Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 7 (2017) 141–148

Structural Integrity Procedia

www.elsevier.com/locate/procedia

3rd International Symposium on Fatigue Design and Material Defects, FDMD 2017, 19-22 September 2017, Lecco, Italy

Damage development and damage tolerance of structures manufactured by selective laser melting – a review

U. Zerbst * and K. Hilgenberg

Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, D-12205 Berlin, Germany

Abstract

The additive manufacturing technology of Selective Laser Melting (SLM) experiences a rapid development within an increasing marked of quite different application fields. The properties of SLM materials and structures are influenced by a number of technological parameters such as the metal powder (particle size, homogeneity, cleanliness), the laser tool (power, beam diameter, pulse lengths), the scanning operation (speed, sequence and orientation of melting paths), parameters of the over-all equipment (design and preheating of the base plate, currents and turbulence in the protective gas atmosphere) and, last not least, the hatching strategy including the build-up direction of the structure with respect to the loading direction of the component.

For the perspective use of SLM structures as load carrying, safety-relevant components the knowledge of their mechanical properties is necessary. It is essential to understand these in the context of the manufacturing-related features and at the background of the basic characteristics of metallic materials: crystal lattice, microstructure and material defects. The paper provides an overview on factors which affect the mechanical parameters stiffness, strength, ductility, toughness, fatigue crack propagation and fatigue strength in the context of selective laser melting.

Keywords: Fatigue strength; fracture mechanics; initial crack size; short crack propagation; multiple crack propagation

Introduction

Fig. 1 (a) gives an overview on the factors that influence the principal mechanical properties of metallic materials (stiffness, strength, ductility, toughness, fatigue crack propagation and fatigue strength). These properties are affected by the materials basic characteristics (crystal lattice, microstructure and material defects) in quite different ways. In the following sections a brief overview is provided on the potential relationships with special emphasis to structures manufactured by Selective Laser Melting (SLM). Because of its paramount importance, this shall be preceded by the definition of the build-up direction with respect to the applied

---

* Corresponding author. Tel.: +49 (0) 30 8104 1531; fax: +49 (0) 30 8104 1537.
E-mail address: uwe.zerbst@bam.de

10.1016/j.prostr.2017.11.071

loading direction in different test configurations (Fig. 1b). For the fracture mechanics specimens, the nomenclature of ISO 12135 (2002) is used.

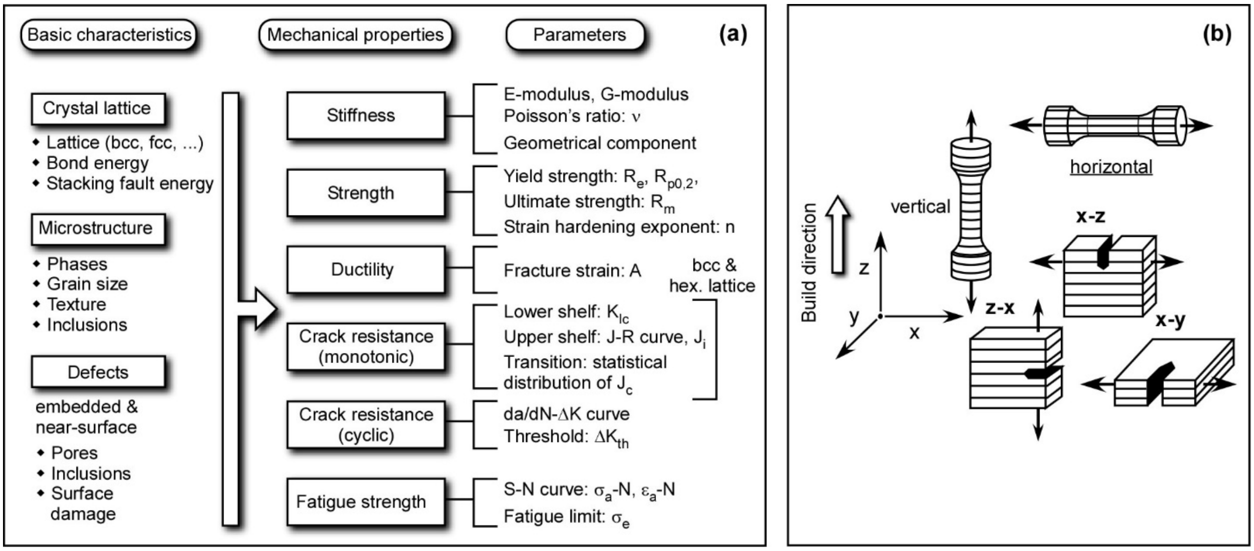

Fig. 1 (a) Relations between the basic characteristics, the basic mechanical properties and the mechanical parameters describing the latter in metallic materials; (b) Nomenclature for the build-up orientation with respect to the applied loading direction in SLM structures.

Stiffness

The stiffness, which is important with respect to the elastic form stability of components as well as for the avoidance of local stress concentrations due to stiffness discontinuities in compounds, e.g., between implants and bones, is usually characterized by the modulus of elasticity which is a function of the crystal properties, particularly the metal bounding and which can be influenced by alloying with high-melting elements (Rösler et al., 2006). Note, however, that stiffness is not only a materials property. Not least SLM provides unique possibilities for influencing this property by "tailoring" the internal structure of components, e.g., by the build-up of controlled porous and net-like patterns, e.g. Rotta et al. (2015). It should, however, be noted that porosity, beside the stiffness, also affects other properties such as the strength and the fatigue strength, usually in a negative way with respect to component performance, e.g., Ahmadi et al. (2016).

Strength and ductility

Besides the lattice type, which determines the number of active slip systems, the strength of polycrystalline materials is controlled by strengthening mechanisms such as grain boundary strengthening (of Hall-Petch materials with low stacking fault energy), solid solution strengthening, precipitation hardening or strain hardening. Fig. 2 shows two examples for the influence of SLM on the stress-strain behavior of austenitic steels (Cartlon et al., 2016; Meier & Haberland, 2006). Compared to the reference mate-rials manufactured by conventional technology both, an increased strength and a reduced ductility (in terms of the fracture strain) can be stated. Note that this is a quite common pattern also for other materials. Reasons are the steep temperature gradients, rapid solidifycation and fast cooling of the very small material volume of a SLM "welding layer" which cause martensitic transformation (in titanium alloys (e.g., Vrancken et al., 2012), dendritic fine columnar microstructures in austentitic steel (e.g., Carlton et al, 2016), etc. As the consequence, subsequent heat treatment of the as-built components becomes necessary in many cases. An example for this is shown in Fig. 2 (b). Besides the metastable microstructure, other features such as porosity as a material defect affect the stress strain properties of SLM structures. Note that porosity is a problem of SLM which it shares with technologies such as sintering, casting and (partially) welding, however, enhanced by texture formation due to the build-up process. Pores can be the result of unmelted powder, the balling effect or gas entrapment. Which mechanism dominates and how pronounced the effect is, is affected by the technological parameters, most of all the laser power and scanning speed (Kasperovich et al., 2016). Ibbett et al. (2105) demonstrate in a numerical simulation of the crack behavior of Nylon-12 that the location, the size and the number of unmelted particles can have a significant effect not only on crack initiation but also on crack paths. It is not hard to imagine that any texturizing of porosity, e.g., following the build-up pattern might be dramatic for properties such as ductility and fatigue crack propagation and, in combination with these, fracture toughness and the fatigue strength. The disadvantageous effect of porosity on the ductility is illustrated in Fig. 2 (a) and (b). Fig. 2 (c) shows the effects of the build-up direction and layer thickness. Note that