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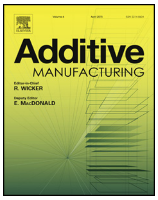

Full Length Article

Partitioning of laser energy during directed energy deposition

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ABSTRACT

An energy balance that describes the transfer of energy is proposed for the laser-based directed energy deposition process. The partitioning of laser energy was experimentally measured and accurately validated using a special process calorimeter for Ti-6Al-4V and Inconel 625^{TM} alloys. The total energy provided by the laser was partitioned as: the energy directly absorbed by the substrate, the energy absorbed by the powder stream and deposited onto the substrate, the energy reflected from the substrate surface, and the energy reflected or absorbed and lost from the powder stream. Titanium alloy Ti-6Al-4V showed higher overall or bulk absorption than the Inconel 625^{TM} alloy. Processing with powder resulted in lower laser energy absorption within the substrate than without powder, due to the "shadowing" effect of the powder stream within the beam and loss of energy representing unfused powder. During processing at a laser power of approximately 1 kW the total energy absorbed during the deposition process was found to be 42% for the Ti-6Al-4V alloy and 37% for the Inconel 625^{TM} alloy. Under these conditions 14% of the total energy was lost by the Ti-6Al-4V unfused powder; whereas only 11% was lost by the Inconel 625^{TM} powder.

1. Introduction

The absorption of energy is an important factor to consider when modeling additive manufacturing (AM) processes, since it is responsible for initiating the thermal response of the material. The amount of energy absorbed will directly govern the resulting thermal profiles throughout the part; therefore, the determination of how energy is partitioned and utilized during the process is necessary for developing accurate thermal models, as well as providing insight for improving the efficiency of the process.

Several prior studies have been conducted to determine energy absorption and related phenomena in laser welding processes [1–3]. Tadamalle et al. recently examined the effects of travel speed, heat input, and other parameters on energy absorption and melting efficiencies during laser welding [1]. This research examined how melting efficiencies of 304L austenitic stainless steel varied over a range of velocities during pulsed laser beam welding, and provided insight into the absorption phenomena that occurred during the welding process. Tadamalle, et al. also proposed the use of two dimensionless parameters derived from the Rosenthal heat flow analysis, and an important aspect of the results was that a small percentage of total absorbed energy from the laser welding process was actually used to melt material. Other researchers had also conducted experiments over a range of selected laser beam welding velocities to examine the resultant dimensionless parameters and subsequent melting efficiencies. Weld pool volumes were estimated through curve fitting polynomials to empirical data in the form of geometrical cross sections. These analyses had shown that the energy absorbed during the laser beam welding process ranged between 16 and 65%, depending upon specific processing conditions.

Similar experiments and analyses have also been applied to the laser deposition process. Picasso et al. realized the imporantance of energy absorption in the creation of a simple but realistic model for laser cladding [4]. Their research involved a series of laser cladding experiments in an attempt to generate a two-step energy balance. Through the use of several processsing parameter inputs and geometric melt pool assumptions, they were able to determine energy absorption values based on varying velocity and powder feed rates. Calorimetric experiments were utilized for the powder bed fusion (PBF) process for measuring both Ti-6Al-4V and Inconel 625^{TM} [5,6]. The absoptivity of the powders were determinded by measuring the increased temperature of a refractory metal under the pre-placed powder. The absoptivity of

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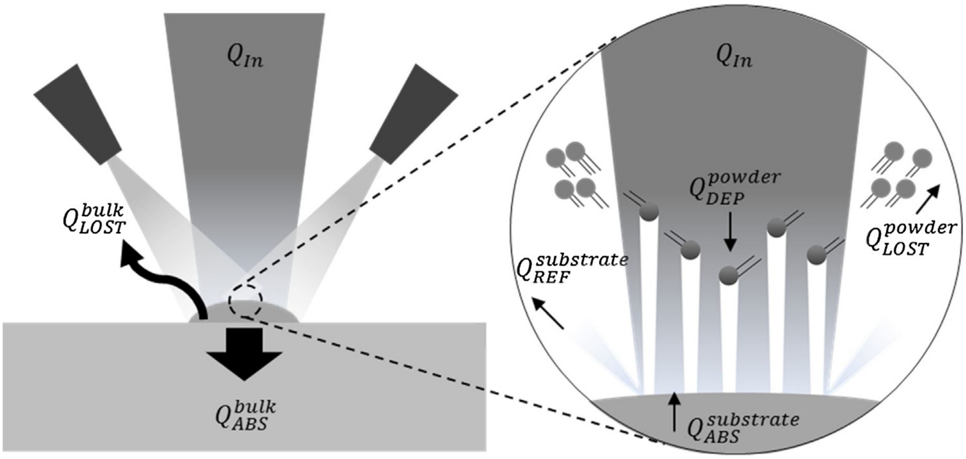

