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Experimental Investigation Of Mechanical Properties Of SS304L And Inconel Alloy Bimetallic Structure Fabricated By Wire Arc Additive Manufacturing

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Abstract: Wire arc additive manufacturing is particularly suited for producing large-scale metal components, making it ideal for industries such as aerospace, automotive, and construction. It offers several advantages, including lower material costs, high deposition rates, and the ability to work with a wide range of metals. By changing or adding another material locally during the process, more than one type of material can be used simultaneously in a single component. The deposition of dissimilar metals can also be achieved using wire arc additive manufacturing technique. In this study, bemetallic Inconel 625 alloy was taken for the fabrication of the component. By adding particle reinforcement to the bemetallic Inconel 625 alloy there is a significant enhancement of mechanical and metallurgical properties. The Inconel alloy was reinforced with ceramic powder from 1%wt to 4%wt of silicon carbide powder. The mechanical properties of the resulted component have significantly changed when compared it to the pure Inconel alloy component. the microhardness of the pure Inconel alloy has an average value of 280.56HV and it increases to 331.7HV when powder was added. And also, there is a significant change in wear rate, tensile strength and impact energy. The results from these mechanical and metallurgical properties provide guidance for the fabrication of powder reinforced bemetalic Inconel 625 alloy through wire arc additive manufacturing.

Index Terms **-** Wire Arc Additive Manufacturing; Inconel alloy; silicon carbide; particle reinforced alloy; Microstructure; Mechanical behaviour.

I. INTRODUCTION

To meet the growing demand for complex, high-performance components, manufacturing has shifted toward Additive Manufacturing (AM), which builds parts layer-by-layer from digital models. While powder-based methods like SLM offer precision, they are often limited by high costs and low deposition rates. Wire Arc Additive Manufacturing (WAAM) has emerged as a cost-effective alternative, utilizing an electric arc and metallic wire feedstock to produce large-scale structural components. This process integrates robotic motion control with fusion welding principles—such as GMAW or CMT—to deposit molten metal beads that solidify into near-net-shape parts. By precisely managing heat input and cooling cycles, WAAM can achieve mechanical properties comparable to wrought alloys, making it ideal for aerospace and marine applications using high-value materials like Inconel 625 and Stainless Steel 304L.

The mechanical integrity of WAAM components is heavily influenced by complex thermal cycles, which often result in anisotropic properties and columnar grain growth. To overcome these challenges, recent research focuses on fabricating metal matrix composites by introducing ceramic particles, such as Silicon Carbide (SiC), into the melt pool. SiC is a high-performance ceramic valued for its extreme hardness, thermal stability, and wear resistance. When incorporated via methods like interlayer sprinkling or direct powder feeding, these particles act as heterogeneous nucleation sites that refine the grain structure, restrict dendritic growth, and enhance the material's microhardness and load-bearing capacity. This transition from single-material deposition to composite fabrication allows for the tailoring of specific properties, such as improved high-temperature performance and superior wear resistance.

Inconel alloys, particularly Inconel 625, are preferred for these advanced WAAM applications due to their exceptional corrosion resistance and stability under extreme thermal loads. While these alloys are generally weldable, they are susceptible to microstructural heterogeneity and the formation of undesirable phases like Laves phases during the deposition process. The addition of SiC particles helps mitigate these issues by promoting a more uniform, fine-grained microstructure. Although excessive reinforcement can lead to particle agglomeration or brittleness, optimized levels of SiC significantly improve the tensile strength and dimensional stability of the bimetallic structure. Ultimately, the synergy between WAAM's high productivity and the reinforcing properties of SiC positions this technology as a critical driver for next-generation industrial production and component repair.

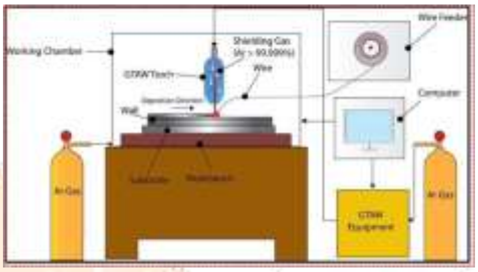

Fig. Schematic of experimental setup

Wire Arc Additive Manufacturing (WAAM) has emerged as a cost-effective method for fabricating large-scale, near-net-shape metallic components and Functionally Graded Materials (FGMs). Research indicates that while WAAM can successfully produce defect-free interfaces in systems like SS321–Inconel 625, the process often leads to challenges such as dendritic growth, element segregation (Nb and Mo), and the formation of brittle Laves phases [Wang et al.]. These microstructural features directly influence mechanical performance, often resulting in varying hardness and anisotropic tensile behavior along the build direction [Wang et al.; Alonso et al.]. To mitigate these issues, studies suggest that direct interface strategies can sometimes be mechanically superior to smooth compositional gradients, as the latter may promote harmful precipitates and higher residual stresses [Rodrigues et al.].

