International Journal of Engineering Science 99 (2016) 74–91

Contents lists available at ScienceDirect

International Journal of Engineering Science

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

Modeling and efficient simulation of the deposition of particulate flows onto compliant substrates

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ARTICLE INFO

Article history:
Received 17 October 2015
Accepted 19 October 2015
Available online 6 December 2015

Keywords:
particles
substrates
computation
deposition
manufacturing

ABSTRACT

There are many emerging manufacturing processes whereby structures are formed by depositing materials onto substrates in order to build up layers or coatings. The processes are often referred to as "additive manufacturing". Particle-based additive manufacturing processes utilize deposition of streams of particles to build layers upon substrate surfaces. Oftentimes, the substrates are fragile/sensitive, and could become damaged if the induced stresses due to deposition are too high. In these cases, knowledge of the substrate stresses is important. This paper develops a computational-mechanics framework to *rapidly* evaluate the induced substrate stresses due to multiple, simultaneous, surface particle contact events. The aggregate substrate stresses are efficiently computed by superposing individual particle contact solutions, based on classical Boussinesq solutions, coupled to a multibody dynamics formulation for the interacting particles. The utility of the approach is that process designers can efficiently compute the results of selecting various system parameters, such as deposition speed, particle-stream configuration, etc. This allows one to rapidly compute system parameter studies needed in new product development. Three-dimensional examples are provided to illustrate the technique.

1. Introduction

There are a variety of advanced multi-step manufacturing processes which utilize deposition particles onto a surface in order to build a component. These are known as "additive" (adding material) manufacturing methods.[1] In 2014, print-based additive manufacturing technologies, which often employ deposition of particulate materials, such as ceramics, metals, plastics, organics and biological materials was a 2.2 billion dollar industry. In certain applications, because the substrate is fragile, knowledge of the induced stresses is important in order to control the process (Fig. 1). Such concerns have become increasingly important due to the rise of printed flexible electronics involving sensitive, potentially fragile dielectric and optical materials. Applications include, for example, optical coatings and photonics (Nakanishi et al., 2009), MEMS applications (Fuller, Wilhelm, & Jacobson, 2002) and (Samarasinghe, Pastoriza-Santos, Edirisinghe, Reece, & Liz-Marzan, 2006) and even biomedical devices (Ahmad, Rasekh, & Edirisinghe, 2010). There are a wide variety of additive-like processes and we refer the reader to Gamota, Brazis, Kalyanasundaram, and Zhang (2004), Sirringhaus et al. (2000), Wang, Zheng, Li, Huck, and Sirringhaus (2004), Huang, Liao, Molesa, Redinger, and Subramanian (2003), Choi et al. (2010a), Choi, Stassi, Pisano, and Zohdi (2010b), Choi et al. (2012),

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[1] This is opposite to classical "subtractive" processes whereby material is removed (such as milling) to build a component.

