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A Coupled Thermal and Microstructure Model for Laser Processing of Ti-6Al-4V

Kelly, S. M.,[1,4] Babu, S. S.,[2] David, S. A.,[2] Zacharia, T.,[3] Kampe, S. L.[4]
kellysm@ornl.gov

Abstract

The current challenge in laser processing titanium alloys using methods such as Laser Metal Deposition (LMD) is in understanding the complex microstructure evolution during multiple passes of the laser. The microstructure is affected by the repeated thermal cycling that occurs during the deposition process. The current work focuses on the thermal and microstructural modeling of multilayered Ti-6Al-4V deposits. Prior work with LMD-Ti-6Al-4V has shown that a complex microstructure evolves consisting of a two-phase alpha+beta structure that is measurably different across the deposit. A thermal model has been developed using finite difference techniques to predict the thermal history of LMD processes. The characteristics of a thermal cycle are used to semi-quantitatively map the evolution of equilibrium and non-equilibrium phases in the deposit. The results of the thermal and microstructure models will be discussed in relation to the as-deposited microstructure.

(1) Joint Institute for Computational Sciences, Oak Ridge National Laboratory
(2) Metals and Ceramics Division, Oak Ridge National Laboratory
(3) Computing and Computational Sciences Directorate, Oak Ridge National Laboratory
(4) Materials Science and Engineering Department, Virginia Tech

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Introduction

The current challenge in laser processing of titanium alloys using methods such as Laser Metal Deposition (LMD) is in understanding the complex microstructure evolution during deposition of multiple layers of material. The current work focuses on the thermal and microstructural modeling of multilayered Ti-6Al-4V deposits. Prior work with LMD-Ti-6Al-4V has shown that a complex microstructure evolves consisting of a two-phase alpha+beta structure that is measurably different across the deposit. A thermal model has been developed to predict the thermal history of the LMD process, the results of which are used to map the evolution of microstructure within the deposit.

Experimental Procedure

The thermal model utilizes the implicit finite differencing scheme to numerically solve the two-dimensional transient heat conduction equation with temperature-dependent properties. Laser heating is modeled using an elliptical volumetric distribution of the laser power. In the current work involving Ti-6Al-4V, the following process conditions are modeled: a laser power of 11kW, laser scan speeds varying from 0.625mm/s to 2.5 mm/s, and corresponding interpass times of 200 to 800 seconds, and an eight layer deposit. Microstructure maps are developed using thermal cycle characteristics (cooling rate and peak temperature) obtained from the thermal model and by coupling with computational thermodynamics and kinetics.

Results and Discussion

The thermal model predicts that heat flow is dominated by conduction through the substrate and is generally one-dimensional. The variation of cooling rate and peak temperature as a function of laser scan speed within the first deposited layer as additional layers of material are added has been examined. For the deposition of the second through fifth layers, the values of the cooling rate and peak temperature are nearly independent of laser velocity. During the deposition of layers 6 through 8, the peak temperature of the fastest laser scan speed begins to increase above that for the slowest. This is a result of the interpass time not being sufficient to allow the part to completely cool.

Our current understanding of the microstructure evolution predicts that during the initial deposition of the layer, cooling rates are sufficiently fast to produce a microstructure consisting of martensitic (α') and massive ($\alpha_{massive}$) non-equilibrium alpha phases. During the deposition of subsequent layers, a region of this initially non-equilibrium microstructure is predicted to have a peak temperature greater than the beta transus and a subsequent cooling rate slower than that required to transform to the non-equilibrium phase, resulting in a diffusional transformation product ($\beta \rightarrow \alpha + \beta$). Hence, a characteristic microstructure layer is predicted to develop consisting of regions of non-equilibrium and equilibrium phases. The total thickness of the characteristic layer is on the order of a physically deposited layer (~7mm). The thickness of the diffusional layer is approximately 1 mm in thickness for the slowest laser velocity, and 0.5 mm thick for the fastest. This is true for the first 5 deposited layers; thereafter, as laser velocity increases, the thickness of the diffusional layer begins to increase. Currently different microstructure models are being evaluated for coupling with the thermal model.

Conclusions

A framework to model microstructure evolution during laser processing has been developed. The results from a process thermal model have been used to predict microstructure evolution in Ti-6Al-4V laser metal deposition builds. The deposit is predicted to contain a characteristic microstructure layer that is repeated within the deposit. This characteristic layer is predicted to contain non-equilibrium and equilibrium transformation products. The thicknesses of the characteristic layer components are dependent upon laser velocity and the number of layers deposited.