Journal of Materials Processing Technology 245 (2017) 207–214

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

# Study on deformation restraining of metal structure fabricated by selective laser melting

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ARTICLE INFO

*Article history:*
Received 8 August 2016
Received in revised form
30 December 2016
Accepted 24 February 2017
Available online 27 February 2017

*Keywords:*
Additive manufacturing
Selective laser melting
Metal powder
Thermal-structure interactive analysis
Thermal deformation

ABSTRACT

This paper pertains to the thermal and strain behaviour in laser consolidation of metal powders by additive manufacturing. The temperature and strain induced in the substrate during the laser consolidation process were theoretically estimated by the thermal-structure interactive analysis with two-dimensional finite element method, and experimentally evaluated in order to investigate the influence of thermophysical and mechanical properties on the resistance to thermal deformation in the consolidated structure. Additionally, the effects of different ferrous-based materials on the deformation were also investigated. The results reveal that the deformation of the consolidated structure was mainly caused by the thermal expansion and shrinkage induced by the laser beam which was repeatedly irradiated to the deposited powder. The deformation direction varied depending upon the temperature gradient which was induced inside the structure and stiffness of the consolidated structure which was added on the substrate. The analytical results obtained coincided well with the experimental results. The coefficient of thermal expansion was one of the most effective factors in restraining the thermal deformation, and the thermal deformation was reduced by combining the materials in which the coefficient of linear expansion was similar. In addition, the deformation was minimized by adjusting the temperature gradient induced by the laser beam irradiation.

## 1. Introduction

Since Kodama (1981) proposed a new method for the automatic fabrication of a three-dimensional resin model, many types of layered manufacturing techniques have been developed. This method was named the rapid prototyping (RP) technique due to the limitations on the materials which were applied to layered manufacturing (Kruth, 1991). Improvements in the mechanical and thermal properties of materials made it possible to manufacture end-use products which led to the terms “rapid manufacturing” (RM) and “rapid tooling” (RT) (Levy et al., 2003). Later on, “additive manufacturing” (AM) was defined by the International Committee of the American Society for Testing Materials (ASTM) as a “process of joining materials to make objects from three-dimensional model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2012), and AM is now commonly used in all layered manufacturing technologies.

Metal powder-based AM is one of the most promising techniques that is widely applied in the practical industrial community, as it contributes greatly to reducing the manufacturing cost and production time (Wohlers, 2009). The main advantages of metal consolidation by the AM technique are the process flexibility and the possibility to fabricate geometrically complex products (Kruth et al., 2007). Metal consolidation is classified by the type of binding mechanism, which mainly varies depending upon the energy density of the heat source irradiated on the deposited metal powder. Another advantage is the variety of metal powders which can be used in the AM process. Various materials such as steel, aluminium alloy, titanium, nickel-based alloy and tungsten carbide are suitable for use as powders which produce functional end products.

The metal powder-based AM techniques are mainly classified into the powder bed fusion (PBF), directed energy deposition (DED), binder jetting (BJ) and sheet lamination (SL) (Flynn et al., 2016). In

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http://dx.doi.org/10.1016/j.jmatprotec.2017.02.017

order to improve surface quality and dimensional accuracy of the consolidated structure by metal powder-based AM processes, the machine tools with hybrid manufacturing process, in which a metal powder is selectively consolidated and the edge of the consolidated structure is cut with an end mill, has been developed. Amon et al. (1998) developed "shape deposition manufacturing" (SDM) processes which were the hybridization of arc-based DED and CNC machining. They concluded that the important factors to optimize the quality and the material properties of parts fabricated by SDM processes were the cooling rates, the remelting of substrate and the build-up of residual thermal stress. Song et al. (2005) also proposed the hybrid manufacturing process by which gas metal arc welding (GMAW) was combined with the conventional 3-axis milling to directly fabricate the metallic parts. They suggested the application of two types of GMAW guns to use the different materials or sizes, and investigated the influence of welding parameters on the fabricated part in these processes. In order to improve the surface quality and the wear resistance of consolidated structure, Himmer et al. (2003) proposed the integration of laser build-up welding unit within a CNC machining center. They concluded that this system had a potential to integrate the 5-axis CNC machining center for manufacturing the complex parts in addition to the time and cost reduction in the product development. Abe et al. (2006) developed the multitasking machine in which the metal powder was consolidated in the PBF processes and the edge of consolidated structure was finished by end milling. They showed that the application of multitasking machine made it possible to reduce the production time and the manufacturing cost for manufacturing the molding die. Thus, the machine tools with hybrid manufacturing process had achieved the improvement of surface quality and dimensional accuracy of the consolidated structure. However, the application of hybrid machine tools was limited due to the process complexity and the machine tool cost. Therefore, the understanding of the effects of thermal and strain phenomena on geometric deformation was required.

