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ORIGINAL ARTICLE

# Research on the fabricating quality optimization of the overhanging surface in SLM process

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**Abstract** Overhanging surface is inherent geometric restraint during selective laser melting (SLM), which is suitable for various complex parts fabrication. In order to improve the fabricating quality of overhanging surface, a series of experiments were designed to investigate the effects of inclined angle, scanning speed, laser power, accumulated residual stress, and scanning vector length on overhanging surface fabrication. Analysis found that overhanging surface would warp easier when the inclined angle and the scanning speed became smaller and the warping trend will be larger as the laser power became larger. The relationships of laser power, scanning speed, and the critical inclined angle were mutual restraint, that is, larger inclined angle will be designed when the laser power becomes larger and scanning speed gets smaller, or vice versa: the selection of the fabricating parameters will be determined by established inclined angle of the overhanging surface. More serious warp would happen as the processing layers increased as a result of residual stress accumulation, and it was found that longer scanning vector were more helpful to stress accumulation, leading to more serious warp than shorter vector. At last, two effective methods were adopted to optimize overhanging surface fabrication, including adjusting part orientation to improve the inclined angle at the key position, and controlling regional parameters to reduce energy input. Above two ways were adopted to manufacture complex parts with typical overhanging surface, the results proved that adjusting part orientation and controlling regional parameters were effective ways to improve the fabricating quality of overhanging surface. In this study, the basis for building overhanging surface by SLM was provided from the view of process and design, and the preliminary solutions were proposed to manufacture complex metal parts with lower risk.

**Keywords** Selective laser melting · Overhanging surface · Design rules · Geometric restraint · Critical inclined angle

## 1 Introduction

In RP technology, most of the processes must be added supports for certain entities as the result of CAD models are discrete and layered manufacturing. The purpose of adding supports is to solve fabricating failure for complex parts with overhanging surfaces, which are always low inclined angles [1]. RP processes can be classified according to support adding methods, including manual-added supports (SLA, laser melting (SLM), and DMLS processes), self-supporting (LOM, selective laser sintering (SLS), and 3DP processes), and processes that cannot add supports (for example LENS).

In theory, any complex entities can be manufactured by SLM, however in practical, not all geometrical features can be perfectly fabricated [2, 3]. The overhanging surface will make the final parts' shape and dimensional accuracy not meet the requirements, even the whole process not go smooth. Overhanging surface also has other names as downward facing surface [4] or low-angled surface. The inclined angle of the overhanging surface is defined as the angle between the horizontal plane and a certain surface. Surface whose angle to the horizontal plane is bigger than the critical angle is supposed to be self-supporting; otherwise, manual-added supports are needed. How to determine the value of critical angle is very important in SLM process stage, which is also a focus of this paper.

At present, SLM fabrication of overhanging surface is mainly by adding a number of metal supports to ensure

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stability in manufacture process, then followed by removal of supports and surface grinding, sandblasting or shot blasting to guarantee the surface quality [5]. However, compared with vertical surfaces fabrication, the overhanging surface's fabricating quality is not always satisfactory. There are also a few cases that the overhanging surfaces are made by traditional manufacturing methods after the SLM production, such as side holes. However, when the entities are fine and intricate, or the overhanging surfaces are inside the parts, then both by adding manual supports and by post-processing cannot achieve the desired effects. So if the overhanging surfaces can be fabricated directly without supports, or designers can avoid and minimize the overhanging surfaces during designing stage, then it would be of great significance for the improvement of SLM technique and its application scope. However, the designing restraints and methods for SLM are not well known to designers, most of the information comes from the requirements of laboratory and experiences of the craftsmen. Until now, the investigations on the fabrication of overhanging surfaces by SLM technique are rare. The team led by Kruth JP from Leuven University carried out a preliminary study on overhanging surfaces [6, 7]; they devised a monitoring unit which had feedback function in the optical system to measure signals emitted from the melt pool, then compared those signals with the ideal signals, and changed the laser power flexibility to improve the quality of the overhanging surfaces fabrication by SLM.

This article detailed the principle of the defects forming during overhanging surface fabrication by SLM, and analyzed the effects of inclined angle, energy input (scanning speed and laser power), residual stress accumulation, and the scanning vector length on the overhanging surfaces fabrication. The relationships between key process parameters and the critical inclined angle were also discussed. Finally, two effective methods would be proposed to improve the fabricating quality of the overhanging surfaces.

These experiments were purposed to provide designing basis for SLM to avoid the inherent geometric restrains, and give a preliminary process optimization way on overhanging surfaces fabrication. Some of the results could be part of the design rules, which is valuable to low-risk manufacturing in RM field.

## 2 Overhanging surface fabrication

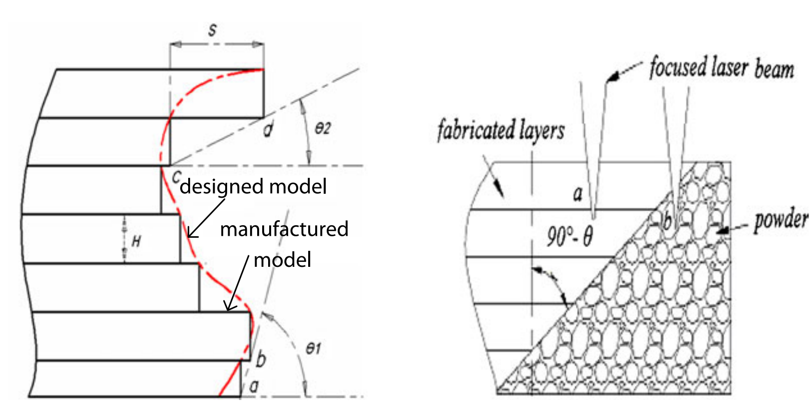
### 2.1 Fabrication principle

Figure 1 shows the schematic diagram of overhanging surface fabrication by SLM, and Fig. 1a shows the schematic diagram of slice model of curved surface, in which a~b segment and c~d segment are overhanging surfaces during SLM fabrication, therefore both segments may have no self-supporting parts after being sliced. The overhanging length S between adjacent two layers can be obtained by formula (1):

$$S = H \times \mathrm{ctg}\theta \quad (1)$$

In formula (1): $H$ is layer thickness, the angle $\theta$ is defined as the angle between the horizontal plane and the tangent line of a certain surface. In SLM process, the larger of the value $S$, the more will the dross form and the warping degree will be got, which affect much on the whole SLM manufacturing process.

