Surface quality control of holes with overhang features in additive/subtractive hybrid manufacturing

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Selective laser melting (SLM) based additive/subtractive hybrid manufacturing (ASHM) enables near-net shaping of complex parts with good surface quality. Hole with overhang features is a typical structure in the complex parts. However, it is difficult to improve the internal surface quality for the holes with overhang features due to the constraint of the three-axis milling in the SLM-based ASHM. This study investigated the surface quality control of overhang holes in ASHM process. An ASHM experiment was conducted to fabricate holes with different diameter for TC4. The depth of sinkage was used to evaluate the ASHMed surface quality. A shielding height method was proposed to protect the machined surface by separating the preceding milled surface from the current melting layer. The result shows that the sinkage occurring at the alternating interface deteriorated the surface quality of overhang holes in ASHM. The shielding height was proved to be effective at the surface quality improvement for overhang holes in ASHM process. This study could provide guidance to the surface quality improvement of complex parts in ASHM process.

NOMENCLATURE

h = shielding height

1. Introduction

Additive manufacturing, also known as 3D printing, is a process used to create physical objects by layering materials one by one based on a digital model [1]. Selective laser melting (SLM) is an additive manufacturing process using a high-powered laser to selectively melt and fuse metallic powders to create three-dimensional objects [2,3]. SLM was widely used in the production of metal components with complex geometries in the aeronautic and aerospace industries [4,5]. However, poor surface quality caused by adherence of powder and staircase effect in SLM hinders the application of SLM technology [6].

Hybrid additive/subtractive manufacturing (ASHM) integrates the benefits of both AM and conventional subtractive machining (SM) [7]. In the additive process, a laser beam is utilized to melt metal powder. In the subtractive process, a milling cutter was employed to machine the as-built part. The integration of additive and subtractive process has a remarkable ability for near-net shaping of complex parts with good surface quality [8, 9]. Hole with overhang features is a typical structure in complex parts, which requires extremely high surface quality and precision [10, 11]. However, it is difficult to improve the internal surface quality for the holes with overhang features due to the constraint of the three-axis milling in the SLM-based ASHM [12].

TA Amine et al [13] proposed a shielding height method for the vertical surface in LMD-based ASHM. They found that the shielding height improved the surface quality. Bai et al [14] employed shielding height for parts with different overhang angles in SLM-based ASHM. The result showed that the shielding height could improve the surface quality for overhang features. Although the above literature utilized the shielding height in the milling process, they all focused on outside surfaces. For holes with overhang feature, it is necessary to investigate the quality of internal surface.

Ti6Al4V titanium alloy is characterized by high strength, low density, and excellent corrosion resistance, which is widely used in aerospace and biomedicine field [15,16]. In this paper, overhang holes were fabricated in ASHM for Ti6Al4V. The surface quality control of the overhang holes was investigated.

2. Experimental procedures

2.1 Experimental equipment and materials

In this paper, an ASHM experiment was conducted to fabricate the overhang holes. The ASHM experiment was performed on an ASHM machine. As shown in Fig. 1, the machine equipped with a fiber laser, a scanning system, and a milling cutter, combining the additive and the subtractive process. High-purity argon atmosphere was maintained in the working chamber to minimize the oxygen contamination.

The gas atomized Ti6Al4V powders were used in the SLM-based ASHM process. The chemical composition of the Ti6Al4V powder particles were shown in Table 1. The particle exhibited a nearly spherical shape. The diameters of the powders presented a gaussian distribution, with particle size distribution of 10–45 μm and average diameter of 35 μm. A 45 stainless steel substrate of 125 × 125 × 15 mm was used in the experiment.

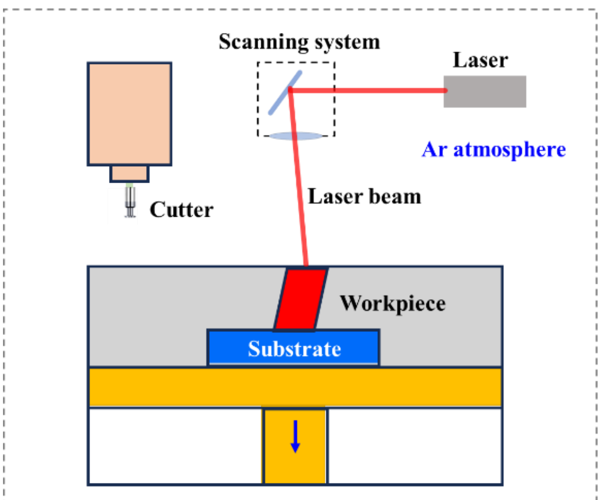


Fig. 1 Schematic diagram of ASHM machine

Table 1 Chemical composition of Ti6Al4V powder (wt%)

Items	Ti	Al	V	Fe	C	O	V	N
Ti6Al4V	Bal	6.04	4.1	0.15	0.014	0.06	0.11	0.011

2.2 ASHM experimental parameters

In the additive process, the strip scanning strategy was utilized. The scanning angle in the adjacent layer was 90°. The spot diameter of the laser beam was 200 μm. The optimum processing parameters for Ti6Al4V (laser power of 420 W, scanning speed of 2000 mm/s, and layer thickness of 50μm) were utilized.

