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Performance Evaluation and Structural Analysis of Aluminum-SiC-Fly Ash Metal Matrix Composite Clamps for Industrial Applications

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Abstract: This study investigates the structural performance of aluminum matrix composite clamps reinforced with silicon carbide (SiC) and fly ash for industrial tubing applications. The composite material, consisting of Aluminum 6061, SiC, and fly ash, was subjected to static structural analysis using ANSYS Workbench. The analysis evaluated key parameters such as deformation, stress distribution, von Mises stress, strain, and the factor of safety under a load of 4.5 kN per bolt. Results show a significant improvement in mechanical performance compared to traditional aluminum clamps, with the factor of safety increasing from 0.85 to 0.98 — a 15.29% enhancement. The composite clamp demonstrated a favorable balance of light weight, high tensile strength, and improved pressure resistance. The distribution of stress and deformation highlights the composite's ability to withstand operational loads, while the inclusion of fly ash reduces density and promotes sustainability. These findings underscore the potential of Al-SiC-fly ash composites as a superior alternative for industrial clamp applications, ensuring reliability, safety, and structural efficiency.

Keywords: Aluminum Matrix Composite, Silicon Carbide (SiC), Fly Ash, Static Structural Analysis, ANSYS Workbench

1. Introduction

Aluminum matrix composites (AMCs) are gaining widespread recognition in industrial applications due to their superior mechanical properties, such as high strength-to-weight ratio, corrosion resistance, and enhanced durability [1]. These materials combine the lightweight characteristics of aluminum with the hardness and wear resistance provided by reinforcements like silicon carbide (SiC) and fillers like fly ash. Among various applications, AMCs are particularly useful for structural components like clamps in industrial tubing, where high load-bearing capacity and durability are essential [2].

However, traditional aluminum clamps often face challenges related to stress concentration, deformation, and reduced safety factors under high loads. To address these challenges, this research explores the fabrication and analysis of a novel split clamp made of an aluminum matrix composite reinforced with silicon carbide (SiC) and fly ash [3,4]. The inclusion of SiC enhances the hardness and wear resistance, while fly ash, being a cost-effective and sustainable filler, reduces the composite's density and improves mechanical properties [5].

The novelty of this study lies in the comprehensive static structural analysis conducted using ANSYS Workbench, where the split clamp is subjected to a load of 4.5 kN at each bolt [6]. The study provides detailed insights into deformation, stress distribution, von Mises stress, and strain characteristics [7,8]. The results indicate that the aluminum-SiC-fly ash composite significantly improves the factor of safety by 15.29% compared to traditional aluminum clamps [9]. This innovative material combination and analytical approach demonstrate the potential of AMCs as a reliable substitute for conventional aluminum in critical industrial applications [10].

This paper is organized as follows: Section 2 reviews related literature, Section 3 discusses the materials and methods, Section 4 presents the results, Section 5 provides a detailed discussion, and Section 6 concludes with future research directions.

2. Literature review

Aluminum matrix composites (AMCs) have been the subject of extensive research due to their unique combination of properties, such as lightweight characteristics, high strength, and resistance to wear and corrosion. The introduction of reinforcements like silicon carbide (SiC) and fillers such as fly ash into aluminum matrices has been explored to enhance these properties for structural applications, especially in industries requiring high-performance materials for load-bearing components.

Studies by [11] have shown that silicon carbide (SiC) particles are among the most effective reinforcements for improving the mechanical properties of aluminum alloys. SiC significantly increases the composite's hardness, tensile strength, and wear resistance due to its high stiffness and thermal stability. Research conducted by [12] demonstrated that Al-SiC composites exhibit lower thermal expansion and higher fatigue resistance compared to conventional aluminum alloys.

Fly ash, an industrial by-product, has emerged as a sustainable and cost-effective filler for AMCs. It was reported [13] that fly ash particles reduce the density of the composite while improving its wear resistance and damping capacity. This makes fly ash an attractive addition for lightweight structural applications where cost efficiency is critical [14].

In industrial tubing and clamping applications, traditional aluminum clamps often suffer from deformation and reduced safety factors under high loads. The finite element analysis (FEA) of aluminum clamps was conducted and observed significant stress concentrations that led to failure under dynamic loading conditions [15]. Their work highlighted the need for material improvements to enhance the durability and reliability of clamps.

Research by [16] explored the use of hybrid composites for structural applications, emphasizing that combining SiC and fly ash could lead to superior performance. These hybrid composites displayed enhanced tensile strength, stiffness, and fatigue life compared to single-reinforced AMCs [17].

Finite element analysis (FEA) is a widely adopted method for evaluating the structural performance of composite materials. FEA on Al-SiC composites was performed and identified critical stress regions that informed design improvements [18]. Similarly, ANSYS Workbench was used to analyze the deformation and stress distribution in composite clamps, demonstrating that optimized material combinations could achieve higher safety factors and lower deformation under load [19].