According to formula (1), the value $S$ is closely related to layer thickness $H$ and inclined angle $\theta$. The larger the layer thickness $H$, and the smaller the inclined angle $\theta$, the larger will the $S$ get. In practical SLM manufacturing process, the layer thickness used in SLM is generally determined by metal powder's size, and most of the commercialized machines' layer thickness choose at the range of 20 to 50 µm [8]. In this experiment, according to the size of 316L stainless steel powder's size, $H$ was set at 35 µm, so the value $S$ was mainly related to inclined angle $\theta$. In Fig. 1a, the inclined angle $\theta_2$ of segment c~d is obviously smaller than inclined angle $\theta_1$ of segment a~b, so segment c~d is more prone to have fabricating defects.




(a) sliced model of typical curved surface (b) laser beam scan overhanging surface

**Fig. 1** Schematic diagram of overhanging surfaces fabrication by SLM. **a** Sliced model of typical curved surface. **b** Laser beam scan overhanging surface

### 2.2 Fabricating defects

The two defects that frequently happen during overhanging surface fabrication are dross formation and warp [9]. As Fig. 1b shows, when laser irradiates solid-supported zone (point a) where the heat conduction rate is high; however, when laser irradiates powder-supported zone (point b), the heat conduction rate is only 1/100 of the solid-supported zone [6], and this situation often happens during overhanging surface fabrication by SLM. Therefore, if the rest of processing parameters are similar, the absorbed energy input will be much bigger when laser irradiates powder-supported zone than when laser irradiates solid-supported zone, which leads the melt pool to become too bigger and sinks into the powder as the result of gravity and capillary force [6]. For the above reason, dross will be formed and dimensional accuracy should be bad during SLM fabrication of overhanging surface.

Warping defect is due to the thermal stress formed by rapid solidification of melt pool during SLM process. When the thermal stress exceeds the strength of the material, then plastic deformation happens [10]. The warping defect of overhanging surface is also due to the lack of supports to secure its firm bonding with the previous layers. Residual stress accumulation was the main cause for forming failure of the overhanging surface. Figure 2 shows the warping principle during SLM fabrication overhanging surface. When the warping defect happened, the practical inclined angle $\theta'$ between the overhanging part of the present layer and the previous layer was larger than the designed inclined angle $\theta$. When the overhanging part of a layer started to warp, it will influence the practical fabricating layer thickness of the next layer and cause larger warp, as Fig. 2b shows. When the warp accumulated to or becomes higher than the pre-set height of the next layer, then it will make part of the fabricating zone to have no powder to be recoated and the whole work piece will become more and more vulnerable. The overhanging surface may suffer from repeated laser scanning, or even the overhanging part would break away from the whole component due to its repeated collision with the powder scraper. When the warping defect became too serious, the whole forming process had to be stopped, and it was necessary to re-design the part or optimize the process to solve the problem. Therefore, when fabricating the overhanging surfaces, whose building angles are smaller than the critical inclined angle will need special processing parameters.

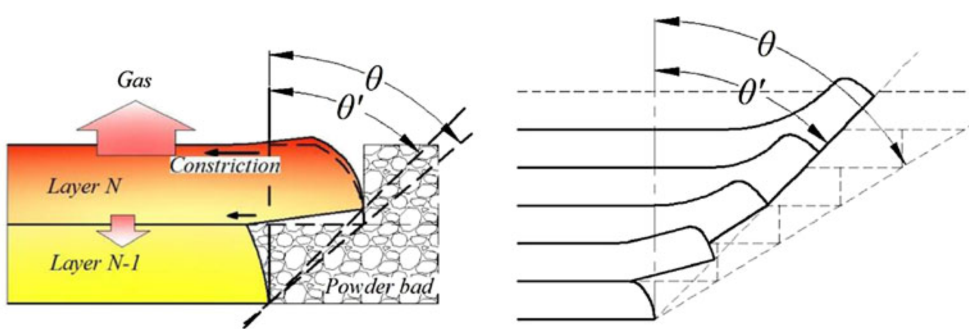
### 2.3 Critical inclined angle

During overhanging surface fabrication, there exists a critical angle, when the inclined angle is smaller than the critical angle, the overhanging surface will warp more easily and have more dross, or even the whole process has to stop as the result of serious warping.

As depicted in Fig. 1a, the smaller the inclined angel $\theta$ means the lager the overhanging length S between adjacent layers. In order to guarantee the forming quality of overhanging surface, overhanging length S has to be smaller than the beam radius so that most of the laser beam can be focused on the solid-supported zone. Therefore, when the layer sliced thickness $H$=35 μm, according to formula (1), overhanging length $S$ should be smaller than the beam diameter 70 μm, and it can be theoretically calculated that inclined angle $\theta$=27° is the minimum building angle of the overhanging surface by SLM; when overhanging length $S = H \cdot \mathrm{ctg}\ \theta$ should be smaller than the beam radius, it can be calculated that inclined angle $\theta \geq 45°$ is the reliable building angle of the overhanging surface by SLM. Generally, overhanging surface with minimum building angle can only be produced using low energy input (high scanning speed or low laser power), while overhanging surface with reliable building angle can be produced using high energy input (low speed scanning or high laser power) or low energy input according to the part's density requirement.

### 2.4 Influential factors

There are a number of factors that can affect overhanging surface fabrication, and it is complicated to judge the warping degree and how much dross formed. Firstly, the laser energy input obviously has great effect on the warping degree of the overhanging surface. The amount of energy input is determined by laser power and scanning speed at the




(a) warping principle (b) warping accumulation

**Fig. 2** The warping principle during SLM fabrication of overhanging surface. **a** Warping principle. **b** Warping accumulation condition that layer thickness and spot diameter are fixed. Too much energy input will increase the amount of molten metal and prolong the time for the pool to solidify, which are helpful to the warp. At the same time, high energy density will melt the layer too deep, which is an important cause for dross formation.

