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Horizontal dimensional accuracy prediction of selective laser melting

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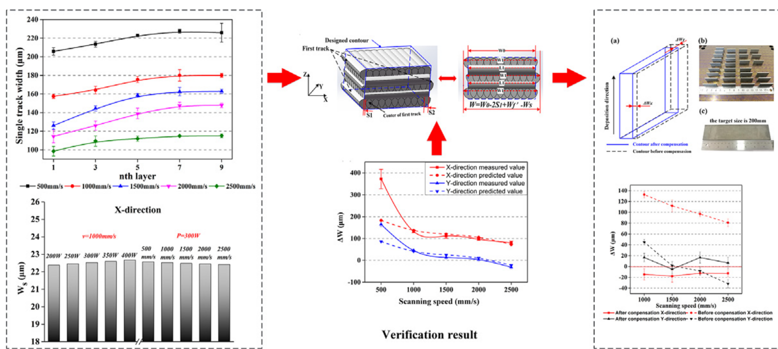
HIGHLIGHTS

- A theoretical model has been proposed to predict and optimize the horizontal dimensional accuracy.
- The dimension of SLMed Ti6Al4V thin-wall samples were measured to verify this model.
- Two parts of the horizontal dimensional accuracy were calculated.

GRAPHICAL ABSTRACT



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ABSTRACT

A theoretical model has been proposed to predict the horizontal dimensional accuracy of selective laser melting (SLM) in this paper. It is found that the horizontal dimensional deviation of SLM consists of two parts. The first part is related to the mode of track filling and the track width. The effect of heat accumulation on track width is also taken into account in this model. The second part is the solidification shrinkage which is dominated by the temperature history of the tracks of a layer when the material and dimension size are fixed. Then, the SLMed Ti6Al4V parts fabricated to verify this theoretical model has been performed in this paper too. The results show that the predicted and experimental results has a good correspondence. At last, less than 20μm dimension deviation of SLMed thin-wall samples was achieved by pre-compensation using this theoretical model.

1. Introduction

Selective laser melting (SLM), as one of the promising Additive Manufacturing (AM) technologies, has been developed rapidly in recent years [1,2]. It selectively melts a thin layer metal powder adopting a laser with a diameter about 100 μm [3]. Through track by track and layer by layer, a 3D metal part with high density, performance and accuracy is fabricated [4]. During the past decade, there are a lot of literatures focused on the SLM research, such as materials, process, mechanism and properties [5–7]. At present, the SLM technology has been utilized in many industrial fields [8–11]. Compare to other high-performance metal additive manufacturing, such as Wire Arc Additive Manufacture (WAAM), Electron Beam Melting (EBM), Fused Deposition Modeling (FDM) etc., the SLM is claimed to have advantages of fabricating parts with a complex shape and high dimensional accuracy. The printing accuracy of SLM is not only related to the devices, but also to the size and geometry of the part. Thus, the accuracy is generally claimed to be able to up to ±20–50 μm even 100 μm, the fact is that it cannot achieve this level for the fabricated 3D parts and meet the industrial requirements especially for the case of part with extremely complex shape such as internal channel and cavity.

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Nomenclature

b_1	dimension of the part beyond designed contour by the side of the first track
b_2	dimension of the part beyond designed contour by the side of the last track
C_p	heat capacity (J g^{-1} K^{-1})
h	hatch space (mm)
k	thermal conductivity (W m^{-1} K^{-1})
L_0	designed filling length (mm)
L_1	dimension in Y-direction of single-layer (mm)
n	number of the filling tracks
P	laser power (W)
R	distance from the laser beam center (mm)
S_1	distance between the designed contour at the beginning and the laser moving centerline of the first track (mm)
S_2	distance between the designed contour at the end and the laser moving centerline of the last track (mm)
T	layer thickness (mm)
T_0	ambient temperature (K)
T_d	holding temperature (K)
T_{ni}	temperature of the *i*th track among the whole *n*th track (K)
t_j	jumping time (s)
v	scanning speed (mm/s)
v_j	jumping speed (mm/s)
W	actual dimension of final part (mm)
W_0	designed filling width (mm)
W_1	width of single-layer (mm)
W_f	width of the first track in first layer(mm)
W_l	width of the last track in first layer (mm)
W_f'	width of the multi-layer's first track (mm)
W_l'	width of the multi-layer's last track (mm)
W_s	total solidification shrinkage (mm)
W_{s1}	first part of the shrinkage (mm)
W_{s2}	second part of the shrinkage (mm)
W_{s3}	third part of the shrinkage (mm)
ΔW	dimensional deviation (mm)
x,y,z	coordinates (mm)