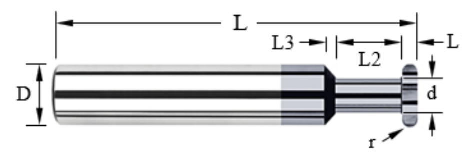
In the subtractive process, the spindle speed of 15000 rpm, feed rate of 1500 mm/min were used. Radial depth of cut was 0.05 mm. The continuous building slab height in each alternating sequence of the ASHM was 1 mm. Table 2 showed the machining process parameters in ASHM.

In SLM-based ASHM, the milling process was three-axis milling, determined by the process characteristic of powder bed machine [17,18]. The T-slot milling cutter（4 Flute, HSS, TiAlN Coating）was chosen for milling the overhang holes. The dimensions of the cutter were shown in Table. 2. The fillet radius of the milling cutter r was 0.25 mm. The length of the cutter L1 was 0.5mm. The neck length L2 was 3.5mm.

Table 2 Machining process parameters

Process parameters	Value
Layer thickness *t* (μm)	50
Laser power *P* (W)	420
Laser scan speed *v* (mm/s)	1000
Laser beam diameter d_0 (μm)	200
Substrate dimensions (mm)	125×125×15
Spindle speed (rpm)	15000
Feed rate (mm/min)	1500

Table 3 Machining process parameters

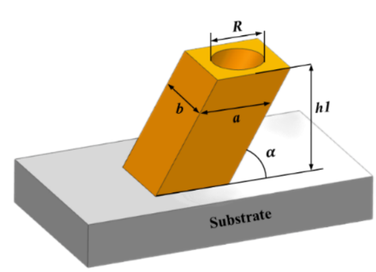


Dimension	L	L1	L2	L3	D	d	r
Value (mm)	40	0.5	3.5	7	6	3	0.25

2.3 Overhang holes

In this paper, the overhang holes were manufactured in SLM-based ASHM. The diameters of the hole were set to 6 and 8 mm. The overhang angle of the sample was 70°. The height of the sample was 30 mm. The shape and dimensions of the overhang hole model were presented in Table 4.

Table 4 Machining process parameters



Dimension	Value
a (mm)	5
b (mm)	5
h1 (mm)	30
R (mm)	6, 8
α (°)	70

3. Results and discussion

3.1 The surface quality of overhang holes in ASHM

In this paper, overhang holes with diameter of 6 and 8 mm were fabricated to investigate the surface quality control in SLM-based ASHM. As shown in Fig. 2, the samples were cut from the substrate by wire electrical discharge machining method. The surface roughness of the machined internal surface was measured by using the 3D optical profilometer (NV9000, Zygo, American).

As shown in Fig. 3(a, c), significant sinkage was observed at the alternating interface of the additive and subtractive process. As shown in Fig. 3(b), the depth of sinkage was defined to the maximum distance between adjacent crests and troughs. It was proposed to evaluate the surface quality for overhang holes in ASHM. The average depth of sinkage of the overhang hole with diameter of 6 and 8 mm were 6.948 and 7.099 μm, respectively.

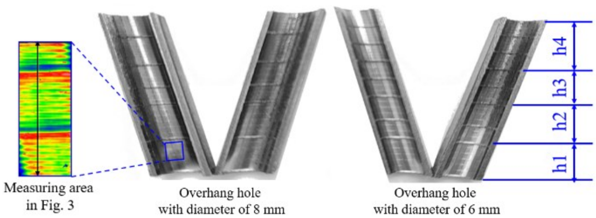


Fig. 2 Overhang holes with different diameter in ASHM

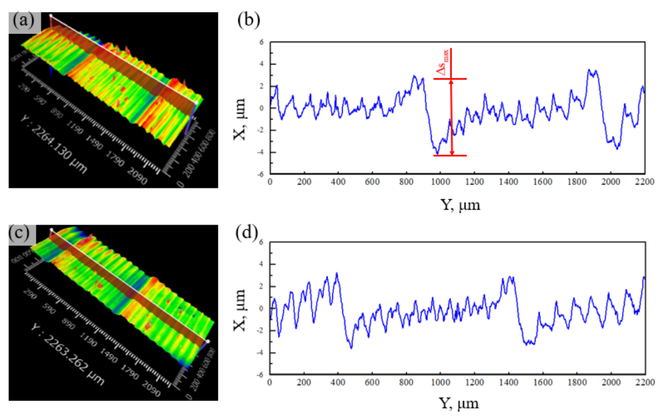


Fig. 3 (a) Morphology and (b) surface roughness for the hole with diameter of 6 mm, (c) Morphology and (d) surface roughness for the hole with diameter of 8 mm