A promising strategy to enhance WAAM components involves the introduction of ceramic and carbide reinforcements, such as Silicon Carbide (SiC), Titanium Carbide (TiC), and Alumina (Al_2O_3). Inoculating the melt pool with these particles promotes heterogeneous nucleation, which transforms coarse columnar grains into fine equiaxed structures [Ghaffari et al.; Rodrigues et al.]. For instance, SiC reinforcement has been shown to significantly increase microhardness and wear resistance due to the formation of hard secondary phases, although excessive amounts can lead to micro-voids and brittle fracture [Bayar & Ulutan; Rooprai et al.]. Similarly, Al_2O_3 particles act as grain boundary pins, enhancing tensile strength through refined grain size and improved dislocation interactions [Osman et al.].

Post-processing and environmental control are also critical for optimizing the structural integrity of WAAM-built superalloys like Inconel 625 and 718. While thin oxide layers (Cr_2O_3–Al_2O_3) form during deposition, they often act as self-limiting protective films that do not significantly compromise tensile properties [Xu et al.]. However, the inherent thermal history of WAAM often results in a microstructure that responds less effectively to standard heat treatments compared to wrought materials [Xu et al.]. Advanced heat treatment strategies, such as homogenization at high temperatures (e.g., 1185 °C), are required to dissolve detrimental Laves phases and ensure a uniform distribution of strengthening precipitates (γ'/γ''), thereby bringing the mechanical properties closer to wrought standards [Xi et al.]. Proper management of these thermal cycles and phase evolutions, particularly the δ-phase (Ni_3Nb), is essential to prevent strength deterioration and premature failure [Xi et al.; Rashid et al.].

II. METHODOLOGY

The selection of materials for Wire Arc Additive Manufacturing (WAAM) is a critical factor, as the alloy must endure high heat input, large melt pools, and repeated thermal cycling without cracking. Materials must possess high weldability, stable microstructural behavior, and the capacity for post-processing to refine the final properties. Inconel 625 (IN625) was selected as the base material for this study due to its exceptional high-temperature stability and superior resistance to hot cracking compared to other nickel-based superalloys. Its strength is derived from precipitation-hardening phases, specifically γ' and γ'', which allow it to maintain mechanical integrity up to approximately 700 °C. This makes it an ideal candidate for high-stress applications in the aerospace and energy sectors. While the WAAM process can lead to niobium (Nb) segregation and the formation of brittle Laves phases, IN625 is highly responsive to heat treatments that dissolve these phases and restore its strengthened microstructure. The alloy's availability in high-quality, ductile wire form further ensures stable and continuous deposition, providing an optimal balance between industrial performance requirements and additive process ability.

Silicon Carbide (SiC) was selected as the reinforcement material for this study due to its exceptional hardness, high elastic modulus, and superior wear resistance. Its strong covalent bonding ensures high thermal stability, allowing the particles to remain structurally intact within the extreme temperatures of the WAAM melt pool, thereby maintaining their strengthening effect during solidification. Beyond its role as a physical reinforcement, SiC serves as an effective heterogeneous nucleation site that promotes grain refinement within the Inconel 625 matrix. By interrupting the growth of coarse columnar grains and facilitating a more uniform equiaxed microstructure, SiC enhances the overall mechanical performance and load-transfer strengthening of the composite. Additionally, SiC's chemical inertness and oxidation resistance make it ideal for high-temperature and corrosive applications. Its compatibility with various WAAM delivery methods, such as interlayer sprinkling and powder feeding, further confirms its suitability for producing high-performance metal matrix composites.

