Acta Materialia 108 (2016) 26–35

Contents lists available at ScienceDirect

Acta Materialia

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

Full length article

Normalised model-based processing diagrams for additive layer manufacture of engineering alloys

Meurig Thomas [a, *], Gavin J. Baxter [b], Iain Todd [a]

[a] *Department of Materials Science & Engineering, University of Sheffield, Sheffield S1 3JD, United Kingdom*
[b] *Rolls-Royce plc, Derby DE24 8BJ, United Kingdom*

A R T I C L E I N F O

Article history:
Received 14 December 2015
Received in revised form
10 February 2016
Accepted 10 February 2016
Available online xxx

Keywords:
Additive layer manufacture
Processing diagrams
Microstructure
Titanium alloys
Mechanical properties

A B S T R A C T

Additive Layer Manufacturing (ALM) is becoming a more widely accepted method for the production of near net-shape products across a range of industries and alloys. Depending on the end application, a level of process substantiation is required for new parts or alloys. Prior knowledge of the likely process parameter ranges that will provide a target region for the process integrity can save valuable time and resource during initial ALM trials. In this paper, the parameters used during the powder bed ALM process have been taken from the literature and the present study to construct normalised process maps for the ALM process by building on an approach taken by Ion et al. in the early 1990's (J.C. Ion, H.R. Shercliff, M.F. Ashby, Acta Metallurgica *et* Materialia 40 (1992) 1539–1551). These process maps present isopleths of normalised equivalent energy density ($E_0{}^*$) and are designed to provide a practical framework for comparing a range of ALM platforms, alloys and process parameters and provide *a priori* information on microstructure. The diagrams provide a useful reference and methodology to aid in the selection of appropriate processing parameters during the early development stages. This paper also applies the methodology to worked examples of Ti–6Al–4V depositions processed using different Electron Beam Melting parameters.

1. Introduction

Additive Layer Manufacture (ALM) is an emerging near-net shape production technology that utilises a high-energy heat source (typically a laser or high-energy electron beam) to selectively melt or fuse together metallic powder to produce a three dimensional part direct from a CAD model on a layer by layer basis [1]. Powder ALM can be broadly divided into two forms; Blown Powder Direct Laser Deposition and Powder Bed Additive Manufacture [2]. In both cases, the powder is locally fused together using a moving heat source, although the delivery system for the powder differs. In Blown Powder Deposition systems [3,4], the feedstock powder is fed directly onto a work-piece using a pressurised inert gas flow, whilst in Powder Bed Additive Manufacturing systems, the feedstock powder is supplied from one or more hoppers and applied across a baseplate using a raking or rolling mechanism [5,6]. For powder bed systems, two distinct sub-categories exist; those for which the heat source used to fuse the metal powder is a laser (Laser Additive Manufacture, or Laser AM) and those which use a high-energy electron beam (Electron Beam Manufacture, or EBM).

The viability of laser-based and electron beam-based ALM has been successfully demonstrated for Titanium alloys [5,7–12], Nickel-base Alloys [2,6,13–16] and 316L Stainless Steel [17,18]. A key challenge facing researchers interested in the ALM of engineering alloys is developing the understanding of how to determine the key process variables to yield both a sound microstructure, acceptable mechanical properties and significantly reduce the probability of a finished component containing undesirable microstructural aberrations such as gas porosity, lack of fusion voids or internal cracks [10]. For example, insufficient heat-input due to high laser beam velocities is reported to introduce a high fraction of internal voids in CM247 LC by Carter et al. [2,6] and in 316L Stainless Steel by Kamath et al. [17], whilst Juechter et al. [8] were able to define an acceptable processing parameter window for Electron Beam Manufacture (EBM) of Ti–6Al–4V.

Efforts are currently underway to develop numerical models to predict void formation during Additive Manufacturing Processes [19,20], and whilst these models offer a good degree of precision,

* Corresponding author.
E-mail address: Meurig.thomas@sheffield.ac.uk (M. Thomas).

http://dx.doi.org/10.1016/j.actamat.2016.02.025
1359-6454/

they can be computationally expensive and may require extensive experimental validation. A practical alternative to numerical process modelling is the construction of empirical and physically-based process maps that can, for example, define "safe" and "unsafe" regions for hot-working [21,22], "weldable" regions for Nickel superalloys [23] or the transition from an equiaxed to columnar microstructure during solidification [24,25].

Diagrams for laser processing of engineering materials have previously been developed by Ion et al. [26], through the application of an analytical heat flow model to identify dimensionless groups of processing parameters. Experimental data were normalised against material thermophysical properties to define a set of practical operating regions for a range of CO_2 laser treatments. The advantage of this approach over, for example, that outlined by Dye et al. [23], is that instructive process maps can be rapidly produced using more straightforward mathematics, data available in the literature and readily available computer software (e.g. Microsoft Excel).