SLM process is carried out at much lower scanning speed than the speed normally used in SLS, since SLM calls for much higher laser energy density to ensure the absolute melting of the metal powder. In SLM, it is not enough just to melt the powder bed of the present layer, but also has to ensure a strong bonding with the previous layer [11]. However, the smaller the scanning speed, the longer time the laser will heats up the powder of the molten pool, so the greater temperature difference between present layer and the previous one, and between the upper part and lower part of the current layer, which will lead to more serious deformation of the fabricated part.

Figure 3 shows the factors that affect the quality of overhanging surface fabrication by SLM.

## 3 Experimental method

### 3.1 Experimental equipment and material

The apparatus used was a self-developed Dimetal-280, which was a pre-commercial SLM workstation with a maximum laser power of 200 W for continuous wavelength of 1,090 nm Ytterbium fiber laser. The building envelop was 280×280×240 mm. The scanning system used was a Dual Axis Mirror Positioning System and a Galvanometer optical scanner, which directs the laser beam in the *x* and *y*-axis through an F-theta lens. The focusing optics were 163-mm focal length lenses, which produces a focused beam spot size of about 70 μm diameter. Since the powder was fully melted during the process, protection of the SLM-processed parts from oxidation was essential, therefore all metal powder processing occurred in an Argon or Nitrogen atmosphere with no more than 0.15 % $O_2$. For the given laser parameters, the optimum thickness of the powder layer spread by scraper is 20–50 μm. Thicker layer is not desirable, as it leads to formation of droplets and [12], thus, to a considerable deterioration of the part's quality. Figure 4 shows the schematic diagram of the operating principle of Dimetal-280 equipment.

Gas-atomized 316L stainless steel powder was used in this experiment. The powder chemical compositions (mass fraction, in percent) were C (0.03), Cr (17.5), Ni (12.06), Mo (2.06), Si (0.86), Mn (0.3), O (0.09), and Fe (balance). The powder was spherical, the powder size distribution (mass fraction, in percent) were <15 (50 %), 15–30 (40 %), and >30 μm (10 %), the mean diameter was 17.11 μm, and apparent density was 4.04 g/cm$^3$. Figure 5 shows the microscopy of 316L stainless steel powder.

### 3.2 Experimental methods

1. Surfaces with different inclined angles were designed and produced with a scanning speed of 200 and 600 mm/s respectively; then discussed the effects of different inclined angles and scanning speeds on the quality of overhanging surface. At this experiment, laser power was set to 150 W, scanning space, 80 μm; layer thickness, 35 μm; and the number of the layers were 100 with each layer size being 10×5 mm, and scanning strategy adopted was inter-layer stagger followed by raster scanning, or the so-called refill scanning strategy [13, 14], as Fig. 6 shows.
2. In order to obtain the relationship among scanning speed, laser power and the critical angle during SLM fabrication of overhanging surface, based on the first experiment, further experiment were done by designing the inclined angle to decrease from 50° to 25°, using a scanning speed of 200–1,200 mm/s and controlling the laser power at 120, 150, and 180 W, respectively. Considering that if the inclined angel is too small or the

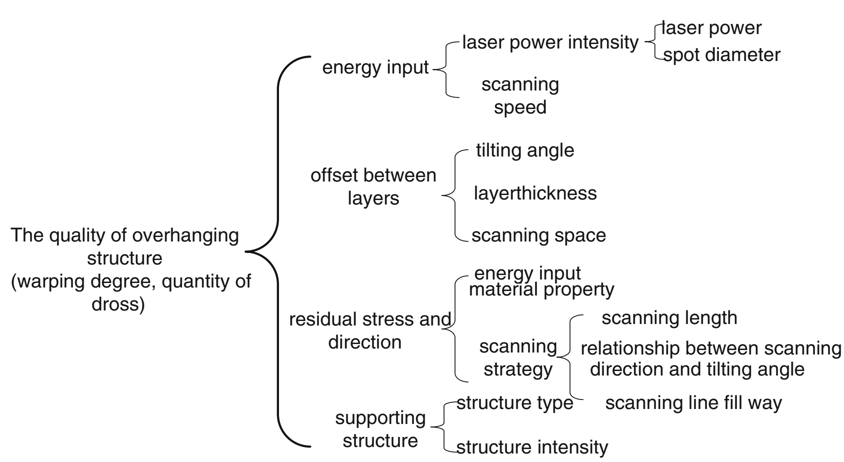



**Fig. 3** Classification of the influential factors

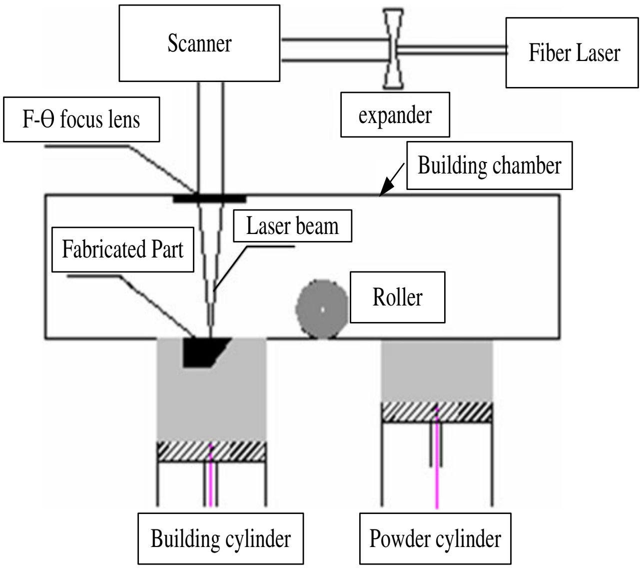



**Fig. 4** The operating principle of SLM equipment

energy input is too large, the overhanging surface will suffer serious defects, which will hinder the smooth fabrication of the experiments. Therefore, in order to ensure the completion of the experiments, the overhanging surface's document corresponding to the moment when it had serious defect will be shut down according to the defective level during the process. The slice thickness was 35 μm; the processing size of each overhanging surface was 10×5 mm; the scanning space was 80 μm; and inter-layer staggered scanning strategy was used.

