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On the thermal response of a surface deposited laser-irradiated powder particle

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ABSTRACT

This paper provides a basic analysis of the temperature rise of a particle in a powder that is being irradiated by a laser and simultaneously conducting heat with its surroundings. The work is motivated by the widespread use of laser post-processing of deposited particles in additive manufacturing technologies. The study focuses on one of the "building blocks" of additive, powder-based, technologies, namely the controlled irradiation of a single particle. The analysis employs two models: (a) a classical model, based on a balance of energy in conjunction with Fourier-type conduction and (b) a thermally relaxed model, based on a balance of energy in conjunction with thermally relaxed conduction, which is important when using fast-pulsing lasers. Analytical and numerical results are generated to qualitatively ascertain the time-transient trends as a function of particle size, heat capacity, material density, laser irradiance, conductivity and the thermal relaxation. The objective is to provide researchers with methods to quickly determine the required laser input to bring the particle to a desired temperature, which is an essential step in powder-based additive manufacturing.

1. Introduction

1.1. Motivation

Powder-based additive manufacturing has received a great deal of attention in recent years. We refer the reader to the recent overview article by Huang et al. [1] on the wide array of activities in the manufacturing community in this area. Today, large quantities of inexpensive, high-quality, particles for additive powder-based manufacturing processes, are readily available due to advanced materials processing techniques such as (a) sublimation from a raw solid to a gas, which condenses into particles that are recaptured (harvested), (b) atomization of liquid streams into droplets by breaking jets of metal, (c) reduction of metal oxides and (d) precise comminution/pulverizing of bulk material. Subsequent to the deposition of particles onto a substrate, there are a number of related sub-processes which can make up an overall additive manufacturing process. In particular, oftentimes, one key component is laser processing, which utilizes high-intensity beams to heat particles in a powder to desired temperatures either to subsequently soften, sinter, melt or ablate them. (Fig. 1). Laser-based heating is quite attractive because of the degree of targeted precision that it affords.[1] Because of the monochromatic and collimated nature of lasers, they are an attractive, highly controllable, way to process powdered materials, in particular with pulsing, via continuous beam chopping or modulation of the voltage. For example, Carbon Dioxide (CO_2) and Yttrium Aluminum Garnett (*YAG*) lasers are commonly used. The range of power of a typical industrial laser is relatively wide, ranging from approximately 100–10,000 W. Typically, the initial beam produced is in the form of collimated (parallel) rays that are 1–2 mm apart, which are then focussed with a lens onto a small focal point (approximately 50 mm away) of no more than about 0.00001 m in diameter. *However*, one concern of manufacturers are the microstructural defects generated in additively manufactured products, created by imprecisely controlled heat affected zones, brought on by miscalibration of the laser power needed for a specific goal. For example, due to the rise of one family of additive manufacturing, printed flexible electronics, involving sensitive

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[1] There are a variety of other techniques that may be involved in an overall additive manufacturing processes, such as: (a) electron beam melting, which is a process by where metal powder is bonded together layer per layer with an electron beam in a high vacuum, (b) aerosol jetting, which consists of utilizes directing streams of atomized particles at high velocities towards a substrate and (c) inkjet printing, which works by projecting small droplets of ink towards a substrate through a small orifice by pressure, heat, and vibration. The deposited materials is then heated by UV light or other means to rapidly dry.

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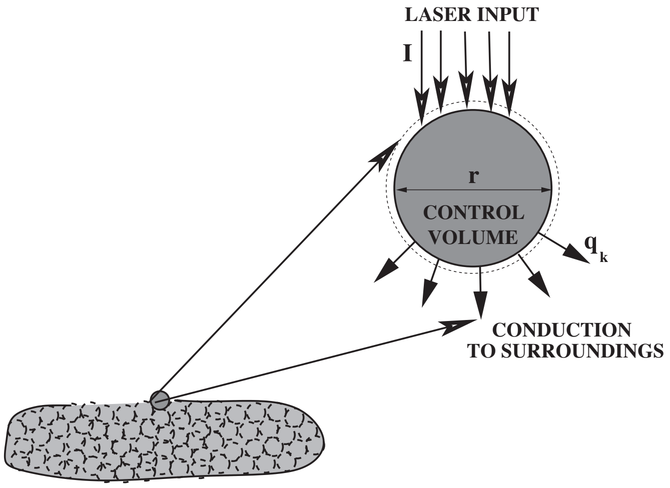

Fig. 1. A schematic of laser input applied to a particle control volume.

substrates, it is important to precisely understand how much laser-input is needed. Furthermore, in many cases one may need to pulse the laser, either for technological reasons, such as to avoid overheating, or to activate certain thermal relaxation effects, which are discussed later. In particular, because many substrates can become thermally damaged, for example from thermal stresses, ascertaining the appropriate amount of laser input is necessary. Applications include, for example, optical coatings and photonics (Nakanishi et al. [2]), MEMS applications (Fuller et al. [3], Samarasinghe et al. [4] and Gamota et al. [5]) and Biomedical devices (Ahmad et al. [6]). In terms of processing techniques, we refer the reader to Sirringhaus et al. [7], Wang et al. [8], Huang et al. [9], Choi et al. [10–13] and Demko et al. [14,15] for details. Thus, in order for *emerging additive approaches to succeed, one must draw upon rigorous theory and computation to guide and simultaneously develop design rules for upscaling to industrial manufacturing levels. This motivates the present analysis.*

