Journal of Manufacturing Processes 28 (2017) 550–557

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

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

Thermal effect on clad dimension for laser deposited Inconel 718☆

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ARTICLE INFO

Article history:
Received 18 November 2016
Received in revised form 10 February 2017
Accepted 3 March 2017
Available online 11 May 2017

Keywords:
Additive manufacturing
Direct energy deposition
INCONEL 718
Cooling rate
Volume change

ABSTRACT

Additive manufacturing of components made of nickel-based and high strength materials that endure extreme environments, such as Inconel 718, is gaining traction in aerospace and automotive industries. However, one of the remaining challenges of laser deposited alloys is the volume change of the clad during a build, leading to warping, compromised dimensional integrity of the final part, and an increase in surface roughness. In addition, there has been no work in the prediction and control for volume change of localized areas within a laser deposited component. The dimensional integrity of a completed laser deposited structure is dependent on the uniformity of each individual clad track, with high variability in thermal history and clad height. The approach in this paper is the use of an in-situ infrared camera to capture the thermal history and determine the unique solidification rate of each localized point of each clad. Clad height measurements various points of the clads relative to the tool path were used to establish a relationship between process parameters, solidification rate and the volume change of the clad that verify analytical thermal models in the literature. Expanding these relationships to more complex build geometries, different laser deposited materials and a wider variety of processing conditions will allow for a better understanding, and therefore control, of the laser deposition process for more ubiquity of additive manufacturing in industry.

1. Introduction

Direct Energy Deposition (DED) is an additive manufacturing (AM) process that is rapidly growing as a process to repair and build fully dense and high strength nickel-based components that can endure extreme environments for aerospace and automotive industries. Although DED is growing in ubiquity, one of the remaining challenges in the process is that many components undergo volume change and anisotropic cooling rates.

Blown powder laser deposition, a form of DED, is an AM technique possessing unique potential for the creation of complex geometries that cannot be created by conventional manufacturing methods, including parts with internal cavities, the repair or modification of existing components, and the creation of bi-metallic or gradient material structures [1,2]. In the laser deposition process, powder is pneumatically conveyed via an inert gas into a molten pool, which is generated by a laser beam on an existing substrate, as seen in Fig. 1. As the laser moves relative to the part at some process feed rate, the molten pool solidifies to form a solid material track. A fully dense 3D geometry can be created by overlapping these tracks side-by-side and depositing consecutive layers on top of the previous layers. The dimensional consistency of the completed structure relies on the uniformity and repeatability of the width and height of each individual clad track. If the heights of the individual clad tracks are lower than the programmed layer height in the motion system, the build will move below the focal point of the powder and laser leading to a decrease and eventual cease of deposition. This phenomenon is referred to as "under-building". Likewise, if the heights of the individual clad tracks are higher than the programmed layer height in the motion system the build will move above the focal point of the powder and laser and could potentially collide with the deposition nozzle. This phenomenon is referred to as "over-building." Deposition dimensions depend on process parameters such as laser power, process feed rate, powder flow rate, and substrate temperature [3].

Varying powder flow rates at constant laser power and process feed rate result in differing single-track cross sections with three categories of cross-section shape [4,5]. These cross sections are

☆ 45th SME North American Manufacturing Research Conference, NAMRC 45, LA, USA.

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http://dx.doi.org/10.1016/j.jmapro.2017.04.024
1526-6125/

characterized by the angle between the substrate and the tangent of the single-track cross-section edge, as seen in Fig. 2. Low powder flow rate results in high dilution, low clad height and large clad angle, whereas the opposite trends occur at high powder flow rates. Dilution can be used to quantify the bond between the clad and the substrate as well as the laser power efficiency during the build [6]. High dilution indicates an inefficient use of laser power where there is excessive melting of the substrate. Low dilution indicates poor bonding and possible loss of adhesion. Several studies have investigated process maps to determine optimal combinations of laser power and powder flow rate by using theoretical laser deposition models [4]. A model that included the mixing of powder in the melt pool showed that, in the ideal case where dilution is minimal, the clad thickness varies linearly with laser power and process feed rate [7]. Olivera et al. [3] correlated powder flow rate, process feed rate and laser power with the clad height, clad width, clad area, molten area, and clad angle. Zhang et al. [8] discussed the influence of process parameters in terms of specific energy, calculated by dividing actual power by beam diameter and scanning velocity. They found that the height of the cladding layer first increases, then decreases with increasing specific energy, concluding that specific energy affects size, shape and formation rate of the clad. Liu and Li [9,10] modelled a single clad track and a thin wall created using a low power laser, concluding that the clad shape is dominated by the powder concentration at any point for the duration that the point is molten.