3. The warping trend of overhanging surface was observed, and the influence of stress accumulation on the overhanging surface fabrication was analyzed by observing the manufacturing process in real time during the second experiment.
4. The internal stress generated in the process of SLM is the direct reason leading to the deformation of overhanging surface. To validate the influence of different scanning line lengths on the overhanging surface fabrication, the overhanging surfaces with the scanning line lengths of 20 and 80 mm were designed and produced by SLM. Both the overhanging surfaces had the same manually added structural intensity.
5. According to the above affecting factors investigated, the paper proposed some effective methods to solve or weaken the serious defects during overhanging surface fabrication, and some key points for well-fabricating complex parts with overhanging surface were also discussed.

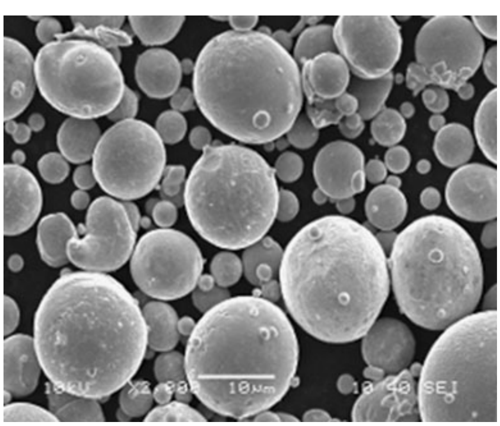



**Fig. 5** Micro-microscopy of 316L stainless steel powder

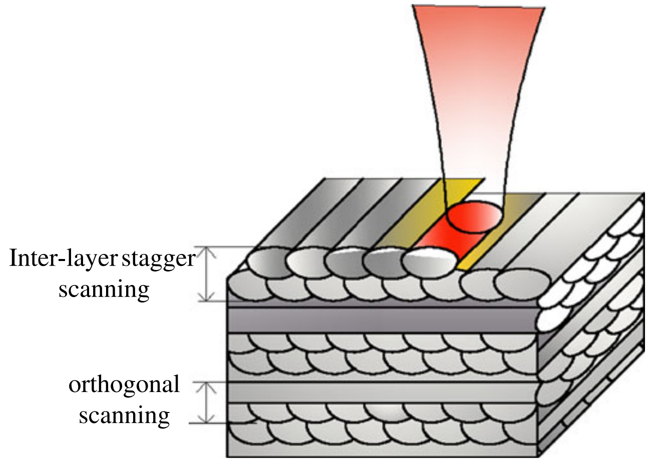


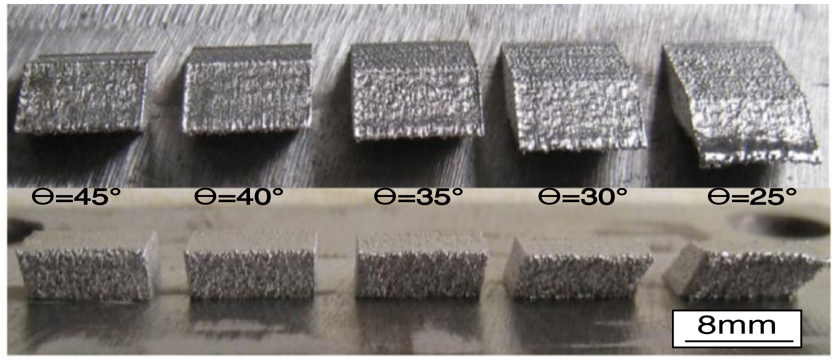

**Fig. 6** Orthogonal scanning and inter-layer stagger scanning strategy was combined together

## 4 Results and discussion

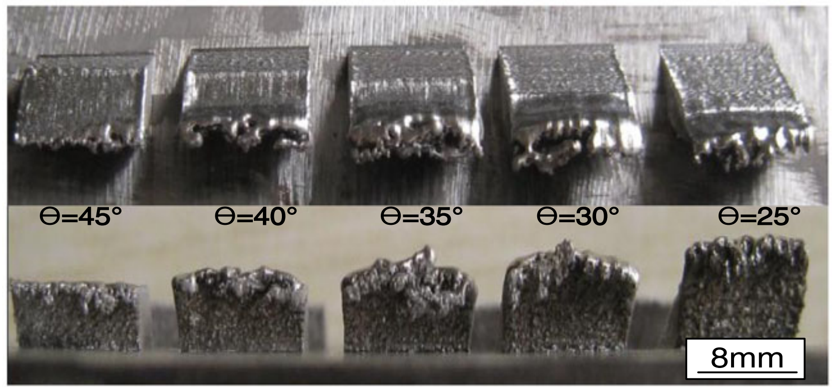
### 4.1 The influence of inclined angle

Figure 7 shows the fabricating results comparison of the overhanging surface when the scanning speed were 200 and 600 mm/s and when the inclined angle decreases from 45° to 25°. It can be seen from Fig. 7a that when the scanning speed was 600 mm/s, the overhanging surfaces whose inclined angle $\theta$ was 25° warped slightly serious, but it can continue to be formed. When inclined angles $\theta \geq 30°$, all the overhanging surfaces can be well be fabricated. However, when the scanning speed was 200 mm/s (seen from Fig. 7b), and the θ decreased from 45° to 25°, it will suffer more and more serious deformation. Even though the inclined angle $\theta$ was 45°, the warping and sinking defects of the surface still existed. It could also be seen from Fig. 7b that the upper surface area of the formed parts will become smaller and smaller as the inclined angle $\theta$ deceased, and the quantity of dross formed will become more and more at the downward surface. Figure 7c shows the side view of the overhanging

**Fig. 7** The fabricating effects of overhanging surfaces with different angles $\theta$ at the scanning speed 200 and 600 mm/s (laser power, 150 W; scanning space, 80 μm; and slice thickness, 35 μm). **a** Scanning speed, 600 mm/s. **b** Scanning speed, 200 mm/s. **c** Side view of the overhanging surfaces fabrication




(a) scanning speed 600mm/s




(b) scanning speed 200mm/s


(c) side view of the overhanging surfaces fabrication

surfaces fabricating effect at a scanning speed of 200 and 600 mm/s, which proved that the warping degree became more serious when the scanning speed was at 200 than at 600 mm/s.