Table: **Chemical Composition properties of Inconel 625+SS304L by wt%**

Element	Wt%
Nickel (Ni)	50-55%
Chromium (Cr)	17-21%
Molybdenum (Mo)	2.8-3.3%
Niobium (Nb)	4.75-5.5%
Iron (Fe)	remaining portion
Cobalt (Co)	1%
Manganese (Mn)	0.5%
Silicon (Si)	0.5%
Aluminium (Al)	0.4%
Titanium (Ti)	0.4%
Carbon (C)	0.1%
Phosphorus (P)	0.015%
Sulphur (S)	0.015%

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The fabrication of Inconel 625-SiC composite walls was conducted using a robotic Wire Arc Additive Manufacturing (WAAM) system. The process began with a mild steel substrate, cleaned and polished to ensure optimal adhesion, and securely clamped to prevent distortion. Welding parameters—including current, voltage, and travel speed—were optimized for Inconel 625 to ensure stable arc formation and consistent bead geometry. Each layer was deposited to a height of approximately 2.5 mm and a length of 90 mm, followed by a 3–5 minute inter-layer cooling period to manage thermal accumulation and minimize residual stresses. For the reinforced structures, a Silicon Carbide (SiC) paste (mixed with ethyl alcohol) was applied evenly over each cooled Inconel layer. The subsequent layer deposition allowed the SiC particles to embed directly into the melt pool. This systematic sequence was repeated to fabricate five distinct wall structures with varying SiC contents (0%, 1%, 2%, 3%, and 4%). Once deposition was complete, the walls were cooled to room temperature and detached from the substrate via machining. The fabricated walls underwent surface grinding and polishing to eliminate irregularities. Finally, standard ASTM-compliant specimens were extracted for tensile, hardness, wear, impact, and metallurgical analysis. All specimens were cleaned with acetone and stored in sealed containers to maintain material integrity prior to testing.

Fig. (a) Fabrication of component using WAAM (b) WAAM fabricated Inconel 625+ SS304 Slab

Post-deposition, the Inconel 625-SiC walls were subjected to a series of controlled machining steps to achieve dimensional accuracy and prepare standardized specimens. Once cooled, the walls were detached from the substrate and transferred to a CNC milling machine. This step removed surface irregularities and bead undulations, ensuring uniform thickness and a smooth finish essential for consistent testing. To preserve the material's microstructural integrity, Wire-Cut Electrical Discharge Machining (EDM) was utilized for specimen extraction. Unlike traditional mechanical cutting, EDM eliminates the risk of thermal distortion and mechanical stress, producing clean, burr-free edges. Specimens were extracted in accordance with ASTM guidelines for tensile, impact, hardness, wear, and metallurgical analysis. The final preparation involved a thorough cleaning with acetone to remove dielectric fluids and machining residues. The specimens were then categorized by SiC reinforcement percentage (0% to 4%), labeled, and inspected for dimensional deviations. This systematic procedure ensured that the experimental analysis was conducted on high-quality, defect-free samples that accurately reflected the material's properties.

Fig. Inconel625+SS304L Specimens after Wire EDM cutting

To evaluate the influence of Silicon Carbide (SiC) reinforcement on the Inconel 625-SS304L bimetallic structure, the fabricated specimens underwent a comprehensive series of metallurgical and mechanical tests.

3.1 Microstructural Characterization

The internal structure was analyzed to assess phase distribution, grain morphology, and the quality of the interfacial bond between the reinforcement and the matrix.

- **Optical Microscopy (OM):** Used for rapid visualization of grain boundaries, solidification patterns, and potential defects like porosity or inclusions at magnifications up to 1000×.
- **Scanning Electron Microscopy (SEM):** Provided high-resolution imaging of fine features, including dendritic structures and particle distribution. This was critical for analyzing the interfacial bonding between the SiC particles and the Inconel matrix.
- **Energy Dispersive X-ray Spectroscopy (EDS):** Conducted alongside SEM to identify the elemental composition. In this study, EDS confirmed the presence of SiC particles and helped detect Nb/Mo-rich carbides and Laves phases within the interdendritic regions.