The above-cited work assumes that with constant parameters the dimensions of the clad track will remain uniform. While this approach may be an acceptable assumption for laser deposition coating where only a few layers are deposited onto a substrate with a much larger thermal mass, the thermal profile of the build radically changes during laser deposition of a 3D component. As new layers of material are successively deposited, heat is conducted into the substrate, which acts as a heat sink [11]. As the process progresses, the thermal gradient decreases, such that with constant process parameters (e.g., laser power, process feed rate, powder flow rate), the melt pool size subsequently increases and the cooling rate decreases, leading to inconsistent track morphology and mechanical properties [12].

Slight changes in process parameters can result in large variations in volume change and cooling rate, which, in turn, influence mechanical properties and the type of post heat-treating or level of post-machining of the surface required to achieve the desired results. In the case of IN718, rapid shrinkage occurs immediately as cooling begins along with unique phase transformations during solidification, depending on solidification rate [16]. This provides motivation for future work in investigating microstructure evolution. Optimal deposition parameters have been investigated by many researchers for several materials and geometries [1–8,17–19]. These studies have investigated the influence of parameters such as laser power, powder flow rate, process feed rate, and powder size. However, these parameters are generally only valid for the specific geometry the researchers optimized, since the thermal history of the component through the deposition process is highly geometry dependent.

By tying final component properties to solidification rate, process maps and control parameters to give specified clad dimensions can be made that are transferable across machine platforms and varying part geometries. Consequently, the purpose of this study is to relate process parameters to thermal history and thermal history to clad dimensions in such a way that dimensional changes can be quantified in terms of thermal history and parameter interactions. Such relationships, introduce flexibility and control of process parameters for various build geometries and temperature conditions.

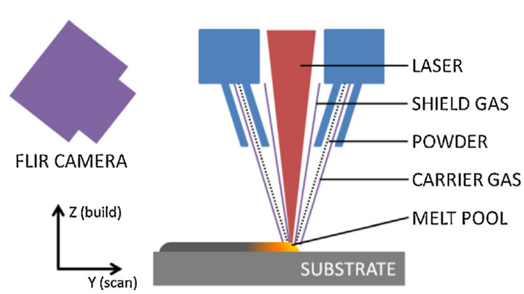

Fig. 1. Coaxial laser deposition process.

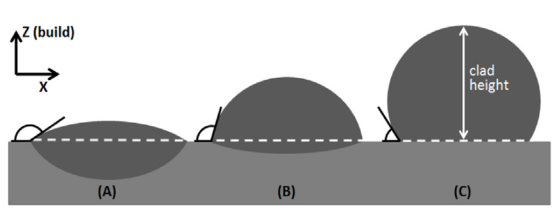

Fig. 2. Single clad cross section profiles. (A) Clad with relatively low powder flow rate and high dilution; (B) Clad with ideal powder flow rate; (C) Clad with relatively high powder flow rate and low dilution.

2. Methods

2.1. Laser deposition process

For this experimental study a DMG MORI LaserTec 65 3D, a hybrid additive and subtractive five-axis machine tool, was used. The machine includes a direct diode laser with a maximum power of 2500 W at a wavelength of 1020 nm. The beam is focused utilizing a lens with a 200 mm focal length to a 3 mm spot size. Gas atomized super alloy INCONEL 718 powder of particle size 50–150 μm was used. Due to its high temperature yield strength and corrosion resistance, IN718 has numerous applications in aerospace and nuclear industries, particularly in turbine components. Argon gas with a flow rate of 7 L/min was used as the shield gas and the conveying gas to deliver the powder coaxially to the melt pool. The experimental set up can be seen in Fig. 1.

Single line IN718 clads were deposited on a 1045 medium carbon steel disks 89 mm in diameter and 8.9 mm thick. The clads were 50 mm in length. Ten clad tracks were deposited on each substrate disk with 7 mm spacing between clads, as shown in Fig. 3. The laser power was held constant on each substrate disk while the powder flow rate was incremented from 3.5 to 27.1 g/min in 3.5 g/min increments. The laser power was incremented from 1000 to 2000 W in 200 W increments. The feed rate for all depositions was 1000 mm/min. To allow for cooling of the previous clads before subsequent clads were applied, the machine was dwelled 120 s between the deposition of each clad.

Three locations in each clad were studied in detail to understand the effect of cooling rate. The points were located at 10 mm, 25 mm, and 40 mm from the clad's start point. All three points were in the constant velocity region of the clad, where the acceleration was zero, and were expected to present similar characteristics. The thermal data and clad morphology were analysed at each location.

2.2. Infrared (IR) thermal measurements

In situ temperature measurements were performed during the deposition using a digital infrared camera (FLIR). The camera's resolution was 640 × 480 pixels with a spectral range from 7.5 to 14.0 μm and an accuracy of ±2 °C. The camera recorded the infrared