The results above proved that the inclined angle $\theta$ and scanning speed have great impact on the overhanging surface fabrication. The above-obtained experimental results were consistent with the theoretically calculated results: when scanning speed $v$=600 mm/s, the overhanging surface whose inclined angle $\theta$ was 25° had slight warp, while the overhanging surface whose inclined angle $\theta$ was 30° could be well fabricated, which proved that the minimum building angle ranged from 25° to 30° and matched the theoretically calculated minimum building angle $\theta$=27°. When scanning speed $v$=200 mm/s, the energy input was approximately three times as large as that when $v$=600 mm/s, which will make the internal stress increase rapidly during the SLM process. Therefore, to obtain the ideal forming quality, the inclined angle of the overhanging surface should be increased when $v$=200 mm/s during design stage, that is to say, the minimum building angle $\theta$ must be designed larger as energy input get larger. It can be seen from Fig. 5b that when $v$=200 mm/s, almost all the fabricated overhanging surfaces had serious warping defect, even though when the inclined angle $\theta$=45°, it still had a little dross formed at the surface's bottom. The above results showed that when $v$=200 mm/s, the minimum building angle was slightly larger than 45°, proving that the experimental result was consistent with the theoretically calculated result: the inclined angle $\theta \geq 45°$ was the reliable building angle of the overhanging surface by SLM process.

## 4.2 The influence of energy input

### *4.2.1 The influence of scanning speed*

In Fig. 7, by comparing overhanging surfaces fabricating quality at different inclined angles ranged from 25° to 45° when scanning speed $v$=200 and $v$=600 mm/s, respectively, it was found that with the same inclined angle, the warping degree was much more serious when $v$=200 mm/s than $v$=600 mm/s, proving that lower scanning speed will produce greater inner stress. Based on the analysis of the inclined angle $\theta$ influence on overhanging surface, it was known that under the same condition of laser power, the minimum building angle and scanning speed were mutually constraint. When the inclined angle $\theta$ of overhanging surface is small and fixed, it is necessary to increase the scanning speed to reduce the warping trend; when low scanning speed is needed to obtain metal part with higher density, the overhanging surface must be designed with bigger inclined angle $\theta$ in case of larger quantity of manually added supports are needed. Although the warping degree decreased as the scanning speed increased, the scanning speed can only be increased to a certain value. Because too high scanning speed led to the reduction of energy input, this made the laser beam to penetrate to a smaller thickness of the previous layer, influencing the bonding of adjacent layer and causing the defect of delamination.

So as to verify the above conclusions, further experiments were carried out. Figure 8 shows the comparison of the fabricating results of overhanging surfaces when the laser power was 180 W, scanning speed $v$ was increased from 200 to 1200 mm/s, and the inclined angle $\theta$ ranged from 25° to 50°, respectively. In order to ensure the whole experimental process stable, the forming status was observed in real time by camera shooting. When the scanning speed was 200 mm/s, the overhanging surface with inclined angle 25° began to warp at the 15th layer, and all the overhanging surfaces using a scanning speed of 200 mm/s were stopped at 55th layer due to serious warp; all the overhanging surfaces using a scanning speed of 400 mm/s were stopped at the 75th layer. All the overhanging surfaces using a scanning speed of 600 mm/s were stopped at the 85th layer; all the overhanging surfaces using a scanning speed of 800, 1,000, and 1,200 mm/s were stopped at the 115th layer. It can be seen from the above results that both inclined angle $\theta$ and scanning speed had a great influence on the forming quality of the overhanging surface. Besides, the warping sequence of the overhanging surface in Fig. 8 began from the right top zone (inclined angle $\theta$ and scanning speed were low) to the low left zone (inclined angle $\theta$ and scanning speed were high) as the processing went ahead.