3.2 Mechanical Testing

The mechanical performance of the 0% to 4% SiC reinforced walls was quantified using standardized testing procedures:

- **Vickers Microhardness Test (ASTM E92):** A diamond pyramid indenter was used to measure resistance to localized deformation. This test reflects the strengthening effect of the ceramic particles and grain refinement.
- **Pin-on-Disc Wear Test (ASTM G99):** Evaluated the surface durability under sliding conditions. Each sample was tested under loads of 1kg, 2kg, and 3kg to measure weight loss and frictional behavior.
- **Tensile Testing (ASTM E8M):** Conducted using a Universal Testing Machine (UTM) on both horizontal and vertical specimens. This test determined ultimate tensile strength (UTS), yield strength, and percentage elongation, revealing how the WAAM thermal cycles and SiC content affect overall ductility and strength.
- **Impact Testing (Izod Method):** Measured the material's toughness and ability to absorb energy during sudden shock loading. This was essential for evaluating whether higher concentrations of ceramic reinforcement induced brittleness in the bimetallic structure.

IV. RESULTS AND DISCUSSION

The experimental results demonstrate a significant shift in the mechanical and metallurgical behavior of the Inconel 625-SS304L bimetallic structure following the addition of Silicon Carbide (SiC).

4.1 Microstructural Analysis

Optical microscopy revealed a robust bimetallic transition zone characterized by a mixed morphology of equiaxed grains and elongated columnar dendrites. The introduction of SiC promoted heterogeneous nucleation, which refined the dendritic structure and intensified solute partitioning of Niobium (Nb) and Molybdenum (Mo) into the interdendritic regions.

SEM and EDS analysis confirmed that at low concentrations (1% SiC), the particles were uniformly distributed and well-bonded to the matrix, creating effective barriers to dislocation motion. However, at 4% SiC, noticeable particle clustering and interfacial gaps appeared. EDS point analysis identified these regions as being enriched with Ni, Cr, Nb, and Mo, confirming the presence of strengthening carbides and Laves phases, which contribute to hardness but increase localized brittleness.

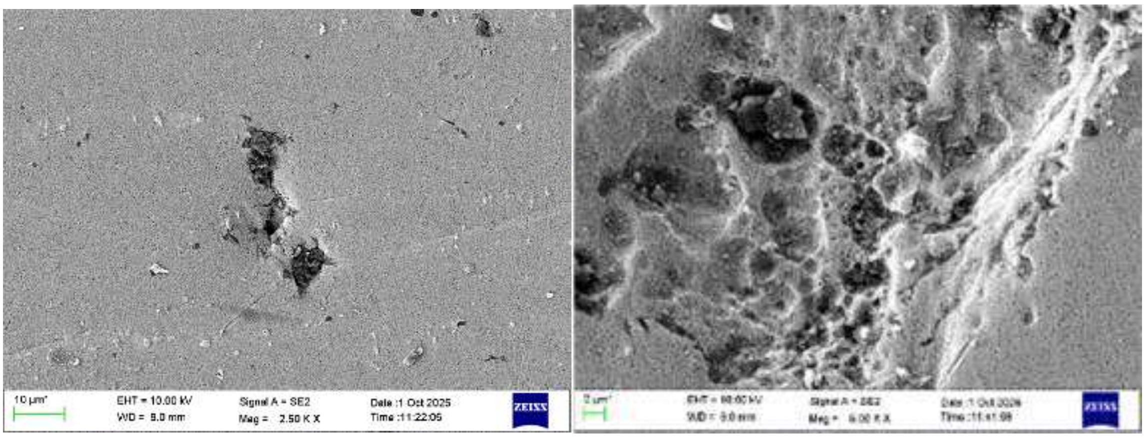

Fig. SEM micrographs

4.2 Mechanical Performance

- **Microhardness:** Hardness values increased progressively from 280.56 HV in the base alloy to a peak of 331.70 HV with 4% SiC reinforcement. The most significant gain occurred between 0% and 3%, suggesting that saturation begins as particle agglomeration occurs.