Remark: In 2014, related print-like additive manufacturing technologies, employing deposition of particulate materials, including ceramics, metals, plastics, organic, and even biological materials was a 2.2 billion dollar industry, with applications ranging from commercial manufacturing, medical technology, art and academia.[2] These types of applications and associated technology are closely related to those in the area spray coatings, and we refer the reader to the extensive works of Sevostianov and Kachanov [16–18], Nakamura and coworkers: Dwivedi et al. [19], Liu et al. [20,21], Nakamura and Liu [22], Nakamura et al. [23] and Qian et al. [24] and to Martin [25,26] for the state of the art in deposition technologies.

1.2. Scientific objectives

The objective of this paper is to study one of the "building blocks" of additive, powder-based, technologies, namely the irradiation of a single particle. We first analytically study the terms that contribute to achieving a target temperature by constructing an energy balance on a control volume accounting for incoming laser irradiance and heat conduction to the body. During the course of the analysis, key parameter groups are identified in order to determine the relative contribution of each type of physics. Numerical examples are provided to illustrate the model's behavior. The framework is, by design, straightforward to computationally implement, in order to be easily utilized by researchers in the field. Importantly, we note that within the last decade, technological advances have enabled the reliable control of ultrafast pulsed lasers to activate small-time scale heat wave effects. These effects are often referred to as thermally relaxed "second-sound" effects, because of their mathematical similarity to wave propagation in acoustics, although normal sound waves are fluctuations in the density of molecules in a substance while thermally relaxed second-sound waves are fluctuations in the density of phonons. Such phenomena are predicted by models which introduce thermal relaxation times into heat-conduction relations. The thermally relaxed second-sound is a quantum mechanical phenomenon in which heat transfer occurs by wave-like motion, rather than by the more usual mechanism of diffusion. This leads to a very high confinement of thermal energy in very targeted zones. Thermally relaxed phenomena can be observed in any system in which most phonon–phonon collisions conserve momentum, and can play a role when the time scale of heat input is quite small. The analysis proceeds by generating results for the response of an irradiated particle, as a function of particle size, heat capacity, material density, laser irradiance, conductivity and thermal relaxation, based on a balance of energy in conjunction with two models: (a) a classical Fourier-type conduction model and (b) a thermally relaxed model. Analytical and numerical results are generated to qualitatively ascertain the time-transient trends as a function of particle size, heat capacity, material density, laser irradiance, conductivity and the thermal relaxation. Furthermore, a numerical scheme is also developed to solve the governing equations for general laser input.

Remark: The additive dynamic deposition process of multibody and inter-particle collisions that occurs before the irradiation by a laser is outside the scope of the present work. We refer the reader to Duran [28], Pöschel and Schwager [29], Onate et al. [30–32], Rojek et al. [33,34], Carbonell et al. [35], Labra and Onate [36], Leonardi et al. [37], Cante et al. [38], Bolintineanu et al. [39], Avci and Wriggers [40] and Zohdi [41–51] for more computationally-oriented techniques aligned with manufacturing processes involving particles.

2. Thermal relaxation/second-sound effects

2.1. Continuum model

The thermally relaxed second-sound type model can be motivated by a Jeffreys-type relation between the conductive flux and temperature gradient (Joseph amd Preziosi [52]):

$$\tau \frac{\partial \boldsymbol{q}_k}{\partial t} + \boldsymbol{q}_k = -\mathbf{IK} \cdot \nabla \theta, \tag{2.1}$$

where τ is the relaxation time, θ is the temperature, t is time, $\boldsymbol{q}_k$ is the conductive heat flux, $\mathbf{IK}$ is the thermal conductivity. A balance of power reads

$$\rho C \frac{\partial \theta}{\partial t} = -\nabla \cdot \boldsymbol{q}_k - \nabla \cdot \boldsymbol{q}_o, \tag{2.2}$$

where ρ is the mass density, C is the heat capacity and $\boldsymbol{q}_o$ is the flux due to other sources, such as laser energy input. By taking the partial derivative with respect to time of the above yields, assuming no material changes,

$$\rho C \frac{\partial^2 \theta}{\partial t^2} = -\frac{\partial(\nabla \cdot \boldsymbol{q}_k + \nabla \cdot \boldsymbol{q}_o)}{\partial t} = -\nabla \cdot \left(\frac{\partial \boldsymbol{q}_k}{\partial t} + \frac{\partial \boldsymbol{q}_o}{\partial t} \right). \tag{2.3}$$

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[2] A rough market percentage breakdown is 30 % motor vehicles, 15 % consumer products, business 11 %, medical 9 % and 35 % spread across other fields. Three-dimensional printing was pioneered in 1984 by Hull [27] of the 3D-Systems Corporation.