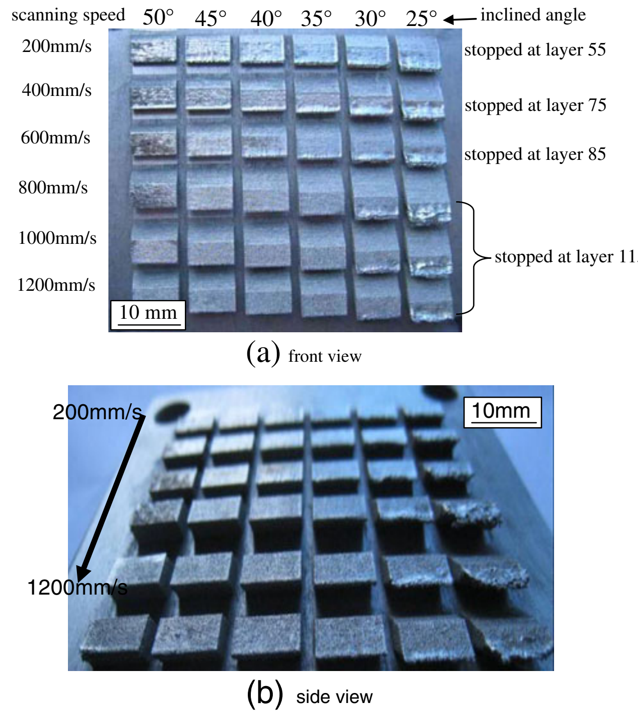


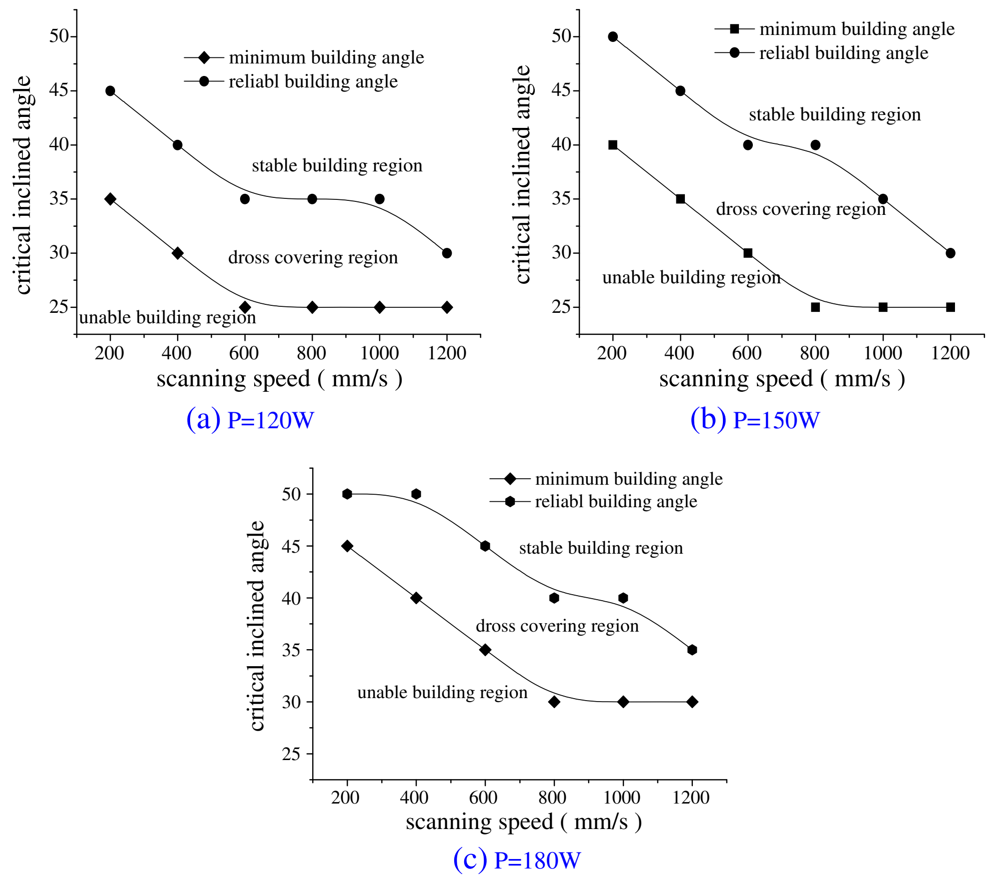

**Fig. 8** Fabrication of overhanging surfaces with the inclined angle θ ranged from 25° to 50°, scanning speed increased from 200 to 1200 mm/s (laser power, 180 W; scanning space, 80 μm; and layer thickness 35 μm). **a** Front view. **b** Side view

### *4.2.2 The influence of laser power*

Comparing Fig. 8 with Fig. 7, it was found that under condition of the same scanning speed and inclined angle, using laser power of 180 W to produce the overhanging surface had larger warping defect than that of 150 W. For example in Fig. 7, when the scanning speed was 600 mm/s, the overhanging surfaces with inclined angle $\theta$ of ≥30° can be well produced by laser power of 150 W; however, in Fig. 8, when laser power was 180 W and the scanning speed was still 600 mm/s, the fabricating document of the overhanging surface corresponding to 600 mm/s was stopped at the 85th layer as the result of serious warp, which showed that laser power had great impact on the fabricating quality of overhanging surface.

According to above results, Fig. 9 summarized the relationship between critical inclined angle and scanning speed at different laser powers. It can be seen from Fig. 9 that scanning speed and laser power restricted the choice of inclined angle. At each laser power there had two curves, called minimum building angle and reliable building angle. When laser power was increased from 120 to 180 W, the range of parameters will shift from lower left to the upper right, which means that value of both minimum building angle and reliable building angle would become bigger.

**Fig. 9** The relationship between critical inclined angle and scanning speed at different laser powers (scanning space, 80 μm and layer thickness, 35 μm). **a** $P$=120 W. **b** $P$=150 W. **c** $P$=180 W




In Fig. 9, it also shows that the curves of minimum building angle and reliable building angle divides the fabricating area into unable forming zone (below the curve of minimum building angle), dross covering zone (between the curves of two critical angles), and stable forming zone (above the curve of reliable building angle). It can also be seen from Fig. 9 that the laser power and scanning speed had the same effect on the overhanging surface in some cases. For example, the reliable building angle when $P$=120 W, $v$=200 mm/s was 45°, and the minimum building angle when $P$=180 W, $v$=400 mm/s was also 45°. Therefore, it was feasible to consider the influence on the overhanging surface's fabricating quality with the value of energy input ($P/v$), which could be a comprehensive impact factor to estimate the fabricating quality of overhanging surface as long as the inclined angle was unchangeable.

To extract how the critical inclined angle depends on power and speed together, it is necessary to extract some generalizable relationships that can be used by other researchers in their different building conditions. In the experiment, the spot diameter was 70 μm, and the line energy input could be defined as formula (2):

$$\psi = \frac{p}{v} \tag{2}$$

Then based on the relationship between critical inclined angle and scanning speed at different laser powers in Fig. 9, the relation between line energy input $\psi$ and the critical inclined angle could be obtained as Fig. 10 shows, in which it can be seen that the trend of the critical inclined angle increased as the energy input $\psi$ increased, especially $\psi$ was at the range from 0.1 to around 0.7 W/mm. However, the

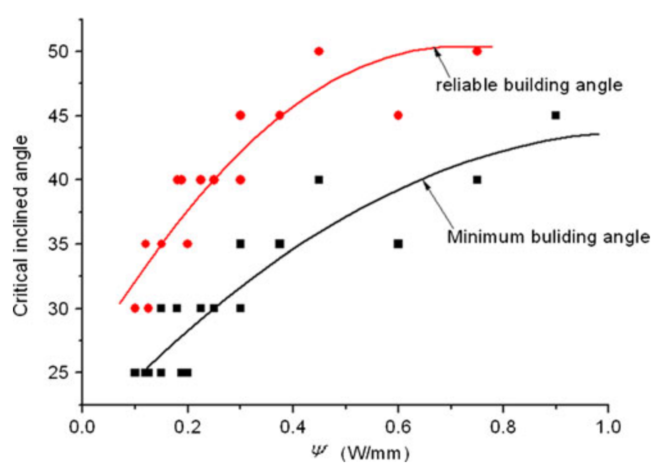



**Fig. 10** The relationship between critical inclined angle and line energy input

relationship in Fig. 10 can only be of guidance significance to other researches, as most of the other researchers' experimental conditions or processing parameters were not the same as in this experiment, for example, the focused diameter, layer thickness, or material property will vary with different people and equipments.

