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Review

A review of defect modeling in laser material processing

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ABSTRACT

Thermomechanical modeling of laser material processing in general, and defect modeling in particular, has raised attention in both academia and industry for the last twenty years. Additive manufacturing (aka, 3D printing) is increasingly studied and utilized by researchers and engineers. Defects created during a part building process are costly to identify and could cause premature part failure, and thus numerous studies and research projects have been conducted in order to predict and analyze defects in laser material processing. The available information for defect modeling is scattered widely in the literature and mostly dedicated to very small and specific areas of focus, making it difficult for others to follow, even though the quantity of information is not small. In this work, a review of defect modeling which focuses specifically on the defect types existing in additive manufacturing industry has been carried out, including over 140 referenced articles.

Contents

1. Introduction

The history of the laser dates back to the mathematical proof of the possibility of stimulated emission of radiation by Einstein in 1916 [1]. Maiman [2] invented the first working laser at Hughes Aircraft Company in 1960. After that, lasers started to be utilized and tested in the display and scanning industries. Since then more and more laser-based applications have been identified, and laser processing has grown with extraordinary speed. Many types of lasers have been developed and commercialized. An early list of commercially available lasers and their corresponding applications was collected by Majumdar and Manna [3] and a selection of major commercial available lasers and their industrial applications are shown in Table 1. Laser material processing generally refers to intense heating of solids using a laser beam to enable material processing. Laser material processing distinguishes itself from conventional ways of material processing in terms of quality, efficiency, and accuracy [3–5].

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Table 1
A selection of commercially available lasers and their industrial applications.

Laser	Discovery	Commercialization	Wavelength (nm)	Application
Ruby	1960	1963	694	Metrology, medical applications, inorganic material processing
Nd:glass	1961	1968	1064	Length and velocity measurement
Diode GaAs/GaAlAs	1962	1965	780–905	Semiconductor processing, biomedical applications, welding
He–Ne	1962	1963	1152	Light pointers, length/velocity measurement, alignment devices
Carbon dioxide	1964	1966	10,600	Material processing-cutting/joining, atomic fusion
Nd:YAG	1964	1966	1064	Material processing, joining, analytical technique
Argon ion	1964	1966	480–515	Powerful light, medical applications
Dye (sodium fluorescein)	1966	1969	535–600	Pollution detection, isotope separation
Copper	1966	1989	511	Isotope separation
Excimer XeCl/XeF	1975	1976	300–350	Medical application, material processing, coloring
Free electron laser (FEL)	1971	1997	2000–10,000	Medical surgery, surface modification, weapon
Ti-sapphire laser	1982	1998	514–532	Multiphoton microscopy, cold micromachining
Gallium nitride laser	1992	1993	400	Optical discs, light-emitting diodes (LED)

In this review paper, we focus on defect modeling for laser material processing in order to enable future laser material processing feed forward and feed backward simulations, with a particular emphasis on optimizations of laser material processing for the additive manufacturing (AM) industry. AM was initially known as rapid prototyping and is now commonly referred to as 3D printing in the literature. AM encompasses many manufacturing processes whereby a part is built directly from a Computer Aided Design (CAD) model without extra manufacturing planning [6]. Some of the most commercially successful AM processes utilize lasers to melt and join materials to form parts. As a result, defects which occur in laser material processing in general are also present in AM-produced components. The major types of defects in laser material processing can be divided into two categories: porosity and cracking. Each category is summarized below based upon currently available research and development described in the literature.

2. Overview of defects in laser material processing

As discussed in Section 1, the defects in laser material processing includes porosity and cracking. Pores in the laser material processing, in general, can be categorized as keyhole and balling. Keyhole is caused by the massive amount of high energy imposed on a small area which results in a melt pool with narrow and deep shape. The resulted melt pool shape makes the inside vapor bubbles difficult to get out within the short period of cooling time before the materials are solidified which leaves a keyhole inclusion inside the part. Semak and Matsunawa [7] found that this defect is highly related to the fluid flow inside the melt pool which is controlled by the temperature gradient, surface tensions of liquid/solid and liquid/vapor surfaces, and recoil pressures on these surfaces. Comparing with other types of pores in laser material processing, keyhole pores are typically small and symmetric. They are less detrimental to the mechanical properties of the parts when they exist in quantities of less than 1% of the overall volume of the geometry for Ti–6Al–4V, however, when the quantities increase to 5%, the tensile strength, fatigue life, and hardness of the parts will be dramatically affected [8]. Fig. 1 shows a keyhole pore formation [9].

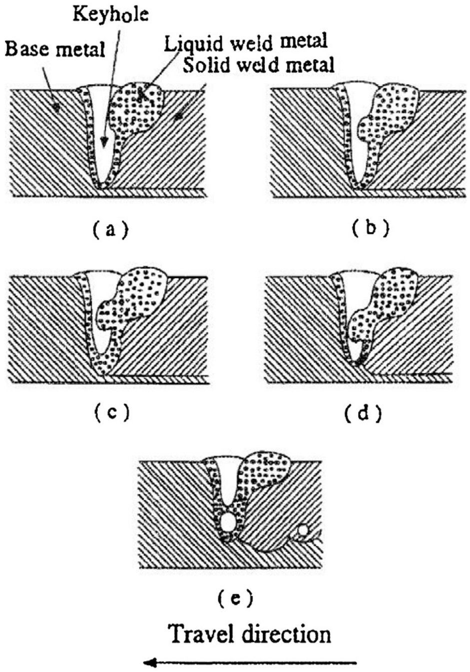

Fig. 1. A diagram of keyhole pore formation [9].

Balling is observed most in the AM manufacturing processes and caused by the laser energy induced non-stabilized melt pool [10]. Balling phenomenon is believed to happen for both low laser energy (incomplete wetting) and high laser energy (liquid splashes onto cohesive powder particles) [11]. It is also referred to as swelling [12,13] or humping [14–16] in the literature. Balling pores are typically larger than keyhole pores and they have a strong impact on the mechanical properties of the parts even when present in only 1% of the overall volume. Moreover, balling may result in the formation of discontinuous scan lines which will significantly affect the melt pool overlapping between scan lines and layers. Fig. 2 provides a melt pool morphology graph of balling pores in laser material processing [17].

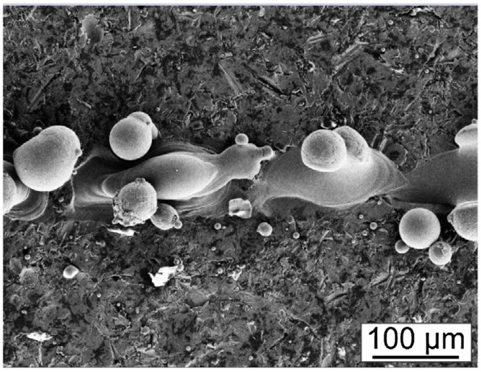

Fig. 2. A melt track morphology graph shows balling pores [17].