Despite having many advantages compared to traditional manufacturing processes, the AM process used to create high-density structures still sustains several deficiencies. In the PBF processes, each layer is formed by rapid heating and cooling which are repeatedly performed on the deposited powder by the irradiated heat source. After one complete layer is formed, another powder layer is added on top of the complete layer, and the heating and cooling processes are repeated. The irregular heating and subsequent cooling are induced by the scanning of the heat source cause thermal deformation of the consolidated structure due to the thermal gradient (Kruth et al., 2004). The rapid cooling of the consolidated structure also leads to thermally induced residual stress (Kruth et al., 2007). In order to improve the dimensional accuracy of the consolidated structure, Shiomi et al. (2004) measured the residual stress distribution within the consolidated structure and concluded that the residual stress was reduced by re-scanning the laser beam across the consolidated surface and heating the substrate used for powder deposition. Denlinger et al. (2015) evaluated the influence of the inter-layer dwell time in the SLM process on the distortion and residual stress inside the consolidated structure. They showed that the dwell time and temperature during the SLM process were the principle parameters for determining the quality of the consolidated structure. Zaeh and Ott (2011) also investigated the thermal behaviour during SLM processes, including the heat flow to the surrounding metal powder, and they concluded that the quality of the consolidated structure could be optimized by heating the substrate, due to the lower temperature gradient.

On the other hand, the thermal deformation in the AM technique with metal powder is also evaluated calculatedly. Wang (1999) suggested the model for predicting the amount of shrinkage in selective laser sintering (SLS) processes. It was concluded that the shrinkage of the consolidated structure and the offset value of laser beam was two most important parameters that affect the parts building accuracy by SLS processes, and the offset value of laser beam was influenced by the weight of consolidated structure. Matsumoto et al. (2002) proposed the finite element (FE) model for calculating the distribution of temperature and stress within the consolidated layer in selective laser melting (SLM) process. They showed that the consolidated layer in SLM process warped due to heating and cooling process during the scanning of laser beam on the powder bed and suggested that the consolidated layer should be divided into small segment to prevent the distortion of the consolidated layer on the powder bed. Nickel et al. (2001) investigated the effect of scan patterns on the laser deposited metal parts which was produced by the shape deposition manufacturing (SDM) processes. They concluded that the scan pattern to deposit the layer of material had the significant effect on the deflection of the consolidated part, and the best pattern for the plate consolidation was the spiral pattern started from the outside to the inside. Paul et al. (2014) calculated the thermal deformation in AM parts by the three-dimensional thermomechanical FE model and evaluated the influence of consolidation conditions, such as slice thickness, laser scanning speed and material properties, on the geometric dimensioning and tolerancing (GD&T) errors. They indicated that the suggested FE model allowed the accurate prediction of GD&T errors in the part which was manufactured by the AM processes.

This research focuses on the thermal and strain behavior in laser consolidation of metal powders by SLM processes in order to reduce the deformation of the consolidated structure. The temperature and strain induced in the substrate during the SLM process were theoretically estimated by the thermal-structure interactive analysis with two-dimensional finite element method, and experimentally evaluated in order to investigate the influence of thermophysical and mechanical properties on the resistance to thermal deformation in the consolidated structure. Additionally, the effects of different ferrous-based materials on the deformation were also investigated.

## 2. Experimental method

### 2.1. SLM equipment

The samples were fabricated using a LUMEX25$^{TM}$ (Matsuura Machinery Corp.). A Yb-fiber laser (IPG Photonics Corp.: YLR-SM) with a wavelength of 1070 nm was utilized, and its single-mode laser beam was irradiated onto the powder surface through a galvanometer mirror. The beam diameter at the point where its intensity fell to $1/e^2$ times its maximum intensity was 100 μm.

The metal powder was deposited on a substrate with a thickness of 50 μm without pressing from the powder surface. Then, the laser beam was focused on this deposition and scanned over the surface in accordance with programmed NC data. The laser irradiation was performed by varying the scan direction of the laser beam by 90° to prevent anisotropy in each layer. The substrate surface was sandblasted by an average grain size of 300 μm to improve the wetting of the molten powder, and its surface roughness was kept constant at $R_a = 3.5$ μm (Furumoto et al., 2009). In addition, a nitrogen atmosphere was used to prevent oxidization of the metal powder during laser irradiation.

### 2.2. Property of metal powder bed and consolidated structure

The properties of the metal powder bed are summarized in Table 1. Two types of metal powder mixtures with a particle means