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Hierarchical Surrogate Modeling and Uncertainty Quantification for Aluminum Profile Process Chain

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ABSTRACT

Due to the widespread use of aluminum profiles and the presence of unavoidable process and material uncertainties [1], quantification of these uncertainties across the complete process chains is essential for reliably controlling the critical-to-quality (CTQ) properties, e.g. wall thickness and springback, of the final products. Such process chains consist of multiple interconnected subsystems linked by so-called linking variables, which serve simultaneously as outputs of upstream subsystems and inputs to downstream subsystems. This coupling poses significant challenges to conventional forward uncertainty propagation methods as their research subjects are mostly individual components [2] or simple sequential systems [3]. In this work, an efficient hierarchical surrogate modeling framework with active learning is proposed to enable forward uncertainty propagation throughout critical process units of a typical aluminum profile process chain consisting of hot extrusion, straightening, bending and heat treatment [4]. Field-type linking variables, e.g. stress field and temperature field, are considered. Epistemic uncertainty is decomposed into upstream-propagated uncertainty associated with linking variables and prediction uncertainty related to surrogate model accuracy of the current subsystem, and a new acquisition function is formulated to identify the most informative sampling points. Aleatory uncertainty is fully characterized through probabilistic descriptions of system inputs, which are determined based on prior knowledge, experimental observations, and Bayesian updating. Uncertainty propagation is then efficiently performed using deterministic surrogate models trained on high-fidelity finite element (FEM) simulations. The proposed framework enables accurate and computationally efficient uncertainty propagation across coupled process units, thereby laying a solid foundation for future robustness optimization and sensitivity analysis.

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