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Quantitative characterization and influence of parameters on surface topography in metal micro-droplet deposition manufacture

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ABSTRACT

Metal micro-droplet deposition manufacture has potential applications and attracts increasing attention in wide areas. By quantitatively describing and predicting the surface topography, the influence of parameters on surface quality could be studied effectively. In present work, a new approach aimed to the characterization of part surface topography was proposed and the evaluation indexes such as arithmetic average height (R_a) and stratification angle (θ) were used to characterize the surface topography. Based on the surface geometrical profile, two prediction models were developed to calculate the evaluation indexes of part surface. Then experiments for fabricating thin wall parts were conducted and the evaluation indexes were measured experimentally. By comparing the experimental values with the predicted results, the mechanism of process parameters affecting surface topography was investigated. The results indicated that the top surface was mainly affected by scan step (W_d) which also could be represented by overlap ratio (μ). While overlap ratio was larger than 25.7%, excessive overlap resulting in poor surface topography occurred and the prediction model was invalid. In another hand, the side surface was mainly affected by offset distance (W_o) which also could be represented by offset ratio (τ). If offset ratio was too large, the ending side would collapse resulting in poor side surface topography and the prediction model would fail to calculate the side surface roughness. The experiment results indicated that collapse would occur while offset ratio was larger than 54.5%. In the last, the surface roughness of a cubic object was measured and the results demonstrated that the method proposed in present work was useful for evaluating surface quality of 3D object.

1. Introduction

As a novel kind of 3D printing technology, metal micro-droplet deposition manufacture (MDDM) [1] is an effective method for fabricating 3D objects directly from CAD model [2]. In the process, molten metal droplets are firstly generated as building blocks. Then the droplets are deposited sequentially and fused together to fabricate 3D structures [3]. Because of its advantages of low cost, high material usage efficiency and wide range of material selection [4,5], the technique has great potential applications in automotive, electronics and other industry fields [6].

In present, the surface quality of the MDDM part is poor and it is affected by many factors. Chao et al. [1] fabricated vertical columns and 3D objects with rough surface. As reported in the paper, the surface topography was affected by the temperatures of droplet and substrate. Fang et al. [2,7,8] indicated that the substrate temperature, deposition frequency and substrate velocity had influence on the forming quality of deposited lines and vertical columns. Also, several researches were conducted to improve the surface quality. Qi et al. [9] developed two models based on mass conservation and proposed a novel method for selecting appropriate process parameters. Amirzadeh et al. [10] produced droplets whose diameters were smaller than the nozzle diameter and the small droplets were useful for improving parts quality. Pandey et al. [11] proposed a real time adaptive slicing procedure which could be used to improve surface quality than the other method while build time was same. The presented procedure was applicable to all RP system.

Though researches on improving surface quality were conducted, the descriptions on the surface quality in these researches were qualitative and subjective that was not conducive to study the influence of parameters on surface topography further. So it is necessary to propose a method to characterize and predict the surface quality. By quantitatively studying the relationship between surface topography and process parameters, the process

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parameters would be optimized and the post processing operation would be reduced. A few researches have been performed recently which focused on evaluating the surface roughness of RP parts and optimizing the technique parameters. Boschetto et al. [12,13] suggested a model to evaluate the roughness of parts fabricated by fused deposition manufacture (FDM) and the model was useful for optimizing the fabricating orientation. Luis et al. [14] presented a characterization of geometric roughness and the effectiveness of model was confirmed by using stereolithography (SLA) manufacturing technique. Based on the model, two possible strategies for rapid prototype manufacture were established. An elaborate prediction methodology was proposed by Ahn et al. [15] and the surface roughness values could be calculated at surface angles which were impossible to measure. However the procedure of metal micro-droplet deposition manufacture is quite different from the technologies referred above and the parts surfaces are not smooth due to the large surface tension of molten metal and fast solidification during droplet deposition. Research on characterizing micrgeometrical profiles of MDDM parts has seldom been reported. Thus it is imperative to quantitatively characterize the micro geometrical profiles and study the effect of process parameters on surface quality of MDDM part.