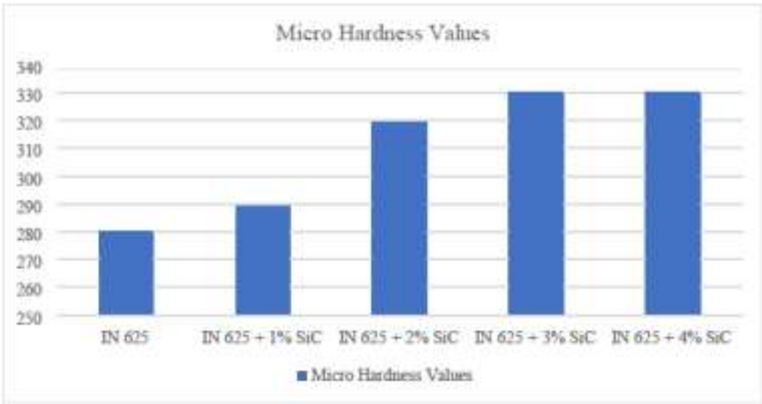

Fig. Microhardness values (HV) Graph

- **Wear Resistance:** A systematic reduction in cumulative material loss was observed across all load conditions (1kg, 2kg, and 3kg). The 4% SiC composite recorded a 31.62% reduction in wear rate at the highest load compared to unreinforced Inconel, attributed to the hard SiC particles acting as a protective tribo-layer.

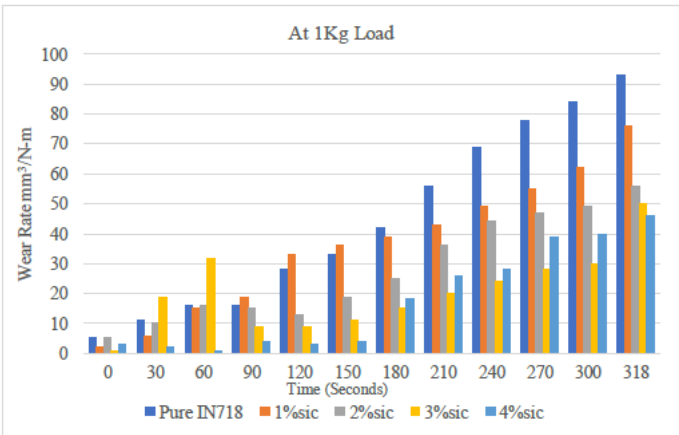

Fig. Graph of Wear at 1kg

- **Tensile Strength:**
  - **Vertical Specimens:** Strength peaked at 2% SiC (727.0 MPa) before declining at 3% due to stress concentrations from particle clustering. A partial recovery was noted at 4% (704.6 MPa).
  - **Horizontal Specimens:** Exhibited more stable performance, with tensile strength peaking at 698.0 MPa for the 4% SiC variant. Horizontal builds generally showed higher elongation (up to 61.06%) as the loading acted parallel to the deposition layers, minimizing the impact of interlayer boundaries.

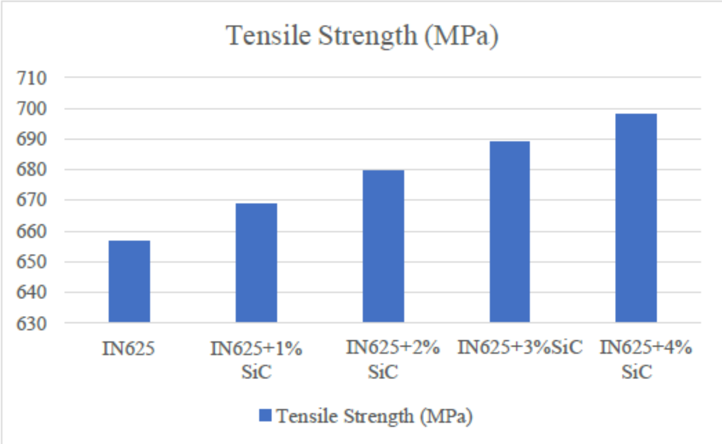

Fig. Tensile Strength Graph

- **Impact Toughness:** Unlike hardness and strength, impact energy decreased drastically as SiC content increased. The impact energy dropped from 121.1 J (base) to 43.1 J (4% SiC), a reduction of 64.4%. This highlights a critical trade-off: while SiC significantly enhances wear resistance and hardness, it reduces the material's ability to absorb sudden shock loads by promoting brittle fracture pathways.