The above experiments and analysis indicated that the value of critical angles (includes minimum building angle and reliable building angle) are closely related to scanning speed and laser power. Building overhanging surface with lower inclined angles is more dangerous, and it is clear that it is less likely to build the geometry successfully as the angle decreases to lower the critical angle.

### 4.3 The influence of stress accumulation

Figure 11 shows the powder-spreading conditions of the fabricating zone at different times when the second experiment was carried out. It could be seen from Fig. 11 that there was no significant warp during the first ten layers' production. A small fraction of the overhanging surface started to warp at about the 15th layer. The warping degree of the overhanging surfaces became more and more serious, and the warping range of the overhanging surface became larger and larger as the processed layers were gradually increased. It can be found that the warping defect started from the upper right corner (as Fig. 11b, c shows), then drifted slowly to the lower left zone (as Fig. 11d–f shows), which means that the overhanging surfaces with smaller inclined angle and formed with smaller scanning speed began to warp at the beginning, and they will get more and more serious warping defect.

It was also found that under the fixed fabricating parameters, the same overhanging surface started to warp only when accumulated to a certain number of layers, which showed that the stress will become bigger and bigger with the layers accumulation under the same forming conditions, leading to overhanging surface warp. Figure 11 shows that the heat cumulative effect had great impact on the warping degree. At the 53th layer, the warping degree had been quite serious, leading to the part's surface much higher than the pre-set layer thickness. Therefore, the whole process should be stopped to ensure the safety of powder recoating device. It is considered that the internal stress of SLM part is hard to measure; however, by observing the warping degree and powder spreading status at different times, a database can be established to correlate overhanging surface's warping degrees, energy inputs, and inclined angles, which should facilitate the technician and designer to prepare the manufacturing data.

As the result of warping defect, the fabricated overhanging surface's height is higher than pre-set layer's height, leading the whole SLM process to fail, affecting the run safety of re-coating device. How to ensure no warp during the SLM fabrication of overhanging surface is very important, because the underlying powder will not restrict the distortion [15].

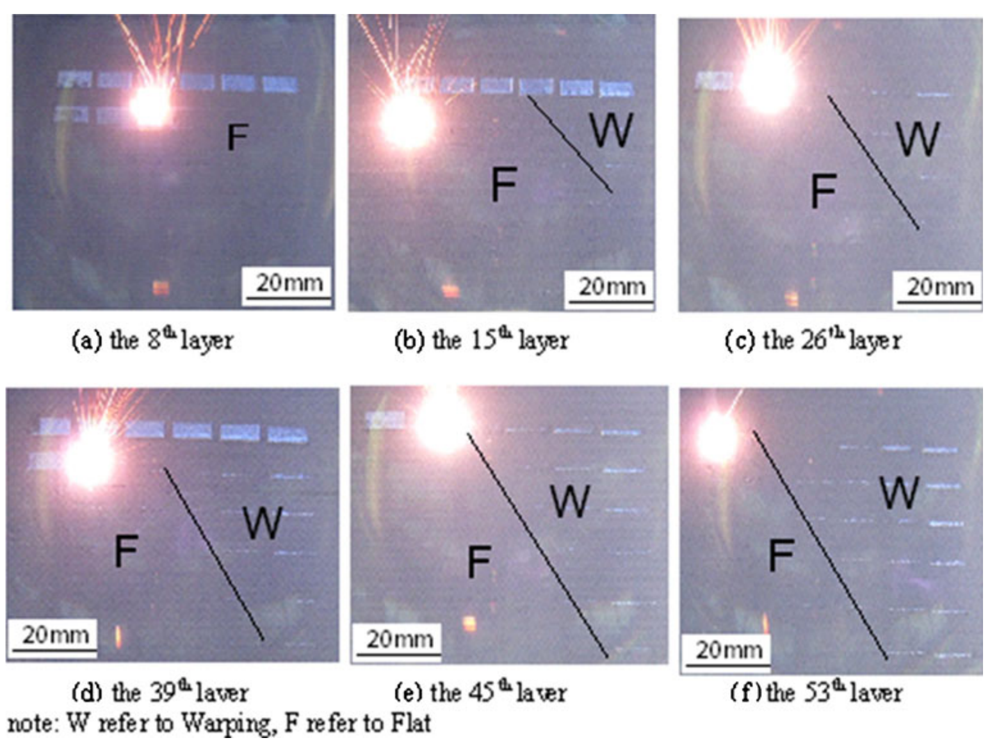



**Fig. 11** The recoating status at different times (laser was turn on; laser power, 180 W; layer thickness, 35 μm; and scanning space, 80 μm). **a** The 8th layer. **b** The 15th layer. **c** The 26th layer. **d** The 39th layer. **e** The 45th layer. **f** The 53rd layer

### 4.4 The influence of scanning vector length

Figure 12 shows the fabricating effect comparison of the overhanging surface when the scanning vector lengths were 20 and 80 mm, respectively. It could be seen that both ends of the overhanging surface with 80 mm scanning vector length had broken away from the manually added supports, proving its serious deformation. The overhanging surface with 20 mm scanning vector length had good fabricating quality (was fabricated, 250 layers).

The experiment of Fig. 12 belonged to the situation when the inclined angel $\theta$ of SLM fabricated overhanging surface was 0°. The experimental result proved that overhanging surface with long scanning vector length will accumulate larger internal stress than the shorter one. It is believe that when the scanning vector's direction is parallel to the long side of the cross-section, the layer contraction behavior caused by solidification mainly depends on the longitudinal contraction of scanning lines, making the contractile compensation quite inadequate and leading to large internal stress. Matsumoto [16] had analyzed the thermal conduction and elastic deformation during laser rapid melting and solidification of metal powder through the FEM method and obtained the conclusion that the warping degree was proportional to the scanning vector's length. Matsumoto also proposed that the sub-regional scanning method could be used to prevent overhanging surface with long scanning vector from serious warp.