Greek symbols

α	thermal diffusivity (m^2 s^{-1})
ρ	density (kg m^{-3})
ζ	laser absorption of powder
λ	thermal expansion coefficient (K^{-1})

Till now, there are a few literatures that have been reported the research on the dimensional accuracy of SLM. Calignano et al. [12] demonstrated that the STL file had an influence on the accuracy. Di W et al. [13] shown that the laser beam width, laser penetration, powder adhesion and stair effect were the main factors on the accuracy for SLMed various geometrical feature. Shukzi Afazov et al. [14] proposed two distortion compensation models to predict the distortion of the macro-scale industrial components and compensated the distortion using these models. For the lattice structure, large geometrical error induces weight and mechanical properties deviating from the target value [15,16] and Han et al. [17] found the accuracy could be improved with high density by using high scanning speed. Thus, it can be found that the investigation on dimensional accuracy of SLM is less, specially, on the theoretical analysis. Some research even shown that the dimensional accuracy of SLM was worse than that of Direct Metal Laser Sintering (DMLS) [18].

However, there were some studies have been focused on the dimensional accuracy of other AM technologies. Guangshen et al. [19] investigated the interactions between the dimension accuracy and the process parameters by means of Taguchi method for Stereolithography Technology. Anoop et al. [20] presented that the shrinkage of FDMed part was the dominant factor of the horizontal dimensional accuracy of built part. A geometrical model of the filament was developed by Boschetto et al. [21] to predict the FDMed parts dimensions. Wang et al. [22] built a neural network to analyze the relationship between the shrinkage and the process parameters of SLS. In addition, a new model for shrinkage which accounts the part geometry and beam offset was proposed by Senthilkumaran et al. [23] to enhance the accuracy of parts produced by SLS. Zhu et al. [24] experimentally investigated the horizontal dimensional accuracy of Direct Laser Melting (DLM) and also found that shrinkage and track width were the major factor on the accuracy. From these literatures, it can be found that the shrinkage is a dominant factor of the dimensional accuracy. However, how to predict the shrinkage is lacking in these research.

In this paper, a theoretical model was established to predict the horizontal dimensional accuracy of SLMed parts by considering the track width and shrinkage as well as the characteristics of SLM, e.g., track by track and layer by layer. Then, the experimental verification was also performed. Finally, high-accuracy thin-wall samples with the deviations of only less than 20 μm were obtained by compensation using this model.

2. Model

2.1. Single-layer dimension

Fig. 1 shows a schematic diagram of the mode of track filling in single-layer. The W_0 and L_0 are the width and length of the designed contour. The n and h are the number of the filling tracks and the hatch space of the adjacent tracks, respectively. S_1 is the distance between the designed contour at the beginning and the laser moving centerline of the first track, while the S_2 is the distance between the designed contour at the end and the laser moving centerline of the last track. The schematic diagram of the single-layer according to the Fig. 1 after SLM is shown in Fig. 2, the width of the single layer (W_1), e.g., the dimension in the X-direction, can be calculated as Eq. (1).

$$W_1 = \frac{W_f}{2} + (n-1)h + \frac{W_l}{2} \tag{1}$$

where the W_f and W_l are the width of the first track and the last track of the single layer, respectively. Moreover, the dimension in the Y-direction is L_1 which is decided by the distance between the starting position and the end position of the movement of the laser as well as the melt point size. Then, as show in Fig. 2, in the X-direction of the single-layer, the dimension of the part beyond designed contour by the side of the first track b_1 is $W_f/2 - S_1$, while the dimension of the part beyond designed contour by the side of the last track b_2 is $W_l/2 - S_2$.

2.2. Multi-layer dimension

In the multi-layer fabrication, the scanning strategy is utilized an orthogonal scanning strategy with the one way scanning which is widely used in SLM technology [25–27], as shown in Fig. 3(a). In addition, the printing accuracy is the same when using other angles between layers. It is caused by the cyclic processing and there will always are layers the same as the layers under the orthogonal scanning strategy. Then the model of the width of the thin-wall structures was established based on the single-layer model. These layers arranged according to the scanning strategy by two different cases, as shown in Fig. 3(b) and (c). In generally, the track length does not excess the borderline in the