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ScienceDirect

Procedia Manufacturing 21 (2018) 92–99

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

15th Global Conference on Sustainable Manufacturing

Influence of process parameters on residual stress related distortions in selective laser melting

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Abstract

Residual stresses pose a major setback in Selective Laser Melting (SLM) and limit the applicability of the process, particularly from the standpoint of form accuracy and mechanical strength. The purpose of this paper is to investigate the influence of SLM parameters namely laser power and scanning speed on thermal stress related warping distortions and porosity. In this study, residual stress related distortions and achievable density for different process parameter combinations are presented simultaneously due to the profound influence of the porosity on residual stress relaxation. The paper also discusses the implications of the process parameters on the sustainability of the SLM process.

Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).

Keywords: Selective laser melting; residual stresses; distortions; porosity; sustainability

1. Introduction

In the selective laser melting process, three-dimensional parts are realised by melting thin (2D) layers of metal powder upon each other based on an initial 3D CAD input, making it possible to produce complex geometries which would normally be difficult or impossible to manufacture using conventional means. One of the greatest advantages of SLM (and additive manufacturing in general) is its ability to sustainably manufacture end use products with virtually no raw material loss as opposed to conventional subtractive methods. However, the process is associated

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2351-9789
Peer-review under responsibility of the scientific committee of the 15th Global Conference on Sustainable Manufacturing (GCSM).
10.1016/j.promfg.2018.02.099

with steep thermal gradients which result in undesirable residual stresses [1, 2]. Depending on the magnitude of these stresses, warping distortions and stress related cracking can occur in finished components. These process defects are a significant challenge in SLM because they are not reversible using post processing methods such as heat treatment. It becomes necessary to establish SLM parameters that result in better management of the effects of residual stresses during the process.

One of the most important goals of SLM is to produce fully dense parts in order to match conventional manufacturing process capabilities, thus research on process parameters has also focused on parameter optimisation for high density. Whereas some level of porosity is desirable in some biomedical applications, it is undesirable in tooling, automotive and aerospace applications as it is associated with accelerated crack initiation and growth, and resultant failure. At the same time, the achievement of full density is often accompanied by residual stresses and distortions. It has been noted that residual stresses are more pronounced in non-porous parts compared to porous parts since pores have an effect of relieving these stresses [3, 4]. The challenge, therefore, is to manufacture parts that meet both density and dimensional/form accuracy requirements.

The effect of SLM process conditions on residual stresses and warping distortions has been carried out using both numerical and physical experiments. Recently, the effect of scanning strategies and support types on residual stresses and distortion during SLM of aluminum and nickel based alloys was studied using simulation and physical experiments [5]. Elsewhere, both numerical simulation and experimental investigation have also been used to study the effect of different scanning strategies on dimensional distortions [6]. Although parameters such as laser power, scanning speed, (powder) layer thickness and hatch spacing have been studied to establish their effect on SLM outcome, most of these studies have focused on achievable surface quality, density, microstructure and mechanical properties [7 – 10]. These parameters (laser power, scanning speed, hatch spacing and layer thickness) are usually considered together through the quantity "volumetric energy density". Variants of this quantity – line energy density and energy density per unit area – are also often used. Separate studies show that different relative densities are achieved even at the same energy density levels, making energy density an unsuitable indicator of porosity profound influence [8, 9]. Furthermore, energy density has been discredited because it does not accommodate material properties and cannot provide important information about the melt pool [11, 12]. Besides mention of the exposure (scanning) strategy, previous researches have concluded that the most important laser and scanning parameters that influence residual stresses (and therefore related distortions) are laser power, scanning speed and layer thickness and to some extent hatch spacing [13, 14]. It has been concluded from another research that layer thickness is the most significant parameter that influences the achievable density of finished parts [9]. Against this background, this paper therefore presents an experimental investigation of the influence of laser power, scanning speed and layer thickness on both distortions and porosity.

2. Experimental methodology

2.1. Sample preparation

To study the effect of laser power, scanning speed and layer thickness on residual stress related distortions, a single-arm cantilever geometry was developed based on previous related studies [5, 15, 16]. The cantilever specimens were built from tool steel powder (hot work steel 1.2709) using SLM. In the geometry shown in Figure 1, the cantilever arm is supported by 1 mm thick blocks, which are separated by 1 mm between them. These "supports" are built using the same parameters as the entire geometry. No additional supports were required. Furthermore, $10 \times 10 \times 9$ mm cuboids were built for purposes of density evaluations.

Two powder layer thicknesses of 30 and 45 μm are considered in this work, therefore two separate builds are necessary so as to allow for exposure every layer for all the specimens. Otherwise, if the two layer thicknesses are to be considered in one build, a slice of 15 μm - a common factor to both 30 and 45 μm - would be necessary. This would result in exposing the powder bed every two layers for those parts fabricated from layer thickness 30 μm and every 3 layers for a layer thickness 45 μm. In such a scenario, the parts fabricated from layer thickness 45 μm have greater time in between laser beam exposure which could impact on the relative temperature gradients and cooling rates. The experimental design followed a full factorial approach, with screening being conducted to remove unnecessary experiments that, from experience and theory, would result in porous parts because the parameter combinations do