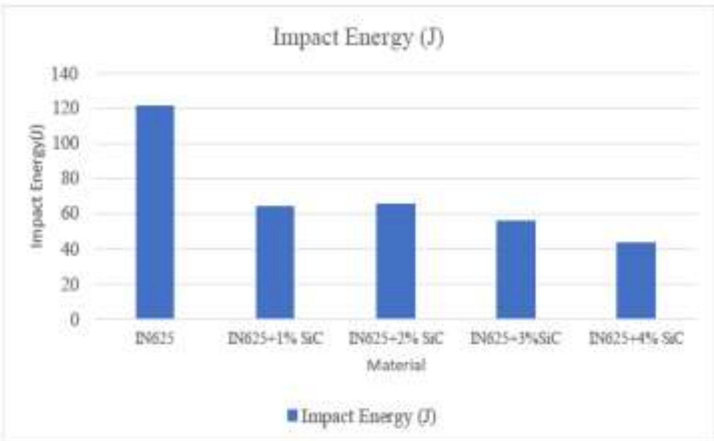

Fig. Impact Energy Graph

V. CONCLUSIONS

The experimental investigation on IN625 reinforced with SiC particulates demonstrates clear and quantifiable modifications in mechanical performance, which are strongly governed by microstructural evolution during the WAAM process. The microhardness values show a consistent rise from **280.56 HV (pure IN625)** to **331.7 HV at 4% SiC**, representing an **~18% increase**. This improvement is primarily attributed to Orowan strengthening, grain refinement due to heterogeneous nucleation from SiC particles, and enhanced load-bearing capability of the hard ceramic phase. The minimal increase between 3% (330.73 HV) and 4% (331.7 HV) SiC indicates hardness saturation due to particle agglomeration and reduced matrix continuity. Wear resistance results across 1 kg, 2 kg, and 3 kg loads confirm a substantial reduction in wear rate with increasing SiC reinforcement. At 1 kg load, wear decreases by **~40– 50%** at 2–4% SiC compared to pure IN625. At 2 kg, wear reduction ranges from **~20% to 45%**, while at 3 kg load, the reduction reaches **~32%** at 4% SiC. These trends correlate directly with higher surface hardness, the load-bearing effect of SiC particles, reduced adhesive wear due to lower metal–metal contact, and formation of a more stable tribofilm. The presence of hard interfacial carbides/silicides further enhances the surface's resistance to micro-cutting and ploughing. Tensile test results reveal that vertical specimens experience improved mechanical response up to 2% SiC, with tensile strength rising from **636.3 MPa** to **727 MPa** (a **~14.2% increase**) and yield strength increasing by **~8.3%**. However, beyond 2% SiC, vertical specimens exhibit a drop in strength and ductility due to clustering, thermal mismatch-induced microcracks, and particle segregation at interlayer boundaries. In contrast, horizontal specimens show more stable enhancement, with tensile strength increasing from **656.9 MPa to 698 MPa** at 4% SiC (**~6.2% improvement**) and elongation remaining relatively higher because the load path avoids weak interlayer zones. This clearly demonstrates the anisotropic nature of WAAM components and the greater sensitivity of vertical builds to reinforcement-induced defects. Impact energy exhibits a reverse trend compared to hardness and wear behavior. The toughness of pure IN625 (**121.1 J**) drops sharply to **64.4 J** at 1% SiC (**~46.8% reduction**) and further declines to **43.1 J** at 4% SiC (**~64.4% reduction**). This reduction is attributed to the brittle nature of SiC, increased interfacial stress 68 concentration, formation of Nb/Mo/Cr-rich carbides and possible silicides, and microvoids arising from CTE mismatch during cooling. These features restrict plastic deformation and facilitate rapid crack propagation, explaining the decline in impact resistance. Microstructurally, the optical and SEM analyses validate these mechanical trends. SiC particles refine grains at lower contents, improving hardness and tensile strength. At higher reinforcement levels, particle clustering, poor interfacial bonding, and microcracking reduce ductility and impact strength despite maintaining high hardness. EDS results confirm enrichment of Nb, Mo, and Cr near SiC, supporting the formation of strengthening carbides (NbC, CrC, MoC) that enhance hardness but compromise toughness. The study establishes that SiC is an effective reinforcement for improving hardness and wear resistance of WAAM-fabricated IN625, with peak performance observed at 2–3% SiC. However, excessive reinforcement (≥3%) introduces embrittlement, microcracking, and anisotropic tensile behavior due to thermal mismatch and particle agglomeration. Therefore, **2% SiC** represents the optimal balance between strength, hardness, and ductility, whereas **3–4% SiC** is suitable for applications requiring wear resistance but not high impact toughness. The metallurgical interplay of Orowan strengthening, grain refinement, carbide/silicide formation, load transfer, and defect accumulation governs the final mechanical performance.

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