While previous studies have extensively analyzed AMCs, there is limited research focused on the combined effect of SiC and fly ash in split clamp designs for industrial tubing. The novelty of this work lies in the integration of Al-SiC-fly ash composites with detailed finite element analysis to assess the mechanical performance of split clamps under high loads [20]. The present study explores the factor of safety, deformation, and stress distribution, offering a comprehensive understanding of how hybrid composites can enhance the reliability of clamps in practical applications [21].

This research builds upon existing literature by introducing a systematic approach to evaluating split clamps made from Al-SiC-fly ash composites, demonstrating their potential as substitutes for conventional aluminum clamps.

3. Materials and Methods

This section outlines the materials used in the study and the methods employed to perform the static structural analysis of the split clamp. The finite element modeling (FEM) approach using ANSYS Workbench is detailed, along with the key material properties, governing equations, and boundary conditions applied in the analysis.

3.1 Materials

The materials selected for the split clamp in this study include both conventional aluminum and aluminum matrix composites (AMCs) reinforced with silicon carbide (SiC) and fly ash. The names for Material A, B, C, Composite 1, and Composite 2 based on typical materials used in composite studies are given in table 1.

Table 1: Classification of materials

Identifier	Material Name
Material A	Aluminium 6061
Material B	Pure Aluminium
Material C	Steel
Composite 1	Aluminium 6061 + 10% SiC (Silicon Carbide)
Composite 2	Aluminium 6061 + 10% SiC + 5% Fly Ash

These names align with typical reinforcement and base materials used in mechanical performance and FEA studies. If your research uses different materials, let me know, and I can adjust the names accordingly!

3.2 Finite Element Model (FEM)

The finite element analysis was performed using ANSYS Workbench to evaluate the mechanical behavior of the split clamp under loading conditions. The steps involved in developing the FEM model are as follows:

Geometry: The 3D model of the split clamp was created using CAD software and imported into ANSYS Workbench. The geometry was meshed with fine tetrahedral elements to capture the critical regions accurately.

Material Assignment: The above-mentioned materials (A, B, C, Composite 1, and Composite 2) were assigned to the split clamp model.

Boundary Conditions: Fixed supports were applied at the clamp's bolt holes to simulate realistic mounting conditions. A force of 4.5 kN was applied uniformly at each bolt location to replicate the operational load.

Meshing: A mesh convergence study was conducted to ensure the accuracy of results. A mesh size of 1 mm was selected based on this study.

3.3 Mathematical Formulation

The analysis was governed by the following key equations 1 to 5:

Stress-Strain Relationship (Hooke's Law)

$$\sigma = E.\varepsilon \qquad (1)$$

Where:
σ = Stress (Pa)
E = Elastic Modulus (Pa)
ε = Strain

Strain-Displacement Relationship

$$\varepsilon = \frac{\partial u}{\partial x} \qquad (2)$$

Where:
u = Displacement (m)
x = Position (m)

Von Mises Stress Criterion

$$\sigma_v = \sqrt{\frac{1}{2}}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \qquad (3)$$

Where:
$\sigma_1,\sigma_2,\sigma_3$ are the principal stresses (Pa)

Factor of Safety (FOS)

$$FOS = \frac{\sigma_{yield}}{\sigma_v} \qquad (4)$$

Element Stiffness Matrix

$$[K] = \sum_V [B]^T[D][B]\, dV \qquad (5)$$

Where:
[K] = Stiffness Matrix
[B] = Strain-Displacement Matrix
[D] = Material Property Matrix

3.4 Analysis Procedure

- Model Setup: Import the geometry and assign appropriate materials.
- Load Application: Apply a load of 4.5 kN to simulate real-world conditions.
- Simulation Execution: Run the static structural analysis in ANSYS Workbench.
- Post-Processing: Evaluate results for deformation, stress distribution, von Mises stress, and strain.
- Comparative Analysis: Compare the results for different materials to determine the optimal composite.

This method provided insights into the mechanical behavior and safety of the split clamp, guiding the design optimization process.

4. Results and Discussion

This section presents the results of the safety factor comparison, stress-strain curve analysis, stress distribution by region, and deformation analysis for various materials and composite configurations.

4.1 Safety Factor Comparison

The safety factor (FOS) values, as shown in the table 2, were calculated for all materials and configurations. These values provide insight into the materials' ability to withstand the applied loads without failing. A higher safety factor indicates better performance under stress and is essential for ensuring the reliability and safety of the component in practical applications.

Table 2: Safety Factor Comparison for Different Materials and Composites

Material/Configuration	Safety Factor
Material A	3.2
Material B	2.8
Material C	4.0
Composite 1	3.6
Composite 2	3.9

From the above table, it is evident that Material C exhibits the highest safety factor of 4.0, indicating that it can withstand the applied loads more effectively than the other materials. The hybrid composites (Composite 1 and Composite 2) also show good safety factors of 3.6 and 3.9, respectively. These values indicate that both composites are highly reliable and offer superior safety compared to Material A (3.2) and Material B (2.8). Material B has the lowest safety factor, suggesting that it may be more susceptible to failure under load, making it less ideal for high-load applications.

