Materials and Design 104 (2016) 404–413

Contents lists available at ScienceDirect

Materials and Design

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

Development and characterization of Ti-6Al-4V to 304L stainless steel gradient components fabricated with laser deposition additive manufacturing

Ashley Reichardt [a,*], R. Peter Dillon [b], John Paul Borgonia [b], Andrew A. Shapiro [b], Bryan W. McEnerney [b], Tatsuki Momose [c], Peter Hosemann [a]

[a] Department of Nuclear Engineering, University of California, Berkeley, CA, United States
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States
[c] Department of Materials Processing, Tohoku University, Sendai, Japan

ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form 15 March 2016
Accepted 5 May 2016
Available online 10 May 2016

Keywords:
Laser deposition
Functionally graded
Ti-alloy
Stainless steel 304L
Fe-V sigma phase

ABSTRACT

In this study, a multi-hopper laser deposition system is used to additively manufacture functionally graded Ti-6Al-4V to 304L stainless steel components with a vanadium interlayer. Grain morphology, phase, and composition are mapped along the component gradients with electron backscatter diffraction (EBSD) and energy dispersive X-ray spectroscopy (EDS), and mechanical property changes are assessed utilizing Vickers hardness and nanoindentation. Precipitation of brittle intermetallic compounds such as FeTi and the formation of an Fe-V-Cr sigma phase are confirmed to be the causes of mid-fabrication cracking in the components. Guided by multicomponent phase diagrams, alternate paths in composition space are proposed to strategically avoid unfavorable phase formation along the gradient. Composition-dependent adjustment of process parameters is also proposed to reduce the prevalence of observed powder inclusions, homogenize grain morphology, and improve component mechanical properties.

1. Introduction

Developments in additive manufacturing of metals have introduced a number of capabilities unparalleled by conventional manufacturing [1]. Laser metal deposition (LMD) in particular accomplishes layer-by-layer fabrication of near net-shaped components by introducing a powder stream into a high energy laser beam. In this process, a melt pool is formed by rastering the laser beam across the sample surface, and powder is injected into the melt pool to deposit each layer. In addition to the geometric freedom afforded by LMD, precision tailoring of composition and microstructure can be achieved to produce highly specialized components [2–4]. Gradient metal alloys, or components with a functional composition gradient, have been demonstrated by layering an alloy directly on a dissimilar metal base using LMD systems with single-powder injection as well as powder bed-based systems [5–9]. However, the introduction of multiple-hopper powder feeders to LMD has made possible dissimilar metal gradients that are traditionally difficult to achieve [10]. By placing different alloy or element powders into separate feeders and simultaneously depositing them in varying quantities, even nonlinear or nontraditional gradient paths between alloys can be followed. Furthermore, large differences in properties such as thermal expansion coefficient may be alleviated through gradual transitions consisting of many steps in composition space.

Recently, Hofmann et al. [10] outlined a systematic approach for designing and fabricating both linear and radial gradient alloys with a multi-hopper LMD system. Guided by multicomponent phase diagrams, a path from one alloy to another can be strategically chosen to avoid unfavorable phase formation in between. Using this method, Hofmann et al. successfully fabricated several functionally graded components transitioning from Ti-6Al-4V to elemental vanadium, as well as from 304L stainless steel to Invar 36 [10].

In this work, prior insight and thermodynamic modeling from Hofmann et al.'s study is applied to investigate the feasibility of additively manufacturing a historically difficult and sought-after joint between titanium alloy and austenitic stainless steel. High-integrity joints between Ti-alloys and stainless steels, such as Ti-6Al-4V to 304L SS, are called for in the nuclear [11], aerospace, and other industries, however they continue to present a problem for both fusion and non-fusion welding techniques [11–13]. Direct joining of the two alloys is ultimately compromised by cracking, unwanted residual stresses, and low bend ductility resulting from the formation of brittle intermetallic compounds FeTi and Fe_2Ti. Differences in coefficient of thermal expansion (Ti-6Al-4V: 8.6 μm/m-°C; 304L SS: 16.9 μm/m-°C, mean value 0–100 °C) and melting temperature (Ti-6Al-4V: 1660 °C, 304L SS:

* Corresponding author at: 4155 Etcheverry Hall, MC 1730, University of California, Berkeley 94720-1730, United States.
E-mail address: areichar@berkeley.edu (A. Reichardt).

http://dx.doi.org/10.1016/j.matdes.2016.05.016
0264-1275/

1450 °C) also contribute to failure of traditional fusion welding processes. It is commonly observed that dissimilar metal welds with significant thermal expansion mismatch can lead to residual stresses upon cooling of the joint, often exceeding the yield stress of the material [14]. Although direct bonding via solid state processes such as explosion welding has been successful at mitigating this issue [15], the geometric limitations of such techniques reduce their widespread applicability.

Recently, some success has been seen with the introduction of an intermediate metal layer which prevents significant mixing between the Fe and Ti, and thus modifies the final phase composition along the joint [16–18]. Common interlayers include Cu, Ni and their alloys, as well as metals which form continuous solid solutions with Ti, including Mo, Zr, Nb, Ta, and V. Tomashchuk et al. [16] showed that Cu and V interlayers reduce the formation of brittle intermetallic compounds and significantly improve mechanical properties in laser and electron beam welded Ti-6Al-4V to 316L SS. Even so, the integrity of the final joint has proven to be extremely sensitive to small changes in the size and location of the melt zone. Sahasrabudhe et al. [8] demonstrated that use of single-powder feeder laser-engineered net-shaping (LENS) to bond a 410 SS substrate to Ti-6Al-4V using a Ni-20% Cr alloy interlayer eliminated cracking in the joint transition and reduced the formation of intermetallic phases. However, further study of the phase formation and segregation observed in the transition region between the Ti-alloy and NiCr alloy is still needed.

