ACCELERATED DESIGN AND INTEGRITY ASSESSMENT OF ADDITIVELY MANUFACTURED METALLIC STENTS USING MACHINE-LEARNING MODELS

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Abstract
In this work, we investigate the potential of laser powder bed fusion (L-PBF) to meet the stringent requirements imposed on metallic stents for the treatment of aortic dissection. Here, we use microstructure-based modeling to describe the mechanical properties of L-PBF 316L stainless steel. The derived structure-property relationships then serve as a database for training machine learning (ML) models, such as convolutional networks (CNN) and graphical neural networks (GNN). Based on the established modeling framework, we are able to predict the deformation and fracture behavior of 316L stents and identify the improved stent design in an efficient manner.

1. Introduction
Laser powder bed fusion (L-PBF), a widely used additive manufacturing (AM) technique, is a rapidly developing technology with great potential for producing complex, low-cost products with enhanced design capabilities. However, L-PBF encounters significant challenges when manufacturing safety-critical metal parts in various fields (e.g., biomedical, aerospace, etc.). One of the major challenges is the lack of a reliable predictive methodology for integrity assessment of L-PBF components. Without this predictive capability, real-time quality control is not possible, nor can resource-efficient production of safety-critical L-PBF components be ensured. This paper presents recent efforts to develop an efficient methodology for accelerated design of L-PBF aortic stents that have high geometric and material requirements. Therefore, we systematically characterize the microstructure and mechanical properties of L-PBF 316L stainless steel as a function of specimen thickness, orientation angle and heat treatment conditions. The results form the basis for the development of a microstructure-based modeling approach to predict the tensile properties of L-PBF materials. The approach involves the generation of a synthetic 3D description of the microstructure in combination with crystal plasticity (CP) to predict the mechanical properties. The deformation and fracture behavior of the aortic stent is then investigated using the parameterized 3D stent model with a 2D micromechanical unit cell. The derived structure-property-performance relationships are used for training and validation of machine learning models, e.g. CNN and GNN. These are expected to enable fast and reliable integrity evaluation and design of L-PBF stent structures.

2. Results
In following preliminary results from experimental and numerical investigations are summarized:

- The lowest yield strength and highest elongation at fracture were obtained for 0° specimens when testing tensile specimens with different orientations (0°, 45° and 90°) to the build directions. The observed anisotropy and the influence of the specimen thickness on the mechanical response are captured by employing both Hill plasticity and microstructure-based models.
- The surface treatment (electropolishing) leads to an improvement of the elongation behavior, a smoothing of the stent surface and a reduction of the excess material volume. As shown in Fig. 1(a), heat treatment reduces the yield strength but increases strain hardening, which has a positive effect on the ductility of the stent and the reduction of global stresses.
- The process of stent deployment into the aortic arch was successfully modeled, including the steps of stent predeformation, positioning of the folded balloon, sequential balloon/stent expansion, and support of the aorta by expanded stent segments, see Fig. 1(b).

- The microstructure-based modeling approach allows the investigation of different microstructure realizations with characteristic pore/defect networks and the identification of the critical microstructures in terms of deformation and fracture behavior.
- The ML models used accelerate the microstructure-based prediction of mechanical properties, especially GNN, as they take into account not only the properties of the individual grains but also the interactions between them.

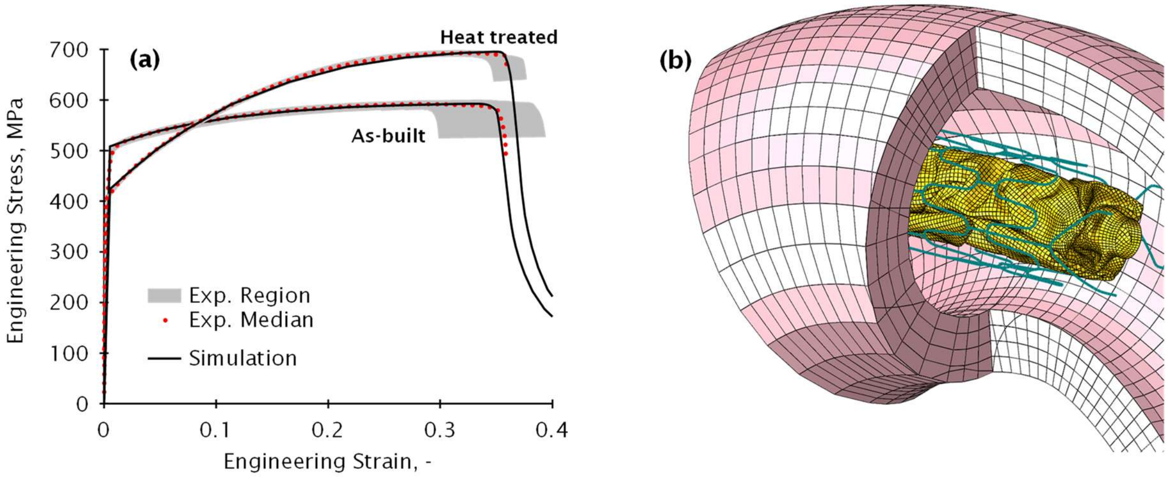

Fig. 1 (a) Influence of heat treatment on stress-strain behavior compared with the as-built condition and (b) simulation of the stent implantation process in the aortic arch with sequential balloon expansion.

3. Conclusions

This work demonstrates the potential of physics-based modeling approaches for improved predictive simulations of the influence of microstructure on the properties and fracture behavior of filigree L-PBF structures, such as stents. In conjunction with ML models, the established modeling framework enables the derivation of high-quality structure-property-performance relationships to extend the use of L-PBF to safety-related applications. This leads to a reduction in computation time, the use of a large number of geometric and material degrees of freedom, and sustainable and efficient design optimization.

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