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Influence of scan strategy and molten pool configuration on microstructures and tensile properties of selective laser melting additive manufactured aluminum based parts

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ABSTRACT

Selective laser melting additive manufacturing of the AlSi12 material parts through the re-melting of the previously solidified layer using the continuous two layers 90° rotate scan strategy was conducted. The influence of the re-melting behavior and scan strategy on the formation of the "track-track" and "layer-layer" molten pool boundaries (MPBs), dimensional accuracy, microstructure feature, tensile properties, microscopic sliding behavior and the fracture mechanism as loaded a tensile force has been studied. It showed that the defects, such as the part distortion, delamination and cracks, were significantly eliminated with the deformation rate less than 1%. The microstructure of a homogeneous distribution of the Si phase, no apparent grain orientation on both sides of the MPBs, was produced in the as-fabricated part, promoting the efficient transition of the load stress. Cracks preferentially initiate at the "track-track" MPBs when the tensile stress increases to a certain value, resulting in the formation of the cleavage steps along the tensile loading direction. The cracks propagate along the "layer-layer" MPBs, generating the fine dimples. The mechanical behavior of the SLM-processed AlSi12 parts can be significantly enhanced with the ultimate tensile strength, yield strength and elongation of 476.3 MPa, 315.5 MPa and 6.7%, respectively.

1. Introduction

Selective laser melting (SLM), as a typical powder bed melting process of the additive manufacturing (AM) process, is increasingly paid attention to both in the academic and industrial fields from the perspective of the flexibility of fabricating near fully dense intricate metal or metal matrix parts in a fairly high degree of accuracy and a cost effective manner [1–3]. During the SLM process, metal powders are heated and subsequently melted by a fast moving high energy laser beam and then the molten pool solidifies rapidly associated with a series of mass, heat and momentum transition in the non-equilibrium metallurgical process, leading to the significant differences in mechanical properties of the SLM-processed parts compared with the casting and forged parts [4–6].

It is obvious that the characteristics of the SLM-processed parts possess the higher tensile strength combined with the undesired low dimensional accuracy and the ductility performance [7]. Prashanth et al. found that the yield and tensile strength of the SLM-processed AlSi12 specimens with 260 MPa and 380 MPa were four and two times higher than the corresponding properties of the samples processed by the casting, while the elongation was merely ~3%, which was significantly decreased with respect to the casting sample [8]. The yield stresses of a series of materials (316 stainless steel, CoCr and In625) fabricated by SLM process were significantly increased by ~50% while the elongation was unfortunately decreased with 20–30% of the forging specimens, which have been systematically concluded by Yadroitsev et al. [9]. In the case of the AlSi12 the variation of the mechanical properties is not sensitive to the building direction angles to the substrate, however, a significant dependence of the mechanical properties on the application of the scan strategy has been studied and concluded by Geiger [10]. Generally, the parts fabricated by SLM process are periodically completed with the feature of the overlapping of

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multi-tracks and multi-layers [11]. The molten pool boundaries (MPBs) will be accordingly obtained with an arc-shaped configuration connected with the neighboring tracks or the surfaces of the previously solidified layers. The MPBs produced through the laser melting process for the various materials have been studied in some previous researches. Thijs et al. has found that the dark band regions, indicating the MPBs in the top view of the SLM-processed AlSi10Mg part using the long bidirectional scanning tracks, were visible due to the distinction of the three different zones and the formation of different microstructures caused by the various solidification modes [12]. The same opinion was supported by Zhang et al. who proposed that the visible dark bands indicating MPBs were typical microstructures derived from the various heat effects and the resultant various crystal growth modes in the SLM-processed parts [13]. Two types of the MPBs in the SLM-processed 316 L stainless steel parts were defined by Wen et al. and then, the effects of the MPBs on the tensile properties fabricated along different directions and the fracture mechanism have been studied [14]. The microstructure of the MPBs differs from that of the other regions caused by the lower solidification rate and higher temperature gradient obtained within the molten pool, which was highly sensitive to the SLM processing parameters and the material properties [15]. Moreover, a complexly spatial topological structure in the connecting regions of the multi-track and multi-layer MPBs plays a crucial role in the performance of the SLM-processed part. Therefore, the microstructure of AlSi12 material fabricated by SLM process modified by the scan strategy is an alternative way to achieve the synergy ascension of the tensile strength and the elongation.