For successful and reproducible joining of Ti-6Al-4V to 304L SS, it is clearly necessary to use a process that allows for careful control over the composition gradient along the joint. Multi-hopper LMD is therefore an excellent contender. Layer by layer composition changes, the introduction of a dissimilar metal interlayer, and close control over the melt zone size and location can all be accommodated. Much research has already been devoted to understanding the effects of various LMD process parameters on single-alloy components [19–22]. These studies indicate that solidified microstructure, porosity, and final mechanical properties vary significantly with laser power, scan speed, powder feed rate, and other parameters. Similarly, fabricating high integrity gradient components will also ultimately require iterative optimization of process parameters and gradient path choice.

For the first stage of this process reported here, several prototype LMD components were manufactured using a simple linear gradient path between Ti-6Al-4V to 304L SS via elemental V. The components were then sectioned and prepared for post-fabrication analysis in order to provide guidance for future improvements in process parameters and composition gradient path. Characterization is performed using scanning electron microscopy (SEM), electron backscatter diffraction (EBSD) and energy dispersive X-ray spectroscopy (EDS). The combination of these techniques provides a full survey of microstructural and compositional changes along the gradient, including mapping of grain size and shape, phase, texture, and relative concentration of elements. Thermodynamic modeling of the Ti-V-Fe and V-Fe-Cr systems confirms the observed phase composition and predicts more favorable gradient paths. Mechanical property changes along the gradient are also assessed with both Vickers hardness testing and nanoindentation. Based on these findings, a modified set of process parameters and gradient paths for future Ti-6Al-4V to 304L SS components is proposed.

2. Experimental

2.1. Component fabrication

Gradient components were additively manufactured using a four-hopper RPM 557 Laser Deposition System with YAG laser and inert atmosphere (RPM and Associates, Inc., South Dakota), shown schematically in Fig. 1. A detailed description of component fabrication is given in [10]. The samples were deposited on metal substrates (Ti-6Al-4V or 304L SS) with a nominal laser power of 600 W, layer thickness of 0.381 mm, and hatch travel speed of 76.2 cm/min. Powder specifications are given in Table 1, including the mesh sizes used to remove particles smaller than (−) and larger than (+) the given meshes to achieve the desired range in particle size. Composition gradient paths and powder feed rates for the samples are given in Tables 2 and 3, and schematic diagrams are given in Fig. 2(a) and (b). It is expected that melting temperature, laser absorptance, and thermal conductivity will vary in each composition step, leading to differences in optimal process parameters, particularly those which affect heat input. In the case of this study it was chosen to maintain constant process parameters throughout the build, such that post-build characterization can be used to guide composition-dependent changes in future builds.

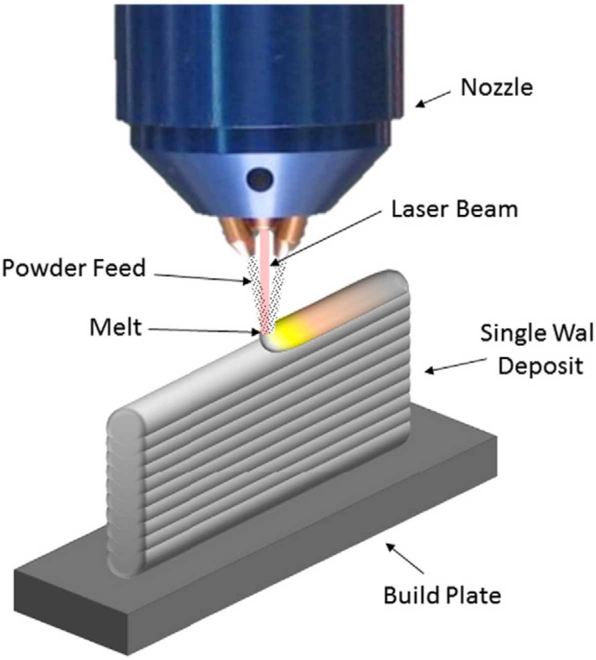

Fig. 1. Schematic of RPM laser metal deposition system.
Provided by RPM Innovations, Inc.

Component A transitions from Ti-6Al-4V to V to 304L SS, and was manufactured by first depositing pure Ti-6Al-4V followed by the addition of vanadium in 25% increments. At least 15 layers were deposited at each composition step to allow for sufficient sample area for post-build analysis. Following the 75% V + 25% Ti-6Al-4V step, the titanium alloy was replaced with 25% 304L SS. At layer 126, the fabrication was prematurely halted due to cracking and delamination observed in the build at the layer in which steel was first introduced.

A reverse transition component was also fabricated (component B), beginning with pure 304L SS followed by additions of vanadium in finer steps of 3%. One or two layers were deposited for each composition step, resulting in a relatively smooth gradient. However, this component was also halted due to cracking in the build, which was first observed at layer 23 or a composition of 36% V and 64% SS.

2.2. Characterization

For microstructural characterization of the gradients, the components were cross-sectioned and prepared with standard metallographic

Table 1
Powder specifications.

Powder type	Mesh size	Powder size (μm)
Ti-6Al-4V	−80/+325	44–177
Vanadium	−60/+325	44–250
304L SS	−140/+325	44–105