In this work, by analyzing the principle of metal micro-droplet deposition manufacture, a novel method for quantitatively characterizing parts surface topography was proposed and two mathematical models for predicting the evaluation indexes of surface quality were developed. By the well-formed formulations, arithmetic average height and stratification angle of parts could be calculated. A series of experiments for fabricating thin-wall parts were conducted and the roughness of parts surfaces were measured. Based on the comparison of experimental and predicted results, the influence of process parameters on surface quality were investigated and the effective ranges for the models were obtained. In the last, a cubic was fabricated and the surface quality was measured which agreed well with the previous experimental and predicted results.

2. Evaluation indexes of surface topography

Fig. 1 shows the schematic of the MDDM system which includes several subsystems e.g. pneumatic droplet generating system, 3D platform and low-oxygen environment. The droplet generating system and 3D platform are combined controlled by an industrial personal computer to deposit droplets in fix location. During the process, components are fabricated by depositing droplets sequentially.

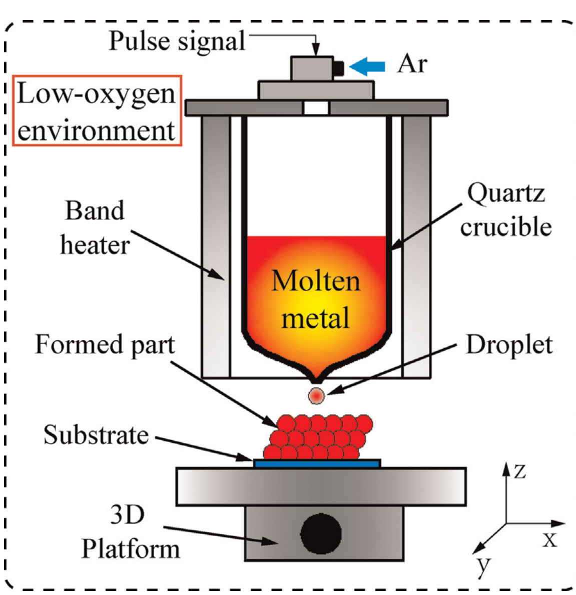

Fig. 1. Schematic of metal micro-droplet deposition manufacture system.

It is known that the shape of single droplet deposited on substrate is rotational symmetric and it could be considered as a spherical crown. Thus the component surface quality can be represented by the surface roughness of the maximum section as shown in Fig. 2. The maximum sections all include top surface and side surface which are affected by different process parameters. The top surface of part was parallel to the substrate and the side of part was defined as the surface which was perpendicular to the substrate or sloped.

In order to study the influence of parameters on surface quality, the microgeometrical profile of the section needs to be characterized quantitatively. In present work, arithmetic average height (R_a) as a roughness parameter was used to characterize the surface quality. R_a was defined as the average absolute deviation of the roughness irregularities from the reference line. The reference line was represented by the least squares line of the profile as shown in Fig. 2(b). The digital implementation of R_a [16] was:

$$R_a = \frac{1}{n}\sum_{i=1}^{n}|Z_i| \tag{1}$$

In addition, stratification angle (θ) was taken as another evaluation parameter to describe the side surface. It was defined as the angle between the least squares line and the substrate.

3. Prediction model of surface topography

In this section, two prediction models were proposed to calculate the evaluation indexes of the surface topography. Previous studies showed that the quality of top and side surface was mainly affected by scan step (W_d) and offset distance (W_o) respectively. So with a view to simplifying the prediction models, W_d and W_o were taken to be the main factor in each model.

3.1. Top surface model

In order to develop the top profile model, several assumptions were made:

(1) The shape of deposited droplet was considered as a spherical crown and the cross-section profile was symmetrical.
(2) While the process parameters were same, deposited droplets were uniform and the part profile was approximated by a periodic sequence of circumference's arcs (Fig. 3).
(3) The profile of previous droplet remained unchanged while the subsequent droplet deposited.

Calling r the radius of the arc and α the solidification angle, the profile was defined by Eq. (2)

$$f(x) = \sqrt{r^2 - x^2} + r\bullet\sin(\alpha - \frac{\pi}{2}) \tag{2}$$

By using Taylor series expansion limited to the second order term, Eq. (2) was computed as follow:

$$f(x) \cong r - \frac{x^2}{2r} + r\bullet\sin(\alpha - \frac{\pi}{2}) \tag{3}$$

As shown in Fig. 3, *L: (y=C)* was the least-squares line. *Q(C)* was defined as the quadratic sum of the distances from profile