The objective of this study is to analyze the effect of the combination of the re-melting process and the continuous two layers 90° rotate scan strategy on the SLM process stability, dimensional accuracy, microstructure feature and the tensile properties. The temperature contour and the velocity field predicted by the finite volume method with the optimized processing parameters to investigate the re-melting process and the densification behavior are conducted. The influence of the continuous two layers 90° rotate scan strategy on microscopic sliding behavior, macroscopic ductility and fracture mechanism of the as-fabricated samples as loaded a tensile force is analyzed and assessed through experiments. The correlation of the enhanced tensile properties combined with the characteristics of the microstructure and the sliding behavior has been elucidated. This study may provide an alternative for the optimization and fabrication of the high performance of SLM-processed AlSi12 parts.

2. Experimental methods

2.1. Powder materials and SLM process

Bulk parts were produced by SLM process from the commercial and spherically shaped powder material prepared by the gas atomization and the particle size is in the range of 20–45 μm (Fig. 1a). The SLM apparatus is independently developed by Nanjing University of Aeronautics and Astronautics (NUAA), mainly equipped with the YLR-500 Ytterbium fiber laser (with a maximum laser power 500 W, a spot size of 70 μm and a continuous wavelength of 1070 ± 10 nm), an automatic powder deposition device, an inert argon gas protection system and the process control system. In order to find the optimal processing parameters for the laser-material interaction, the re-melting process and densification behavior of the previously solidified layer, four cubic parts with the dimensions of 10 mm × 8 mm × 5 mm were fabricated. The single line laser scan strategy was applied and the processing parameters were set as follows: laser power 400 W, layer thickness 30 μm, hatch spacing 60 μm and the scan speeds 4000 mm/s-1000 mm/s. In order to investigate the laser energy input to the powder layer being processed, the integrated parameter, laser volume energy density η, was defined:

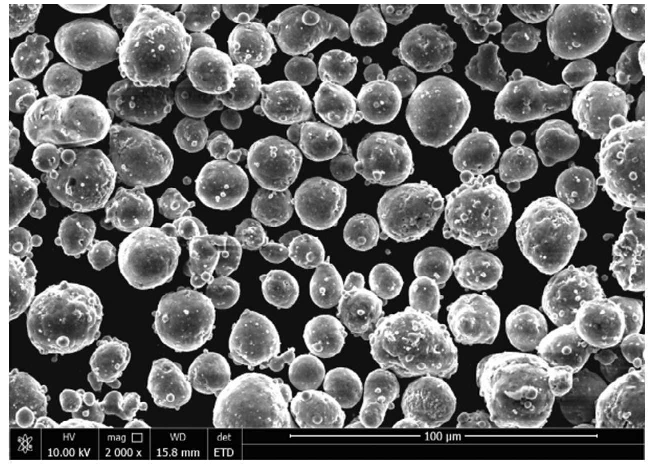

Fig. 1. Initial powder morphology of the AlSi12 material.

$$\eta = \frac{P}{hvl} \tag{1}$$

and therefore, four laser volume densities of 55 J/mm^3, 70 J/mm^3, 110 J/mm^3 and 220 J/mm^3 were selected to study the complexly metallurgical behavior and, as the optimized processing parameters have been verified, the tensile testing parts, with a flat dog-bone shape as proposed by GB/T 228.1-2010, were constructed.

2.2. Microstructural characterization and mechanical tests

After the SLM process, samples were cut perpendicular to the laser beam incident direction, ground and then polished following classical procedures and, the cross-sections of the individual parts and the tensile fracture samples were characterized using a PMG3 optical microscopy (Olympus Corporation, Japan). Specimens for metallographic examinations were prepared according to the standard procedures, and then etched with a solution composing HF (2 ml), HCl (3 ml), HNO_3 (5 ml) and distilled water (190 ml) for 10 s. Microstructure observations of the SLM-processed specimens and the fracture surface morphology were detected by a Zeiss Sigma 04-95 field emission scanning electron microscope (FESEM). The chemical compositions were tested using a S-4800 field emission scanning electron microscope (FESEM) (Hitachi, Japan) equipped with an EDAX energy dispersive X-ray spectroscope (EDX). Tensile tests were carried out at room temperature using a CMT5205 testing machine (MTS Industrial Systems, China) with a cross head velocity fixed at 2 mm/min.

3. Finite volume simulation

Finite volume simulation using the commercial computational fluid dynamics software FLUENT was conducted to study the thermal evolution behavior (focusing on the temperature field in the neighboring region located in the "track-track" boundary to study the re-melting behavior) and the melt mass transfer behavior (focusing on the melt flow characteristics in the neighboring region of "track-track" boundary to investigate the densification behavior) during the SLM process. The as-used AlSi12 thermo-physical properties are depicted in paper [16,17]. The Gaussian laser source is moved along the X-axis direction with various scan speeds and, the laser heat source is mathematically defined as a heat flux

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