The sinkage at the alternating interface of the additive and subtractive process was caused by the thermal influence of the melting layers. As shown in Fig. 4(a-b), the additive and subtractive processes ensured the desired shape of the sample. However, in the next additive process, the melting layers had significant thermal influence to the machined layers, and caused the contraction of the machined layers (Fig. 4(c)). As a result, sinkage occurred at the alternating interface after the subtractive process (Fig. 4(d)). The occurrence of the sinkage at the alternating interface deteriorated the surface of the overhang holes in ASHM.

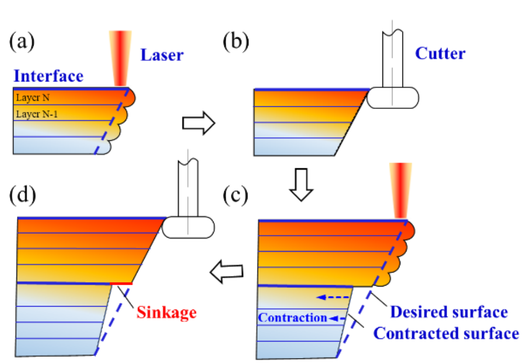


Fig. 4 Schematic diagram of the sinkage occurrence

3.2 The effect of shielding height to the surface quality

A shielding height method was proposed to reduce the sinkage at the alternating interface. As shown in Fig.5(a), in the subtractive process, a certain height of material was unmachined. In the subsequent additive process, the unmachined material acted as a base and separated the machined surface from the melting layer. It would be removed in the next subtractive process. The height of the unmachined material was defined as the shielding height.

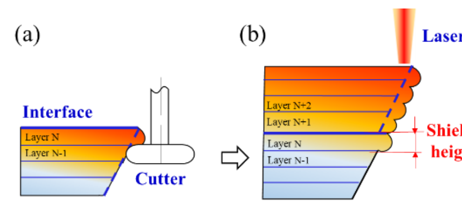


Fig. 5 Schematic diagram of shielding height

The effect of the shielding height on the surface quality was investigated by setting different shielding height for overhang holes. As shown in Fig. 2, shielding height of 0, 0.1, 0.3, 0.5 was employed in the area of h1, h2, h3, h4, respectively. The depth of sinkage and the surface roughness were measured and the result was shown in Fig. 6. D6 and D8 were the result of the holes with diameter of 6 and 8 mm, respectively. As the shielding height increased, the depth of sinkage and the surface roughness decreased. The surface morphology for D6 with shielding height of 0.1 and 0.5 mm were shown in Fig. 6 (c) and Fig. 6 (d), respectively.

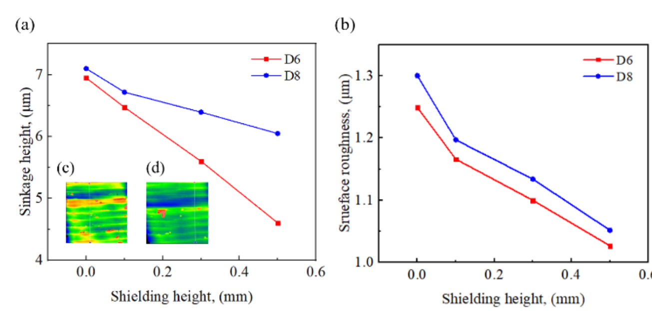


Fig. 6 (a) Effect of shielding height on (a) sinkage height, (b) surface roughness; Surface morphology for D6 with shielding height of (c) 0.1 and (d) 0.5 mm

4. Conclusions

In this paper, holes with overhang angle of 70° and diameter of 6 and 8mm were fabricated in SLMed ASHM. The cause of the sinkage at the alternating interface of additive and subtractive process was investigated. A shielding height method was proposed to reduce the sinkage and improve the surface quality for overhang holes. The following conclusions were drawn:

(1) The thermal influence of the melting layers resulted in the contraction of the machined layers in ASHM. Therefore, the sinkage occurred at the alternating interface of additive and subtractive process,

deteriorating the surface quality of the overhang holes.

(2) The proposed shielding height method, which separated the machined surface from the melting layer, proved to be effective in surface quality control for overhang holes in ASHM. The depth of sinkage of the overhang holes with 6 and 8 mm were reduced by 33.75% and 16.53%, respectively.

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