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Microstructure and mechanical behavior of laser additive manufactured AISI 316 stainless steel stringers

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ABSTRACT

Laser additive manufacturing of stainless steels is a promising process for near net shape fabrication of parts requiring good mechanical and corrosion properties with a minimal waste generation. This work focuses on high aspect ratio AISI 316 steel structures made by superposition of sequential layers. A special nozzle for precise powder delivery together with a monomode fiber laser allowed producing high quality steel stringers on AISI 316 steel substrates. Although the stringers average compositions were inside the austenite plus ferrite range, only austenite phase was verified. The cladded structure presented some internal pores and cracks, responsible by the low Young's moduli. However, the tensile properties were similar to the base material and other literature results. The three-point flexural tests also produced good results in terms of formability. The fabricated structures proved to be useful for use in mechanical construction.

1. Introduction

Laser additive manufacturing (LAM) comprises a set of processes characterized by addition of new component layer by layer using the heating provided by a laser source. These processes are gathering more and more acceptance because of possibility to build entire parts with a minimum discard of material. The freshly deposited material could have properties near to the substrate material or to be a completely different compound [1]. LAM could be used to produce tailor made pieces for prosthesis, aircrafts, top level sports, and so on, as long as a 3D CAD project has been created.

Austenitic stainless steels, such as AISI type 316, are particularly interesting for LAM because they are relatively expensive to be machined. Also welding may produce corrosion sensitive grain boundaries [2]. Near net shaped structures could be manufactured without appreciable material losses, decreasing the waste of expensive metals such as Ni, Cr and Mo. For engineering applications, AISI 316 steel presents outstanding intergranular corrosion resistance, good grain corrosion resistance to most chemicals, salts and acids and Mo content helps increase resistance to marine environments [3]. The low carbon version of AISI 316, called 316L, is virtually immune to sensitization (grain boundary carbide precipitation) [4] and are especially suitable for in vivo applications.

The concept of LENS – Laser Engineered Net Shaping was introduced by first time by Sandia researchers [5]. The process deals with automatic fabrication of a 3D structure direct from a computer aided designed solid model using lasers. In LENS, the laser melts sequential layers of a previously deposited layer on a given substrate. Keicher [6] produced LENS of stainless steels with accuracy of about 130 μm in the deposition plane and about 400 μm in the growth direction. According to the author, for 316 stainless steel, the tensile mechanical properties of a one inch bar were: ultimate tensile strength 590 MPa, yield strength 240 MPa and total elongation 50%. The typical process parameter to achieve tough clads were: laser type Nd:YAG, laser power 250 W, travel speed 8.5 mm/s, hatch line separation 380 μm, laser spot size 600 μm, line offset 190 μm and powder feed rate 3 g/min.

Yang et al. [7] described selective the laser sintering of 316L stainless steel for customized dental bracket implants. These authors use a 200 W fiber laser in a commercial Dimetal-280® equipment to produce almost 99% dense bracket slots. The better results for mechanical properties were: ultimate tensile strength 636 MPa, total elongation 35% and hardness 265 HV.

Zhang et al. [8] studied the effect of powder size on densification of LAM 316L steel. These authors shown that spherical and largely distributed grain produced higher densification of the clad. The effect is due to a better particle packing, reaching 90% densification.

Man et al. [9] used a 5 kW CO_2 laser to produce thick (up to 4 mm height) 316L clads on 316L substrate. Using a CNC table, the authors produced 97.5% dense clads at 1.4 m/min speed using a feed rate of 32 g/min. However, only 20% of the impingent powder was effectively added to the surface. Tensile specimens obtained from the as-deposited clad plus substrate attained the

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Table 1
Chemical composition (weight percent) of the substrate and powder compared to the reference values.

	Co	Cr	Cu	Mg	Mn	Mo	Nb	Ni	P
Substrate	0.06	17.1	0.03	<0.01	1.40	2.59	<0.01	13.66	0.02
Powder	0.15	16.01	0.10	<0.01	0.75	2.37	<0.01	10.41	0.02
Ref	–	16.0–18.0	–	–	2.0_{Max}	2.0–3.0	–	10.0–14.0	0.045_{Max}
	Si	Ti	V	W	C	S	O	N	Fe
Substrate	0.70	<0.01	0.02	0.02	0.015	0.006	0.061	0.089	Bal.
Powder	0.70	<0.01	0.03	0.01	0.105	0.010	0.131	0.100	Bal.
Ref	0.75_{Max}	–	–	–	0.03_{Max}	0.03_{Max}	–	0.10_{Max}	Bal.

following maximum values: tensile strength 510 MPa, yield stress 450 MPa, total elongation 20% and hardness 260 HV.

Dadbakhsh et al. [10] studied the effect of gas flow on the consolidation of 316L steel clads. The authors' results show that the part layout and gas flow condition have a negligible influence on porosity formation, however they notably affect the thermal stress and bonding strength between particles which consequently influences the mechanical properties of final parts.