In this paper, we will firstly employ, and then extend, the approach developed by Ion et al. [26] to construct normalised process maps for ALM. We will identify dimensionless groups of process variables applicable to ALM and construct a practical, normalised process map from which informed decisions on the selection of appropriate processing parameters can be made. Such a process map is intended to provide a framework for comparing and classifying the extensive range of processing parameter data available in the literature, rather than as a predictive tool to provide *a priori* information on microstructural-scale and morphology, or the likelihood that a manufactured artefact will contain an undesirable microstructural feature.

Following this, the application of the proposed normalised process map for Electron Beam Manufacture (EBM) of the α/β Titanium alloy Ti–6Al–4V will be discussed. The effect of systematically varying the process parameters on the microstructure, microhardness and the propensity for undesirable internal features to exist within the deposit will be investigated and the results discussed within the process map framework.

2. Development of normalised process maps for Additive Layer Manufacture

A significant quantity of processing parameter data for powder bed ALM of a wide range of engineering alloys are available in the literature. Table 1 provides a non-exhaustive summary of the additive manufacturing platforms, alloys studied, the corresponding processing parameters extracted from the literature and the source from which thermophysical data were taken. From Table 1, it is evident that a range of heat sources, powder bed temperatures and processing conditions have been investigated, including beam power q, velocity v, layer thickness l, hatch spacing h and beam radius r_B. The large number of potential parameter combinations however, would make the analysis of independent effects of the on microstructure challenging. Ion et al. [26] define the following two dimensionless groups for laser processing of materials:

Dimensionless Beam Power:

$$q^* = Aq/[r_B\lambda(T_m - T_0)] \tag{1a}$$

Dimensionless Beam Velocity:

$$v^* = vr_B/\alpha \tag{1b}$$

where A is the surface absorptivity or coupling coefficient and ranges between 0.3 and 0.8 (See Table 1 in Ref. [26]), r_B is the beam radius, λ and α are the thermal conductivity and thermal diffusivity of the alloy being processed, whilst T_m and T_0 are the respective melting and initial temperatures of the material (*i.e.* the powder bed temperature in the case of the latter).

According to Ion et al. [26], q^* and v^* can be considered physically to control the peak temperature and heating rate of the thermal cycle at a point in the material. In this analysis, the average thermal properties of the alloy (λ and a) at the approximate powder bed operating temperature are used, rather than at 0.6 T_m as assumed by Ion et al., although we will also assume the thermophysical properties are unchanged by melting. The thermal properties of the powder bed will be assumed to be that of fully dense material; ideally, the thermo-physical properties of the alloy in powder form should be chosen, but data relating to bulk powder thermal properties are not as readily available as fully dense material. The surface absorptivity is assumed to remain constant at 0.5, although it is appreciated that values for A can range between 0.35 for Laser Deposition [27] and 0.55 for Electron Beam Welding [28]. The reason for this is that measured values of surface absorptivity are seldom reported by the studies listed in Table 1, and therefore the Absorptivity value for Laser Cladding suggested in Ref. [26] has been adopted. Data for q, v, and r_B are listed in Table 1.

In addition to beam power and velocity, which are typically two of the key process variables in laser welding, ALM introduces two further process variables: Layer height, l, and hatch spacing, h. As a basic approximation and with reference to Fig. 1, consider a moving heat source heating a volume of material of cross-sectional area $2r_B.l$, where l is approximated by the layer height of the powder bed, with a powder packing density of approximately 60–70% relative density. For simplicity, a powder bed relative density of 0.67 (2.d.p) will be assumed in this analysis. If the energy used per unit length of track is q/v then the energy per unit volume E, required to raise the material to a critical temperature, say the melting point T_m, is $q/2vlr_B$. In dimensionless terms, this can be written as:

$$E^* = q^*/v^*l^* = [Aq/(2vlr_B)][1/0.67\rho C_p(T_m - T_0)] \tag{2}$$

where $l^* = 2l/r_B$ is the dimensionless layer height. Physically, the group of dimensionless parameters in Equation (2) represent the amount of energy required in a single laser scan to raise the local temperature of the powder bed to the melting temperature of the material. The minimum amount of heat to cause melting per m^3 of material, H_{min}, including the latent heat, L_m, is:

$$H_{min} = \rho C_p(T_m - T_0) + L_m \tag{3a}$$

where L_m is approximately $0.5\rho C_p(\Delta T)$ for metals and alloys and H_{min} therefore becomes

$$H_{min} \approx 1.5\rho C_p(T_m - T_0) \tag{3b}$$

Substitution of equation 3b into 2 gives:

$$E^*_{min} = q^*/v^*l^* = [Aq/(2vlr_B)][1/\rho C_p(T_m - T_0)] \tag{4}$$

where E^*_{min} is the minimum dimensionless heat input per unit volume required to melt the material.

The Hatch Spacing, h, is an important processing parameter as it controls the amount of overlap between adjacent melt pools. Selection of a large hatch spacing lends itself to more rapid part manufacture, but potentially less re-melt overlap between adjacent scan lines (and the potential for void formation) if the beam power is not commensurately increased. Conversely, a small hatch spacing value will increase the total manufacturing time of the part, introduce more re-melting and thus redundant heat input. In keeping with the dimensionless layer height, l^*, the hatch spacing