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Thermal and microstructural analysis of laser-based directed energy deposition for Ti-6Al-4V and Inconel 625 deposits

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ABSTRACT

Accurate temperature measurements based on careful experimentation and microstructural analysis were conducted for Ti-6Al-4V and Inconel 625 alloys deposited using the laser-based directed energy deposition process. In the case of the Ti-6Al-4V alloy, thermal measurements were made in the first layer during the first and four subsequent deposits to ascertain microstructural evolution during the heating and cooling cycles. Four energy densities were utilized during deposition of the Inconel 625 alloy to alter cooling rates and determine the impact of processing conditions on solidification morphology. The precise experimental measurements enabled a comprehensive analysis of the solid state reactions for Ti-6Al-4V, and the solidification phenomena to be elucidated for Inconel 625. The results for the Ti-6Al-4V alloy indicated that the measured thermal response could be used to anticipate initial microstructure based on cooling rates from the β-transus, and subsequent thermal cycles could be utilized to define potential transformations between α, α′, and β. Analysis of the measured thermal cycles from the liquid through solidification for the Inconel 625 alloy showed that processing parameters could be linked to factors governing the solidification process and microstructural features. Using these relationships, an accurate processing map for laser-based directed energy deposition for Inconel 625 was constructed to enable the identification of solidification morphology and microstructural scale based on critical processing parameters.

1. Introduction

Additive manufacturing or 3D printing is an emerging technology applicable to the aerospace, automotive, and biomedical industries, where parts are built layer-by-layer to create a three-dimensional component [1–3]. Laser-based directed energy deposition (DED) is a process that utilizes powder blown into the melt pool formed by the moving laser beam, to sequentially produce layers that result in a 3D part. During the process, the powder stream and the laser create a molten deposit on the surface of the substrate, that undergoes rapid cooling and solidification. Various process parameters, such as powder flow rate, laser power, scan velocity, and diameter of the beam can affect deposition morphology, microstructure, material properties, and overall deposition quality.

Although there has been significant research exerted towards developing links between process parameters and resultant microstructures for the DED process, very little experimental evidence is available that may be used to directly correlate the microstructural evolution with accurate thermal response of the material during processing. Even in instances where process simulations have been used to provide detailed information on heating and cooling cycles, the ability to alter process simulation results to suit the needs of microstructural analysis may hamper the validity of this approach in providing definite proof of the analysis. Hence, this research has been designed to acquire and utilize highly accurate thermal response data for ascertaining microstructural development for two alloy systems commonly used for the DED process.

Alloy Ti-6Al-4V is commonly used in the aerospace and medical industry due to its relatively low specific density, and exhibits excellent mechanical properties and corrosion resistance in extreme conditions [4]. The ability to track the solidification process for titanium alloys is somewhat unique due to post-solidification solid state transformations that are dependent upon cooling rate. During cooling from above the liquidus temperature, the molten titanium solidifies into a body-centered cubic (BCC), β phase, and depending on alloy content, most of the β phase transforms into a hexagonal close-packed (HCP), α phase, when

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temperature falls below the critical transformation temperature, the β transus [4]. The β phase is present from the melting point at 1604 °C to the β transus at around 980 °C, depending on the chemical composition [5], while at temperatures below the transus the α phase is stable [4,5]. At relatively low cooling rates, less than 3.5 °C/s, the transformation proceeds through a diffusional reaction of β transforming to α, while some β being retained [6]. The martensitic structure, α′, can form during cooling at a rate greater than 3.5 °C/s after passing the martensitic start temperature at 750 °C [4,6–9]. During additive manufacturing, complex thermal cycles may vary the resulting microstructures which influences the resultant mechanical properties. In general, tensile strength is inversely proportional to the α lath width [10], while the presence of the martensitic structure can significantly increase strength [11].

Researchers have attempted to model the microstructural evolution of titanium alloys and predict the microstructural outcome due to repeated thermal cycles associated with DED [7,12–16]. Kelly et al. developed a thermal model for Ti-6Al-4V microstructure evolution during laser DED processing [13,14]. Experiments were conducted with three scan velocities to produce various linear heat inputs with a single deposition direction, and samples were produced with eight layers [14]. Based on the experimental results, a microstructural-evolution map was developed and showed three different regions of Ti-6Al-4V microstructures within the columnar prior-β grains [13,14]. The lower region displayed a $\alpha' + \alpha_{massive}$ structure, which cooled from above the β transus at the rate between 3.5–410 °C/s [6–9]. The middle region consisted of a mixture of α + β microstructure occurring due to α dissolution and growth reactions during repeated thermal cycles. The upper region was identified as β phase formed from the liquid [14]. This research also showed that the Ti-6Al-4V microstructures formed during processing were influenced by the selected cooling rates and resultant thermal cycles [13,14]. Kelly et al. and Crespo utilized a Johnson-Mehl-Avrami-Kolmogorov (JMAK) relationship for describing several diffusional phase transformations operative with the Ti-6Al-4V system during repeated thermal cycles associated with additive manufacturing processes [8,15]. The JMAK relationships were derived to represent several transformation stages, which included the β → α and α′ transformations [8]. Murgau et al. also used a JMAK technique to develop a Ti-6Al-4V transformation model which was similar to Crespo [8,16]. The model was compared with other research results, and the simulation was similar to the experimental results of Kelly et al. [15,16]. An important aspect in much of the microstructural models that have been developed is the use of some form of a thermal model to describe the thermal transients that drive the microstructural models. This poses problems since virtually none of the prior research attempted to validate the thermal cycles obtained from models with experimental data. Because of this deficiency, the accuracy of the results for these microstructural models remains questionable.