Ion [11] also commented the question of the gas flow and quality on the steel clad formation. Nitrogen gas must be avoided because of nitride layers formation which hardens the solid and difficults the lateral dilution between laser tracks. Other process parameters are also stressed by the authors such as workpiece manipulation, pre- or postheating and adaptive control. The question of covering large areas are also discussed in particular the overlap ratio which must be optimized for a given condition.

It could be seen that these previously reported papers concentrated on relatively thin clad layers of stainless steel. A raison for this is that, when superposing more and more LAM layers, metallurgical problems occurs due to the heat gathering.

For some applications, such as stringers in mechanical structures and prosthetic, high or large LAM parts must be considered. In spite of the previous studies of stainless steel clads, there are missing data on the high aspect ratio superposed clads from a microstructural and mechanical points of view. Accordingly, this contribution intends to study the phase growth and mechanical properties of laser additive manufactured 316 stringers with high aspect ratios.

2. Experiment apparatus and method

A monomode fiber laser with maximum 400 W output power was used together with a special coaxial nozzle developed by IREPA Laser [12]. The focal length was fixed at 200 mm with a relative defocusing to the surface of 30 mm, giving a spot diameter of 0.46 mm. The IREPA coaxial nozzle is very precise. The lateral positioning accuracy was 5 μm and repeatability from one point to other, considering a 200 × 200 mm batch, was less than 10 μm.

Argon gas flux was used as transportation medium for the particles (3 l/min) and as well as secondary shield atmosphere around the laser beam spot (1.5 l/min). The average particle flux rate was approximately 1.7 g/min. The standoff distance nozzle to workpiece was 3.5 mm.

Table 1 shows the analyzed compositions of both powder and substrate obtained from IP-AES and combustion techniques. The compositions are compared to the AISI 316 steel values obtained in Ref. [13]. As can be seen, the chemical compositions agree to the standard but the carbon content of the powder. The higher carbon content of the powder helps consolidate the superposed layers.

Fig. 1 shows a schematic picture of the cladded rows on a given substrate. The growth direction is indicated in the figure. Here, the additive manufacturing was accomplished by three sequential rows of melted powder with a spacing shift Δy_r then by lateral superposed rows and so on. There are three types of dilution, one at the substrate with depth Δz_d, other within each deposited row laterally Δy_o and other between each superposed row Δz_c. Fig. 1 also presents the depth of the heat affected zone Δz_h and the clad row height Δz_l. The overlapping (*Ov*) is defined as the ratio $\Delta y_0/\Delta y_r$. For the current experiments, the overlapping was fixed at 33% corroborating the best results attained in the literature [14].

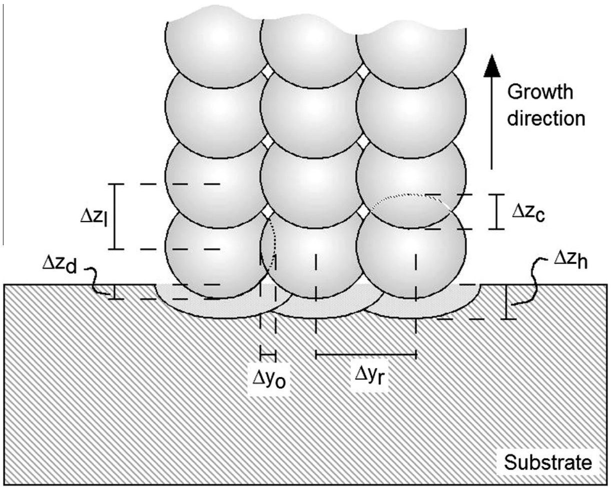

Fig. 1. Schematics of the laser additive manufacturing process showing the different definitions used in the text.

Table 2
Process parameters.

Code	*P* (W)	*V* (mm/min)	Δz_l (mm)	*Ov* (%)	*h* (mm)	*l* (mm)	*t* (mm)
A	200	500	0.26	33	105.4	25.3	3.1
B	200	500	0.26	33	27.3	100.0	3.2
C	200	200	0.44	33	102.2	25.8	3.3
D	200	200	0.44	33	27.4	100.3	3.1
E	350	500	0.40	33	134.1	25.8	3.2
F	350	500	0.40	33	25.5	100.5	3.2

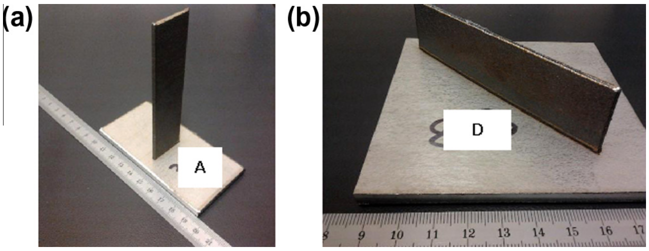

Fig. 2. LAM stringers: (a) 100 mm height and (b) 25 mm height cladded layers.