Fig. 1. Schematics showing the laser-based directed energy process and features of the process that are responsible for allocating energy for deposition, as well as energy lost.

the pre-placed Ti-6Al-4V powder was 0.74 and the absorption of the pre-placed Inconel 625^{TM} powder was found to be 0.67. Martukanitz et al. employed calorimetry to investigate the absorption phenomena during laser deposition with pre-placed powder using a Nd:YAG laser with pure iron and Inconel 625^{TM} powder at varing powder thicknesses [7]. Their results showed the bulk absorption of the powder to be between 40 and 75% for the iron powder and between 45 and 75% for the Inconel 625^{TM}, depending upong the powder layer thickness. A similar calorimetry experiment was used to measure absorption for Inconel 625^{TM} during the directed energy deposition (DED) process by Wirth et al. [8]. The experiment was conducted using a 6 kW high power diode laser and an absorption coefficient of 0.38 for Inconel 625^{TM} was reported using an untreated substrate surface. They proposed an energy flux analysis for the laser-based DED process that included workpiece absorption, powder absorption or reflection within the powderstream, and total reflection representing the fused powder. However, this research only distinguished the absoption coefficient for the workpiece and the powder materials. Heigel et al. reported an estimated absoption coefficient of 0.45 for laser-based DED using Inconel 625^{TM} powder while employing a 2.5 kW ytterbium fiber laser, scan speed of 10.6 mm/s, and powder feed rate of 19 g/min [9].

Pinkerton and Li proposed an energy distribution model for the laser deposition process [10] to describe partitioning of energy during deposition of 316L stainless steel using an 800 W Nd:YAG laser. The results of their analytical model and experimentation indicated that approximately 54% of the laser power was reflected by the substrate, 30% was absorbed by the substrate, 11% was reflected by the powder, 4% was lost due to dispersed powder, and only 1% could be attributed to the deposited powder. Pinkerton also explored the interaction between a direct diode laser and the powder stream during the directed energy deposition process [11]. The results of this investigation indicated the importance of powder tragectories and retention time within the beam on the absorption phenomena, and supported earlier investigations that attempted to relate laser power, powder flow rate, and particle size on energy absorption.

2. Energy absorption during direct energy deposition

A simple energy balance may be used to generally describe the transfer of energy during the laser-based directed energy deposition process:

$$Q_{IN} = Q_{ABS}^{bulk} + Q_{LOST}^{bulk} \tag{1}$$

where Q_{IN} is the total laser energy presented from the processing head to the substrate, Q_{ABS}^{bulk} is the total energy absorbed during the process, and Q_{LOST}^{bulk} is the energy lost during processing. Through process calorimetry experiments, the total energy absorbed may be directly measured and may be defined through the bulk absorption coefficient, β:

$$\beta = \frac{Q_{ABS}^{bulk}}{Q_{IN}} \tag{2}$$

The total energy captured or lost during the process may be further defined as:

$$Q_{ABS}^{bulk} = Q_{ABS}^{substrate} + Q_{DEP}^{powder} \tag{3}$$

and

$$Q_{LOST}^{bulk} = Q_{REF}^{substrate} + Q_{LOST}^{powder} \tag{4}$$

where $Q_{ABS}^{substrate}$ is the laser energy directly absorbed by the substrate, Q_{DEP}^{powder} is the energy absorbed by the powder stream and transported to the substrate, $Q_{REF}^{substrate}$ is the laser energy reflected from the substrate surface, and Q_{LOST}^{powder} represents the energy reflected from the powder stream, energy lost due to evaporation, and energy lost due to unfused powder. The schematics shown in Fig. 1 illustrate the components of energy that result in the formation of the deposit and heating of the substrate during laser deposition, as well as energy lost during the process.

Utilizing Eqs. (1), (3), and (4), the complete energy balance may be defined to describe partitioning of energy during the laser-based directed energy deposition process:

$$Q_{IN} = Q_{ABS}^{substrate} + Q_{DEP}^{powder} + Q_{REF}^{substrate} + Q_{LOST}^{powder} \tag{5}$$

The energy balance may also be formulated in terms of the ratio of the individual components to the total energy input:

$$\beta_{ABS}^{substrate} + \beta_{DEP}^{powder} + \beta_{REF}^{substrate} + \beta_{LOST}^{powder} = 1 \tag{6}$$

where the respective coefficients represent the proportion of energy either captured or lost by the powder and substrate. It should be noted that the use of coefficients in Eq. (6) is useful to define the energy absorbed or reflected from the substrate regardless of whether or not a powder stream is present within the beam path. The presence of powder within the beam will decrease the total laser energy to the substrate due to "shadowing", and the energy that passes through the powder stream will either be absorbed or reflected from the substrate and may be represented as $Q_{ABS}^{substrate}$ and $Q_{REF}^{substrate}$, respectively. However, the proportion of energy that is either absorbed or reflected from the substrate should