http://dx.doi.org/10.1016/j.ijengsci.2015.10.012

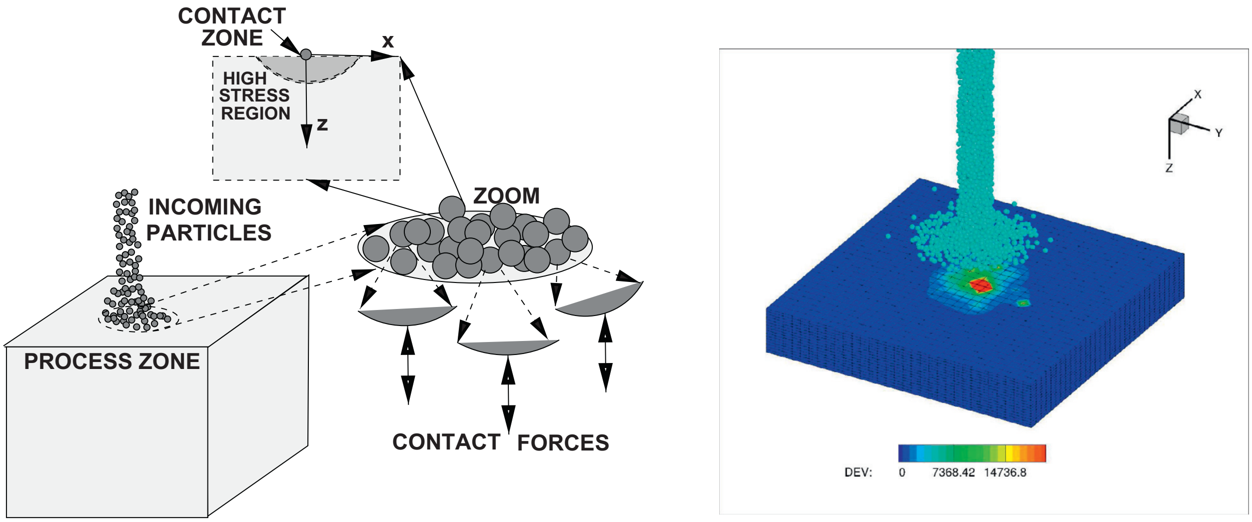

Fig. 1. LEFT:Deposition of a stream of particles onto a substrate. RIGHT: An example of a set of particles inducing loads through surface contact from a deposition of a stream from the simulations presented later.

Choi, Pisano, and I. (2013), Demko, Choi, Zohdi, and Pisano (2012), Demko, Cheng, and Pisano (2010), Fathi, Dickens, Khodabakhshi, and Gilbert (2013), Martin (2009), Martin (2011) and Zohdi (2014d), Zohdi (2014b), Zohdi (2015a) for details. These types are similar to those in the area spray coatings. We refer the reader to the extensive works of Sevostianov and Kachanov (2000), Sevostianov and Kachanov (2001b), Sevostianov and Kachanov (2001a), Nakamura and coworkers: Dwivedi, Wentz, Sampath, and Nakamura (2010), Liu, Nakamura, Dwivedi, Valarezo, and Sampath (2008), Liu et al. (2007), Nakamura and Liu (2007), Nakamura, Qian, and Berndt (2000) and Qian, Nakamura, and Berndt (1998) and to Martin (2009), Martin (2011) for the state of the art in deposition technologies. Oftentimes, the objective is to produce multilayer coatings on curved surfaces (see, for example Grekov & Kostyrko, 2015). The interested reader is referred to the recent overview article by Huang, Leu, Mazumdar, and Donmez (2015) on the wide array of activities in additive manufacturing. This paper develops a computational-mechanics framework to investigate the behavior of such processes. Specifically, substrate stresses due to multiple, simultaneous, surface particle contact events are efficiently computed by superposing individual particle contact solutions, based on classical Boussinesq-like solutions, coupled to a multibody dynamics formulation for the interacting particles. Specifically, in the paper:

- A multibody collision model is used to represent the interaction of the particles with each other, as well as with the substrate.
- Classical point-load solutions on a half-space are used to represent the contribution of each particle to the stresses on the substrate.
- The response of the particles and substrate are coupled together with a recursive numerical scheme.
- Three-dimensional examples are provided to illustrate the technique.

Remark. The modeling approach allows for rapid computation of deposition-induced stresses which allows one to conduct parameter studies, leaving more intensive Finite Element analyses, if warranted, for final process analysis stages. We note that the range of validity of this type of simulation is for relatively slow deposition where elastodynamic effects can be ignored in the substrate. Furthermore, we consider "dry" particle depositions where the interstitial fluid is of negligible importance. Particles in suspension are outside the scope of this paper. We refer the reader to Kachanov and Abedian (2015), Abedian and Kachanov (2010) and Sevostianov and Kachanov (2012) for details on the analysis of that class of particle-laden fluid materials. Such analyses can be useful for determining the rheology of so-called (particle) functionalized-inks (Zohdi, 2014a).

2. A multibody dynamics model for the particles

2.1. Overall contributing forces

We consider a group of non-intersecting particles ($i = 1, 2, \ldots, N_p$). The objects in the system are assumed to be small enough to be considered (idealized) as particles, spherical in shape, and that the effects of their rotation with respect to their mass center is unimportant to their overall motion, although, we will make further remarks on these effects shortly. The equation of motion for the i^{th} particle in system is

$$m_i \ddot{\boldsymbol{r}}_i = \boldsymbol{\Psi}_i^{tot}(\boldsymbol{r}_1, \boldsymbol{r}_2, \ldots, \boldsymbol{r}_{N_p}) = \boldsymbol{\Psi}_i^{con} + \boldsymbol{\Psi}_i^{subs} + \boldsymbol{\Psi}_i^{bond} + \boldsymbol{\Psi}_i^{damp}, \tag{1}$$

where $\mathbf{r}_i$ is the position vector of the i^{th} particle and where $\boldsymbol{\Psi}_i^{tot}$ represents all forces acting on particle i, which is decomposed into the sum of forces due to: