Journal of Materials Processing Technology 213 (2013) 685–692

Contents lists available at SciVerse ScienceDirect

Journal of Materials Processing Technology

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

Modeling and control of a direct laser powder deposition process for Functionally Graded Materials (FGM) parts manufacturing

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ARTICLE INFO

Article history:
Received 22 June 2012
Received in revised form
19 November 2012
Accepted 24 November 2012
Available online 4 December 2012

Keywords:
Additive manufacturing
FGM
Heterogeneous objects
Manufacturing strategy determination
Modeling

ABSTRACT

Functionally Graded Materials (FGM) parts are heterogeneous objects with material composition and microstructure that change gradually into the parts. The distinctive feature of FGM structure gives the possibility of selecting the distribution of properties to achieve the desired functions. Today, multi-material parts manufactured with additive manufacturing processes are not functional. To move from these samples to functional and complex parts, it is necessary to have an overall process control. This global approach requires a control of process parameters and an optimal manufacturing strategy. This paper presents a process modeling and a system control to manufacture FGM parts with a direct laser deposition system. This works enable to choose an adapted manufacturing strategy and control process parameters to obtain the required material distribution and the required geometry.

1. Introduction

The concept of Functionally Graded Materials (FGM) has been proposed in 80s to develop materials capable of withstanding thermal and mechanical stresses in propulsion systems and space shuttle fuselage (Niino et al., 1987). FGM parts are heterogeneous objects with materials that change gradually into the parts (Qian and Dutta, 2003). The result is a variation in composition and structure gradually over volume which enables to choose the distribution of properties to achieve required functions (Ocylok et al., 2010). These multi-material parts offer great promise for aeronautical (Domack and Baughman, 2005) and biomedical (Pompe et al., 2003) applications because it is possible to change physical, chemical, biochemical or mechanical properties.

Since the concept of FGM advent, some research studies was dedicated to manufacture these materials and a large variety of methods of production – gas phase, liquid phase and solid phase methods – has been developed (Kieback et al., 2003). Additive manufacturing processes are potentially suitable to manufacture FGM parts. Moreover they have the advantage to allowing the fabrication of morphologically complex parts by the addition of material which are fused with an energy source. Nowadays, with these processes, it is possible to obtain customized homogeneous parts from digital data with various materials: metals, ceramics and polymers (Bandyopadhyay et al., 2009). Although these processes seem adapted to produce FGM parts, the manufacturing of heterogeneous parts is limited to samples: parts are not functional, with simple morphology (Majumdar et al., 2009) and simple material distribution (Yakovlev et al., 2005).

To move from these samples to functional parts a global approach was proposed (Mognol et al., 2011). It is achieved by a methodology which enables to move from the concept imagined by a designer to the manufacturing of the FGM part (Fig. 1(a)). This methodology includes a description of part – geometry and material distribution – and manufacturing process (Hascoet et al., 2011). From these descriptions, an appropriate manufacturing strategy is determined with the manufacturing process modeling and all the process parameters are controlled with the automatic generation of a Numerical Code (NC) program (Muller et al., 2012).

The manufacturing strategy determination has an important influence in the manufacturing procedure. Methodological tools of manufacturing strategies determination or process planning have been developed for additive manufacturing processes. With some of them, it is possible to optimize the slicing procedure (Ruan et al., 2010), to choose the part orientation (Pandey et al., 2007), to adapt paths (Kao and Prinz, 1998) or to determine a process plan (Ren et al., 2010) but they do not take into account the multi-material aspect. Methodological tools which are appropriate to the fabrication of heterogeneous parts propose a discretization of parts into

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http://dx.doi.org/10.1016/j.jmatprotec.2012.11.020

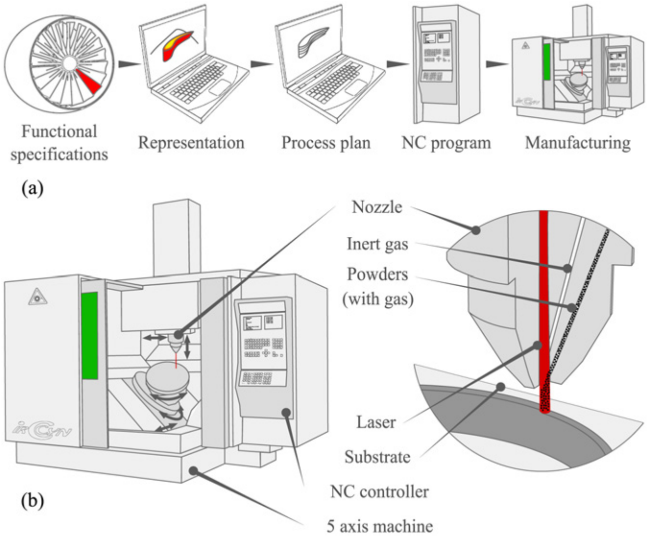

Fig. 1. (a) Numerical chain: from design to manufacturing and (b) direct laser powder deposition system.

areas with homogeneous material (Shin and Dutta, 2002) or do not propose path generation (Zhou, 2004).

For a manufacturing with a continuous approach of material distribution, the selection of a manufacturing strategy has a direct influence on the control of the powder distribution system. This is why a manufacturing process modeling is necessary to choose a strategy and control the commands of the system.

This paper presents a modeling of the direct laser powder deposition process which includes all the steps of the manufacturing procedure, in particular the step concerning the operation of the powder distribution system. A test-part was manufactured, analyzed and discussed in comparison with the model result. Moreover, the method of manufacturing strategy determination and the system control are described.

The direct laser powder deposition system which will be considered and used for this study is the CLAD® system. This system is based on the three dimensions layer by layer deposition of laser melted powders to build the profile of the requested part (Fig. 1(b)). Powders are injected into a high power laser beam. The energy input is partly used to melt both powders and the surface of the substrate. This system consists of a coaxial powder feed system and a fiber laser mounted on a five axis machine. The powders are supplied by two powder feeders, argon gas is used to prevent the melt pool form oxidizing throughout fabrication.

2. Modeling: mathematical data and relationships

The control of the powder flow rates is decisive to ensure the fabrication of a part in compliance with the desired material distribution. The modification of the flow rates is made by the command of the powder distribution system. The differences which may exist between the theoretical distribution and the deposed material are particularly due to the system dynamic behavior. As the powder flow rates are directly determined by the manufacturing strategy, it is essential to choose an adapted strategy. Our model was developed in order to be able to choose an adapted strategy and to control the system commands. A selection of strategies is made and strategies are simulated and compared with performances indexes. It is why the model is based on the comparison between the required material distribution, noted M^*, and the one obtained from the simulation, noted M. For that, mathematical data are used to describe phenomena involved in the steps of description, process planning and manufacturing. An equivalent notation is used for the other data: *data** for required data and *data* for those obtained from the simulation.

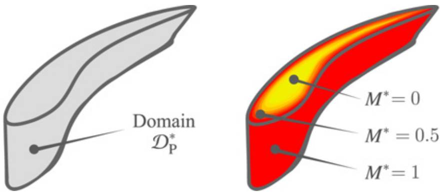

Fig. 2. FGM part description.

2.1. Part description

The geometry is described by a domain $\mathcal{D}_P^* \subset R^3$ corresponding to the part (Fig. 2). The part is made with two basic materials A and B. The function $M^*(x, y, z)$ represents the material composition in the space R^3, it corresponds to the volume concentration of material A:

$$M^*(x, y, z) : \mathcal{D}_P^* \to [0; 1] \tag{1}$$

2.2. Path description

The path is described by a curve $\mathcal{C}_P^*$. The orientation, the height and the width of the bead are expressed in each point of the curve (Fig. 3). The material function in each points depends on the theoretical material function.

2.3. NC program

The Numerical Control (NC) program generate temporal commands, the mathematical data of its model are consequently temporally expressed. For this, the machine axis (Fig. 1(b)), laser, gas and powder flow rates orders are expressed in each point of the curve $\mathcal{C}_P^*$ then they are temporally expressed.

The axes are determined according to the curve $\mathcal{C}_P^*$ and the orientation of the bead. The laser power and the axis speed depend on the height and the width of the bead. The gas flow rates in the pipes are chosen constant to formed an adapted cone of powder at the nozzle outlet.

The volume flow rates of the powder feeders ϕ_A^* and ϕ_B^* (Fig. 4) are modified according to the value of the material function, the control laws chosen are linear, for example:

$$\phi_A^* = M^* \times \phi_{\max} \tag{2}$$

Given that $\phi_{\max}$ is the volume flow rate of powder determined to manufacture a bead with only one basic material and with the process parameters previously chosen.

2.4. Process operation

The system do not always have the desired behavior in particular due to the dynamic behavior of its components.

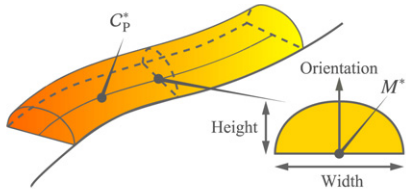

Fig. 3. Path description and bead parameters.