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Short communication

Quantification of tensile damage evolution in additive manufactured austenitic stainless steels

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ABSTRACT

This study aims to quantify the material behavior, mechanical response, damage evolution and fracture characteristics of an austenitic stainless steel fabricated by Laser Engineered Net Shaping (LENS™). An internal state variable (ISV) plasticity-damage model is used to capture the effects of microstructural features, associated with the manufacturing process, on mechanical properties.

1. Introduction

During the past few decades, "Additive" Manufacturing (AM) has evolved as a new means to process parts layer-by-layer, in contrast to "subtractive" traditional manufacturing methods. Due to AM capability in fabricating customized parts with complex geometries, it is currently being considered in many applications including aerospace and medical to produce functional service parts due to AM capability in fabricating customized parts with complex geometries. However, defects and microstructural heterogeneity inherent to AM are major barriers for producing reliable structural components. This issue originates from many of the involved AM process parameters such as: laser power, beam travel speed, powder feed rate, layer thickness, hatching pitch, scanning strategy, and building orientation which result in complex thermal histories by affecting the incident energy as well as melt pool size and shape [1,2]. On the other hand, mechanical properties primarily depend on microstructural features (i.e. impurities, grain size and morphology) which are strongly affected by the thermal history (i.e. the thermal gradients, cooling rates, and reheating) experienced during processing.

Furthermore, even under constant laser process parameters and scanning pattern, distinct thermal histories, and consequently, microstructure variations can result from different inter-layer time intervals (i.e. the amount of time taken for the laser to finish one layer and start depositing the next layer) [3,4]. The inter-layer time interval can vary by laser idle time, part size, and number of parts fabricated on a build plate. The latter is a method to minimize manufacturing time of components in order to increase the adaptability of AM in industry. Thus, the parts can be fabricated all at once (in-parallel) instead of one-by-one (in-series). Mechanical and microstructural properties for parts built in-parallel may be different than those built in-series [4].

Hence, significant effort has been recently devoted to developing effective optimization and control mechanisms for fabricating components with uniform microstructure and desirable mechanical properties [5]. Selection of appropriate process parameters with an interactive control system using thermal sensing and monitoring has been accordingly proposed [6]. Despite all of these research efforts, undesirable consequences of this manufacturing method on material properties are inevitable and overcoming this challenge is still an open issue. However, having the capability to predict the variation in material behavior and mechanical response accurately may accelerate the adoption of AM for a myriad of engineering applications. This can be facilitated by relating the stress–strain response of the AM part to its microstructure (i.e. size and morphology) and defect statistics (i.e. size, spacing, etc.), affected by various thermal histories during fabrication, by a means of calibrating a microstructure sensitive plasticity model.

The internal state variable (ISV) plasticity-damage model

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Nomenclature

c	Triaxiality constant (MPa)
C	Coalescence term
C_{coeff}	Nucleation coefficient
d	Average particle size (mm)
d_0	Average pore diameter (mm)
f	Particles volume fraction
GS	Grain size of experiment sample (μm)
GS_0	Reference grain size (μm)
H	Isotropic hardening modulus constant (MPa)
I_1	First invariant of stress
J_2	Second deviatoric stress invariants
K_{IC}	Fracture toughness ($MPa\sqrt{m}$)
m	Material constant
n	Strain hardening exponent
NND	Average pore NND (mm)
R_0	Initial pore radius (mm)
R_d	Isotropic dynamic recovery constant ($1/MPa$)
t	Time
V	Initial pore volume fraction
Y	Rate-independent yield stress
Y_0	Yield stress constant (MPa)
z	Grain size exponent
$\underline{C}^e$	Elastic stiffness tensor
$\underline{D}$	Total rate of deformation tensor
$\underline{D}^e$	Elastic rate of deformation tensor
$\underline{D}^{in}$	Inelastic rate of deformation tensor
$\underline{n}$	Plastic normal tensor
$\underline{\varepsilon}^e$	Elastic strain tensor
ζ	Modulus-porosity adjustment term
η	Void nucleation term
$\dot{\lambda}$	Lagrange multiplier
ν	Void growth term
$\underline{\sigma}$	Stress tensor
$\underline{\sigma}'$	Deviatoric stress tensor
φ	Damage

introduced by Bammann et al. [7,8] and later modified by Horstemeyer and Gokhale [9] has been shown to have the ability to link microstructural details and heterogeneities to mechanical properties. Considering its capabilities in capturing and modeling microstructural defect induced damage, the ISV model has been extended in this study to quantify behavior and microstructure-property relation of an AM fabricated material subjected to tensile loading. The ISV model is used to link laser deposited 316L austenitic stainless steel (SS) inherent impurities to its mechanical response using the defects statistics of samples built in-parallel and in-series.

2. Materials and methods

For this study, cylindrical bars were fabricated using the LENS™ 750, a Direct Laser Deposition (DLD) AM machine that employs a blown powder system, as shown in Fig. 1(a), in vertical orientations out of gas-atomized 316L SS powder (C 0.042, Cr 20.0, Ni 11.0, Mn 1.4, Si 0.6, Mo 2.5, S 0.1, balanced Fe by wt%). The LENS processing parameters, selected to ensure a low level of porosity, were as follows: 360 W laser power, 8.5 mm/sec beam traverse speed, 1.2 g/s powder feed rate, 0.5 mm layer thickness, and 0.5 mm hatching pitch [4]. Using these process parameters, two groups of cylindrical rods were fabricated, as depicted in Fig. 1(b): (i) one sample at a time, 'in-series' (single-built) and (ii) nine samples all together, 'in-parallel' (nine-built). For the first group (single-built), each sample was fabricated continuously layer-by-layer without any time interval between layers. For the second group (nine-built), one layer of all nine samples was deposited before moving to the next layer; therefore, inter-layer time interval for nine-built samples (9X) takes approximately ten times longer than single-built samples (1X). Differences in the inter-layer time intervals of two groups cause a substantial difference in thermal history (i.e. cooling rate and tempering temperature of the previously deposited material), and consequently, microstructure properties (i.e. grain size and morphology) as well as defect size and distribution [4].

Tension tests were conducted on two sets of four round tensile specimens, machined from 1X and 9X AM rods, based on ASTM E-8 [10] with a strain rate of 0.001/s at room temperature. Details of the experimental setup and results can be found in [4]. Using scanning electron microscopy (SEM), the ISV model constants relating to the defect statistics were determined from the fracture surface analysis of failed specimens and microstructural examinations. In particular, particle size, d, and volume fraction, f, as well as the initial pore radius, R_0, were obtained from fractography of post-mortem tensile specimens, while the pores size, d_0, and their average nearest neighbor distance, NND, were captured from microstructural examinations of the longitudinal and transverse sections (i.e. parallel and perpendicular to the building direction) close to the middle region. The defects data were gathered from all

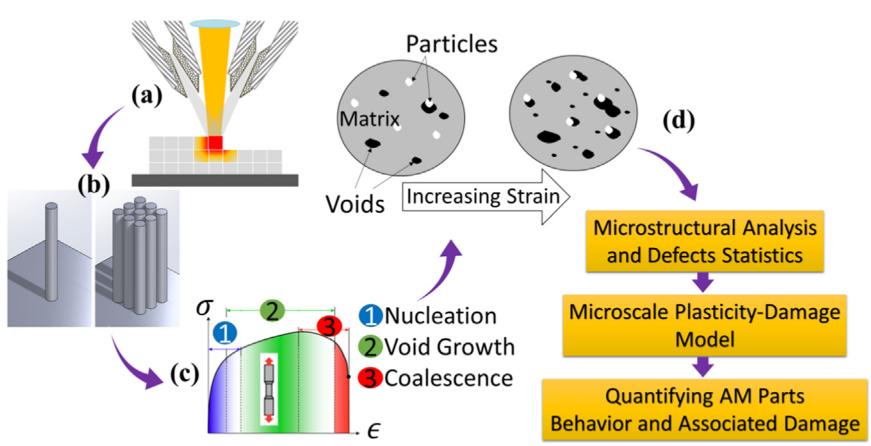

Fig. 1. A schematic showing (a) LENS process, (b) 1X and 9X cylindrical rods, (c) sequences in a ductile fracture mechanism, and (d) the ISV approach.