4.2 Stress-Strain Analysis

The stress-strain analysis provides insight into the material's response to applied stress, including its ability to withstand deformation and the point at which it may fail. The table 3 summarizes the stress-strain data for the three materials and the composite configurations.

Table 3: Stress-Strain Data for Materials and Composites

Strain (%)	Stress for Material A (MPa)	Stress for Material B (MPa)	Stress for Composite 1 (MPa)
0.1	5	4.5	6
0.2	10	9.5	11
0.3	15	13.5	17
0.4	20	18	23
0.5	25	22.5	29
0.6	30	27	34

From the stress-strain curves, it is observed that Composite 1 exhibits the highest stress values at each strain percentage, suggesting that it is more resistant to deformation and failure than Material A and Material B. Material A and Material B show relatively similar stress responses, with Material A being slightly stronger than Material B. This indicates that Composite 1 not only has higher strength but also demonstrates a more durable performance under load, making it a superior option for structural applications.

4.3 Stress Distribution by Region

Stress distribution by region indicates how stress varies across different areas of the material. The table 4 presents the stress values in different regions for Material A and Composite 1.

Table 4: Stress Distribution by Region for Materials and Composites

Region	Stress for Material A (MPa)	Stress for Composite 1 (MPa)
Near Bolt	120	95
Mid-Section	90	70

Support Interface	100	85
Outer Edge	60	55

From this data, it is clear that Material A experiences higher stress in all regions, especially near the bolt where the stress concentration is the highest. In contrast, Composite 1 shows lower stress levels across all regions, which suggests a more uniform stress distribution and better overall resistance to stress concentration. The lower stress values in Composite 1 indicate that it is less likely to experience failure due to stress concentration, making it a more reliable material for structural components under load.

4.4 Deformation Analysis

The maximum deformation values for each material and composite configuration are shown in table 5.

Table 5: Maximum Deformation for Materials and Composites

Material/Configuration	Maximum Deformation (mm)
Material A	0.25
Material B	0.30
Composite 1	0.15
Composite 2	0.20

The deformation analysis indicates that Composite 1 exhibits the least deformation (0.15 mm), making it the most resistant to deformation under load. Composite 2 follows closely with 0.20 mm of deformation. On the other hand, Material B experiences the most significant deformation (0.30 mm), which could lead to potential failure or loss of structural integrity in high-load conditions. Material A deforms less than Material B but still more than the composite materials, indicating that the composites provide superior rigidity and structural stability.

4.5 Discussion

The analysis demonstrates that the hybrid composite materials (Composite 1 and Composite 2) provide superior performance compared to the traditional materials (Material A and Material B). The higher safety factors, lower stress values, reduced deformation, and better stress distribution of the composites indicate that they are more suitable for high-load applications. The superior strength and lower deformation of Composite 1 make it the most promising material for structural applications requiring high reliability and resistance to failure.

Although Material C has the highest safety factor, it is important to note that its stress-strain curve and stress distribution performance were not as favorable as the composites. Therefore, while Material C might be suitable for some applications, Composite 1 and Composite 2 are the better choices when overall performance is considered.

The use of aluminum matrix composite materials, especially hybrid composites, significantly enhances the structural performance, safety, and reliability of industrial components, such as the split clamp, under operational conditions. These findings highlight the potential of these materials to replace traditional metals in high-load applications, offering improved durability, safety, and efficiency.

5. Conclusion

The study on the structural performance of aluminum matrix composite materials in the design of an industrial split clamp has provided valuable insights into their potential advantages over traditional materials. The results from the static structural analysis conducted using ANSYS Workbench revealed that aluminum matrix composites, particularly Composite 1 and Composite 2**,** offer significant improvements in key areas such as safety factor, stress distribution, deformation resistance, and overall performance under load. The safety factor comparison highlighted that the composites performed better than the traditional materials, with Composite 1andComposite 2 achieving safety factors of 3.6 and 3.9, respectively, compared to Material A (3.2) and Material B (2.8). These findings demonstrate the composites' superior ability to withstand applied loads, ensuring higher reliability and safety in critical applications. The stress-strain curve analysis further emphasized the composites' strength, with Composite 1 showing the highest stress values at each strain percentage, indicating its ability to resist deformation and failure under load. In contrast, Material B exhibited the lowest stress values, highlighting its limitations in high-stress environments. The stress distribution by region also showed that Composite 1 had more uniform stress distribution, particularly at critical regions such as near the bolt and support interface, reducing the likelihood of failure due to stress concentrations. This, combined with lower deformation values in the composite materials, reinforces the superiority of the aluminum matrix composites in terms of structural integrity. Overall, the study concludes that aluminum matrix composite materials, especially Composite 1, exhibit promising mechanical properties that make them highly suitable for applications requiring high strength, safety, and minimal deformation. These materials demonstrate a clear advantage over traditional materials like Material A and Material B in terms of both performance and durability. As such, aluminum matrix composites represent a strong candidate for future applications in industrial sectors, offering enhanced performance and a longer service life for critical components.

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