Additive Manufacturing 8 (2015) 12–35

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control

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ARTICLE INFO

Article history:
Received 23 December 2014
Received in revised form 7 May 2015
Accepted 20 July 2015
Available online 26 July 2015

Keywords:
Direct Laser Deposition (DLD)
Additive manufacturing (AM)
Microstructure
Fatigue behavior
Process control

ABSTRACT

The mechanical behavior, and thus 'trustworthiness'/durability, of engineering components fabricated via laser-based additive manufacturing (LBAM) is still not well understood. This is adversely affecting the continual adoption of LBAM for part fabrication/repair within the global industry at large. Hence, it is important to determine the mechanical properties of parts fabricated via LBAM as to predict their performance while in service. This article is part of two-part series that provides an overview of Direct Laser Deposition (DLD) for additive manufacturing (AM) of functional parts. The first part (Part I) provides a general overview of the thermo-fluid physics inherent to the DLD process. The objective of this current article (Part II) is to provide an overview of the mechanical characteristics and behavior of metallic parts fabricated via DLD, while also discussing methods to optimize and control the DLD process. Topics to be discussed include part microstructure, tensile properties, fatigue behavior and residual stress – specifically with their relation to DLD and post-DLD process parameters (e.g. heat treatment, machining). Methods for controlling/optimizing the DLD process for targeted part design will be discussed – with an emphasis on monitored part temperature and/or melt pool morphology. Some future challenges for advancing the knowledge in AM-part adoption are discussed. Despite various research efforts into DLD characteristics and process optimization, it is clear that there are still many areas that require further investigation.

Contents

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http://dx.doi.org/10.1016/j.addma.2015.07.002

Nomenclature

ΔK	stress intensity factor ranges, MPa$\sqrt{m}$
a	crack length, μm
da/dN	crack extension per cycle, mm/cycle
C	specific heat, J/kg K
G	temperature gradient at solid–liquid interface, K/m
GS	smallest grain size, μm
h	height of substrate, mm
J_{Ic}	J-integral fracture toughness, kJ/m^2
k	number of functional dimensions
K	stress intensity factor, MPa$\sqrt{m}$
K_I	stress intensity factor in Mode I, MPa$\sqrt{m}$
K_{IC}	plane-strain fracture toughness, MPa$\sqrt{m}$
K_{max}	maximum stress intensity, MPa$\sqrt{m}$
K_t	system gain
l	melt pool length, mm
L	latent heat of fusion, J/kg
M	powder feed rate, g/min
MS	characteristic length scale for microstructural interaction
N_{sp}	non-dimensional specific energy index
N_f	number of cycles to failure
N_{INC}	number of cycles to incubate a crack
N_{LC}	number of cycles required for long crack propagation
N_{MSC}	number of cycles required for propagation of a microstructurally small crack
N_{PSC}	number of cycles required for propagation of a physically small crack
N_{Total}	total fatigue life
R	solidification rate
R_s	stress ratio or strain ratio
R_a	roughness, μm
Q	laser beam radius, m
r_b	laser power, W
S	nominal stress, MPa
s	transformed coordinate
T_a	ambient temperature, K or °C
T	temperature, K or °C
T_L	liquidus temperature, °C
V	traverse speed, mm/s
α	fitting parameter for Eq. (3)
β	fitting parameter for Eq. (3)
γ	fitting parameter for Eq. (3)
Λ	sphericity coefficient
ε	strain
τ	time constant, s

1. Introduction

Direct Laser Deposition (DLD) is a type of laser-based additive manufacturing (LBAM) process for fabricating metallic, functional parts. In contrast to Selective Laser Melting (SLM), which utilizes a bed of powder metal that is 'selectively' melted via a laser, DLD is accomplished by simultaneously delivering metallic powder (or wire) and focused laser energy. In DLD, a relatively high powered laser (e.g. Nd:YAG or CO_2) is utilized to create a melt pool (or molten pool) atop the surface of a substrate within an inert atmosphere (e.g. argon); simultaneously, powder is injected/blown through the laser beam and into the melt pool. Using a sliced 3D CAD (computer aided drawing) file, parts are then built layer by layer, with each layer assembled track by track via a user-defined tool path. The DLD process can involve multiple nozzles or a single nozzle for the blown powder deposition; for example, a common technology for accomplishing multi-nozzle, blown-powder DLD is Laser Engineered Net Shaping (LENS) [1]. Table 1 demonstrates that, in addition to LENS, there are many other aliases and commercialized technologies related to DLD [2–23]. Further details on the development and variations on DLD are provided in Part I.

Direct Laser Deposition is unique in that it can be used for the additive manufacturing (AM) of functionally graded and pure-metal parts, as well as for laser cladding/repair. It also has the potential to produce materials to exact dimensions for aerospace, medical, or military industries. Some common materials that have been investigated for DLD include: titanium alloys [24–34], steels [6,18,35–41], nickel base superalloys [40,42–47], cobalt base alloys [48–50], aluminum, and copper alloys [51]. Grylls [52] has specifically listed the following alloys from these material systems as compatible with the DLD process: titanium alloys (e.g. Ti-22Al-23Nb, Ti-48-2-2, TiC), steels (e.g. 10V, 15-5 PH, 410, 416, AISI 309, Aermet 100, A2, MM 10, CPM S7), nickel base superalloys (e.g. CMSX-3, Haynes 188, Haynes 230, IN600, IN690, IN713, MarM247, Rene 142, Rene N5), aluminum alloys (e.g. CP Al, 6061, 2024) and copper alloys (e.g. Cu–10%Sn and GRCop-84). DLD is also capable

Table 1
Different powder-based laser deposition additive manufacturing techniques [2–23].

Process	Acronym	References
Laser cladding	LC	[2,3]
Laser direct casting	LDC	[4,5]
Direct metal deposition	DLD	[6]
Directed light fabrication	DLF	[7–9]
Laser forming	Lasform	[10]
Shape deposition manufacturing	SDM	[11]
Laser engineered net shaping	LENS	[12,13]
Laser powder fusion	LPF	[4]
Freeform laser consolidation	LC	[14,15]
Laser-aided direct-metal/material deposition	DMD	[16–18]
Laser-based multi-directional metal deposition	LBMDMD	[19,20]
Laser-aided manufacturing process	LAMP	[21–23]