Various additive manufacturing experiments with Inconel 625 alloy have shown that as-fabricated samples display a wide range of mechanical properties [17–21]. The process parameters of this prior research have also employed a broad range of energy densities for the deposition process. However, in all cases the tensile strength in the horizontal direction, represented by the x and y-orientations, displayed higher strength than the vertical direction or z-orientation. The opposite was found for the elongation. It was postulated by Rombouts et al. [20] that the vertical build direction experienced lower cooling rates, and repeated heating-cooling cycles during the process, which caused a higher carbide phase formation and a coarser microstructure. Other researches also showed that the DED process resulted in the formation of a columnar dendritic microstructure in the build or vertical direction [22]. Within these microstructures, the scale of features indicated an average primary dendrite arm spacing of 5 µm at the bottom of the build, while the average secondary dendritic arm spacing (SDAS) was found to be between 1.5 and 2.5 µm at the top of the build. It was proposed that cooling rates continually decreased as the deposition process moved away from the substrate [22]. These researchers also indicated that the cooling rates could be controlled by selection of process parameters, thus modifying the solidification structure and resultant mechanical properties for Inconel 625 deposits.

2. Experiment

Thermal measurements were conducted using embedded thermocouples along the centerline of a DED deposition track at the top surface of the substrate. This technique enables accurate temperature measurements within the melt pool through cooling. In order to measure the temperatures within the melt pool of a deposition track, high-temperature thermocouples were needed. Therefore, C-type, single-balled, tungsten-rhenium thermocouples with a maximum service temperature of 2320 °C were chosen with wire diameters of 0.38 mm and a ball joint being 0.76 mm (0.03 in.) in diameter. The experiments were conducted using two substrate materials, Ti-6Al-4V and Inconel 625, with the deposition powder materials being the same as the substrates. The powder materials that were utilized for deposition represented a particle size range of between 50–150 µm. Spherical Ti-6Al-4V powder was acquired from Phelly Materials, and spherical Inconel 625 powder was purchased from Allegheny Technologies Incorporated. The morphology of the powder materials are shown in Fig. 1. Both powders exhibited a spherical morphology with the Inconel 625 powder also displaying the presence of minor satellites. This was probably due to the processing used to produce the powders; whereas, the Ti-6Al-4V powder was produced using the plasma rotating electrode process (PREP), the Inconel 625 powder was produced using gas atomization. Prior to placing the thermocouples, the deposition substrates were prepared by machining plates to 15.2 cm long by 7.62 cm wide by 1 cm thick, and mechanically polishing the top and bottom surfaces. The substrate dimensions and the thermocouple locations are illustrated in Fig. 2.

For the placement of the C-type thermocouples, three holes were

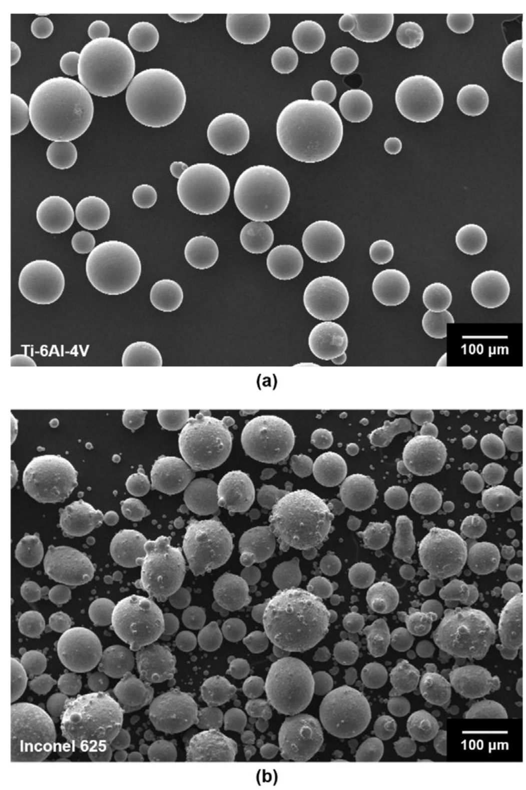

Fig. 1. Scanning electron microscopy (SEM) images for the (a) Ti-6Al-4V powder and the (b) Inconel 625 powder used during the experiment.