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Accounting for Macroscopic Heterogeneities in Gradient Friction-Stirred Aluminum Alloys Using Coupled Experimental–Numerical Approaches

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Abstract

The need for reliable repair of damaged components has increased in recent years, particularly with the development of additive manufacturing technologies. In the aerospace sector, repair processes must be carefully selected depending on the material. Liquid-state deposition techniques, such as Direct Energy Deposition or Wire Laser Arc Manufacturing (WLAM), are widely used; however, rapid solidification induces significant thermal stresses, often requiring post-deposition heat treatments. In addition, 7xxx-series aluminum alloys, commonly employed in aerospace applications for their high strength-to-weight ratio, remain particularly challenging to process using conventional liquid-phase additive manufacturing routes. In this study, an alternative repair strategy based on the recently developed solid-state Additive Friction Stir Deposition process is investigated. Repaired specimens are produced, and their mechanical behavior is assessed in order to support the requalification of repaired components. Such repaired components exhibit pronounced heterogeneities in microstructural evolution, extending from the substrate material through the repair interface to the deposited layers. These heterogeneities must be explicitly accounted for. Achieving this requires an in-depth understanding of the underlying deformation mechanisms, which are governed by local plasticity at the microstructural scale. Consequently, a detailed microscale investigation of plastic deformation is essential to accurately describe the mechanical response of these alloys. The proposed methodology relies on a coupled experimental–modeling framework aimed at developing a grain-scale numerical twin of the repaired region across the substrate–deposit interface. In situ SEM tensile tests combined with digital image correlation, using lithography-based speckle patterns, are conducted to measure local strain fields. In parallel, simulations are performed at the grain-aggregate scale. The mechanical response of the digital twins is described using a Meric–Cailletaud constitutive law, calibrated from tensile tests, nanoindentation measurements, and literature data. Comparison between experimental and numerical results enables the simulation of the mechanical behavior gradient across the repair interface.

Keywords:

Additive Friction Stir Deposition numerical twin in situ SEM tensile tests crystal plasticity