Independent Verification, Predictive Modelling, and Fatigue Life Coupling for Agglomeration-Driven Yield Strength in Metal Matrix Nanocomposites

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Abstract

Nanoparticle agglomeration is the primary obstacle preventing metal matrix nanocomposites (MMNCs) from reaching strengths predicted by idealised micromechanical models. A recent unified yield strength model superposes load transfer, thermal-mismatch dislocation density, and Orowan strengthening, resolving clustering through two dimensionless agglomeration parameters, but its validation relied only on analytical comparison and published tensile data, with no independent numerical check and a sensitivity analysis that structurally excluded matrix yield strength. This work addresses both gaps and extends the model further. All governing equations were independently re-implemented in Python, recovering the source paper's reference values of 153.98 MPa and 169.28 MPa. A single-particle representative volume element in a magnesium matrix, solved by linear elastic finite element analysis, gives a stress concentration factor of 1.9996, consistent with the Eshelby inclusion result; combined with dislocation-hardened matrix strength, first-yield sits 49.3 percent below analytical strength across nine material systems. A gradient-boosted surrogate on 50,000 Latin hypercube samples achieves R-squared of 0.9807 in log-space; Shapley explanations rank matrix shear modulus and yield strength first and second in global sensitivity, agglomeration parameters last. The agglomeration-coupled yield strength is substituted into a fatigue crack growth life model, re-derived and corrected from an earlier draft error, showing fatigue life scales as the cube of yield strength, so agglomeration affects fatigue life roughly three times more strongly than static strength. Monte Carlo propagation gives P5, P50, and P95 percentiles on strength and fatigue life across three volume fractions. Structural weaknesses found during implementation are disclosed, resolved, or flagged for future work.

Biography of Author

Arnav Kumar Lal is a third-year Mechanical Engineering undergraduate at Netaji Subhas University of Technology, New Delhi, and an Undergraduate Research Fellow in its Department of Mechanical Engineering, researching metal matrix nanocomposites under faculty supervision. His work independently verifies an agglomeration-driven yield strength model through SolidWorks and ANSYS finite element analysis, extracting an interfacial stress concentration factor consistent with the Eshelby inclusion limit, and couples the result to fatigue life prediction through a gradient-boosted XGBoost and SHAP surrogate. He trained in AI-assisted research methodologies at the London School of Economics Summer School and previously conducted engineering research at DRDO.

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