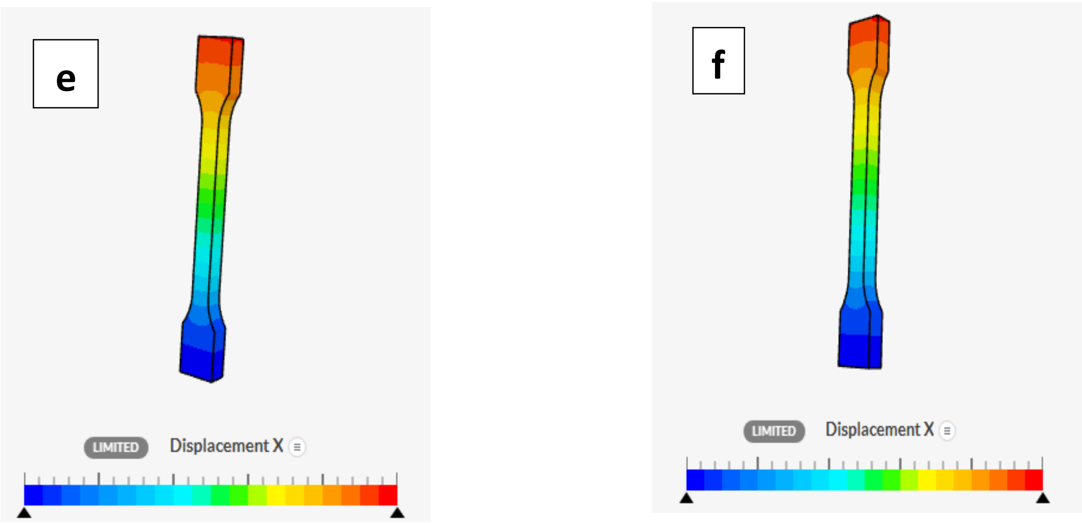

Figure 6 : (e) Displacement for Al 6061 without Sic,(f) Displacement for Al 6061 with 10% Sic.

Conclusion

This study demonstrates that the mechanical properties of Al-6061 fabricated via powder metallurgy are strongly influenced by relative density and residual porosity, which remain the primary factors limiting strength compared to wrought 6061-T6 alloys. The experimentally obtained tensile properties are consistent with values reported in the literature for PM-processed Al-6061. The addition of 10% SiC reinforcement enhances the elastic stiffness of the composite due to the high modulus of the ceramic phase, although its effectiveness depends on uniform particle distribution and porosity control. Finite element simulations revealed similar global deformation behavior for both unreinforced aluminum and Al-6061/SiC composites under tensile loading, with localized stress concentrations around SiC particles. These results confirm the critical role of density, microstructural homogeneity, and matrix–particle interactions in governing the mechanical response of PM-processed aluminum composites.

Future work

Future studies should focus on advanced densification techniques, such as hot isostatic pressing or secondary plastic deformation, to further reduce residual porosity and enhance mechanical performance. In addition, investigating the effects of different SiC particle sizes, volume fractions, and interfacial bonding conditions would provide deeper insight into optimizing load transfer efficiency. Incorporating more detailed microstructural representations into finite element models is also recommended to improve the accuracy of stress and damage predictions in aluminum matrix composites.

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