# Manganese-silicate inclusions in iron: microstructural and mechanical insights to guide steel design

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**Abstract**

Despite significant advancements in steelmaking through history, complete removal of inclusions still remains an elusive goal for the metallurgical industry. In response, inclusion engineering emerged as a scientific endeavour aiming to harness the potential benefits of inclusions, by focusing on tailoring their nucleation, growth, and evolution with specific compositions, shapes, and distributions. Among the wide range of inclusion types, manganese-silicates stand out due to their deformability during hot working and low elastic mismatch with the iron matrix (1, 2), thereby minimizing local stress concentrations during elastic deformation and improving high-cycle fatigue and fracture toughness.

In this study, rhodonite (MnSiO) and tephroite (MnSiO) inclusions are synthesized within a pure iron matrix via sequential deoxidation during arc-melting under an inert atmosphere. Microstructural characterization and compositional analyses are conducted using scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS), electron backscatter diffraction (EBSD), Raman spectroscopy and transmission electron microscopy (TEM). Local mechanical properties of the inclusions, namely, hardness and elastic modulus, are measured via nanoindentation, taking into account elastic contributions from the matrix (3, 4). Findings reveal a strong influence of the inclusion microstructure, stoichiometry and crystallinity on their mechanical properties, hence offering a range of hardness and stiffness combinations within the MnO-SiO pseudo-binary phase system.

Microcantilever bending beams, produced by FIB milling on free specimen surfaces are designed to probe both the bending strength of individual inclusions and their inclusion-matrix interfacial strength through a series of displacement-controlled in-situ SEM micromechanical testing (5). These experiments yield two findings: (i) manganese-silicate inclusions can exhibit significant plastic deformation at room temperature, and (ii) the inclusion-matrix interfacial strength is comparable to the local strength of the oxides. Additional evaluation of the fracture toughness is performed in microcantilever bending beams micromachined within individual inclusions, estimating crack propagation through beam measurements of deflection in combination with FEM-derived crack length vs compliance curves.

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