

A MIXED-INTEGER TOPOLOGY OPTIMIZATION FRAMEWORK FOR POWDER METALLURGY PROCESSES LEVERAGING SENSITIVITY-GUIDED STOCHASTIC SEARCH

Kazuki Kominami, Naoyuki Ishida, Kazuhiro Izui, Shinji Nishiwaki

Kyoto University

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Abstract

The design of multi-material components in powder metallurgy (PM) requires addressing the discrete nature of material distribution, as the final structure is formed by assembling distinct powder granules or blocks. PM is an increasingly vital manufacturing process due to its high material utilization and ability to produce complex, near-net-shape components with unique material compositions that are difficult to achieve through traditional subtractive methods. However, to fully exploit these advantages, specialized design methodologies are needed. Conventional topology optimization methods often rely on continuous density variables, which frequently produce intermediate densities that are physically unattainable in PM without complex post-processing. This study proposes a novel optimization framework specifically tailored for PM processes, formulated as a large-scale mixed-integer non-linear programming (MINLP) problem.

The proposed method integrates a sensitivity-guided Simulated Annealing (SA) algorithm with gradient-based local tuning. Unlike conventional density-based approaches, our framework directly manipulates the discrete placement of "granule blocks," ensuring that the optimized design strictly adheres to PM manufacturing constraints from the outset. By utilizing sensitivity information derived from the governing physical equations to bias the stochastic transition probabilities in the SA, we significantly improve the convergence rate compared to pure heuristic searches, making it applicable to high-dimensional design spaces.

To demonstrate the versatility of this framework, we apply it to the microstructural design of composite electrodes in all-solid-state batteries. In this context, the optimal spatial distribution of active materials and solid electrolytes is sought to maximize electrochemical reaction efficiency. The numerical results show that the proposed method can identify high-performance discrete structures that outperform conventional homogenized designs while maintaining 100% manufacturability. Furthermore, the framework's ability to handle multiple material phases and geometric constraints inherent to PM is discussed. This research provides a robust computational tool for the systematic design of next-generation functional materials

and components manufactured through powder-based processes, bridging the gap between theoretical topology optimization and practical industrial fabrication.