We had analyzed several important factors that influence the fabricating quality of overhanging surface. These factors include inclined angle $\theta$, scanning speed, laser power, thermal stress, and scanning vector's length. There are still some factors would have great impact on the fabricating quality of overhanging surface, such as scanning strategy, manually added support's way, and so on. Considering the length of this article, each of these factors cannot be discussed in detail, but we know that all of the factors will have major or minor impact on the fabricating quality of the overhanging surface, depending on the manufacturing situation.

Although at present the solution to optimize the fabricating quality of overhanging surface is mainly by adding metal supports, then followed by hand polishing, sand blasting, and so on, as discussed above, some geometrical shapes cannot be added metal supports.

## 5 Optimized solutions

According to above analysis of the affecting factors, optimized solutions were adopted to improve the quality of overhanging surface based on the relationships among the critical angle, scanning speed, and laser power. The solutions included adjusting part's orientation and controlling local energy input.

### 5.1 Adjusting part's orientation

The part's orientation can be adjusted to improve the quality of the overhanging feature. The purpose to adjust part's orientation is to alter the inclined angles of overhanging surface. More specifically, the inclined angle at key positions of overhanging surface will be improved, and the unimportant positions which could be easily polished by post treatment are adjusted to low inclined angle. Therefore, those unimportant positions need manual-added supports. Another important purpose of adjusting part's orientation is to minimize the amount of manual-added support as much as possible.

The experiments above provided theoretical basis for adjusting part's orientation: that is the relationships among energy input and critical building angle were mutually constrained. According to the conclusion shown in Fig. 9, the important overhanging surface's inclined angle should be adjusted to be bigger than the reliable building angle, by means of being at the expense of the quality of unimportant surfaces, where the inclined angle will be decreased and the amount of manual-added supports are increased. Figure 13 represents a typical example of adjusting overhanging surface's orientation to change the inclined angle and manual-added support's style.

In Fig. 13, placing style (a) has the smallest $z$-directional height, so the fabrication time will be the shortest. However, placing style (a) needs the most of manual-added supports, so it will have the worst forming quality at the downward surface. Placing style (b) needs the least amount of manual-added supports, but it has the biggest $z$-directional height, so longest forming time will be needed. Placing style (c) is the desired one, where the inclined angle $\alpha$ is reliable building angle according to Fig. 9. Considering the placing style (c), it not only needs smaller amount of manual-added supports,

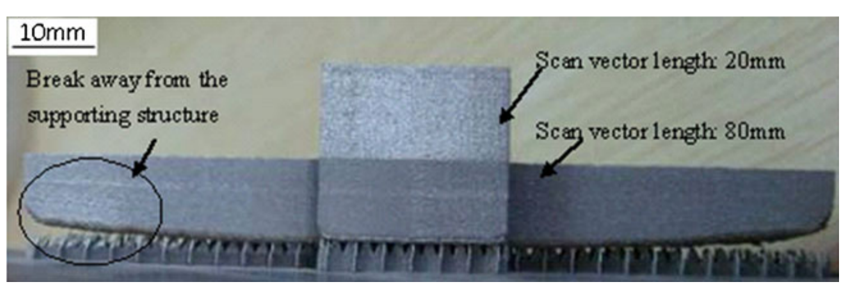



**Fig. 12** Fabricating effect comparison of overhanging surface (supported) with the scanning vector length of 20 and 80 mm (laser power, 150 W; scanning speed, 200 mm/s; layer thickness, 35 μm; and scanning space, 80 μm)

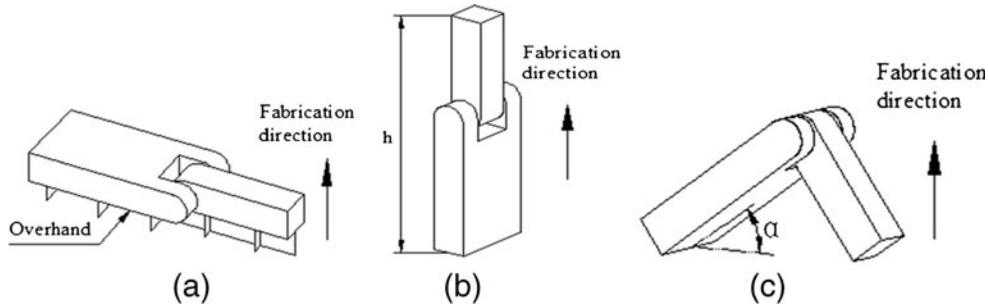



**Fig. 13** Effects of part's orientation on SLM fabrication critical position. **a** Fabrication direction. **b** Fabrication direction. **c** Fabrication direction

but also has smaller *z*-directional height than style (b). Another advantage of placing style (c) is that the supporting pattern is "line," which is convenient to be removed; while the supporting patterns of placing styles (a) and (b) should be "web" or "contour." which are much more difficult to be removed than "line" pattern. Based on above analysis, the fabrication of overhanging surface will commonly use placing style (c).

Figure 14 shows the example of SLM manufactured non-assembly mechanisms using placing style (c), where the inclined angle of the key clearance part was adjusted to be a little bigger than the reliable building angle. It is found that the amount of manual-added supports were little (Fig. 14a, b), and all the metal supports could be easily removed. The non-assembly mechanisms can be swung directly and smoothly after supports were removed (Fig. 14c).

Multi-layered part is built from multi-single layers, and a single layer is composed of multi-single tracks. During laser scanning the metal powder, the laser energy is transferred to heat absorbed by metal powder, which makes the powder melt and bind together. When the laser energy input is enough and the metal powder is absolutely melted, then regular and continuous track can be obtained [17], while the laser energy input is insufficient to melt the metal powder, then sintering status will be got. There exists a heat affect zone around the molten pool during laser scanning metal powder, making the metal powder around the molten pool not fully melted or in sintering status [18], as Fig. 15 shows, many stainless steel powder particles were adhered to the both sides of the tracks.

The clearance was critical during SLM fabrication of non-assembly mechanisms [19] (Fig. 14). The smaller the clearance, the more stable the mechanisms will works. The adhered powder particles will affect much on the size of the clearance, leading to the movement of the mechanisms not so smooth, that's because the adhered powder particles were

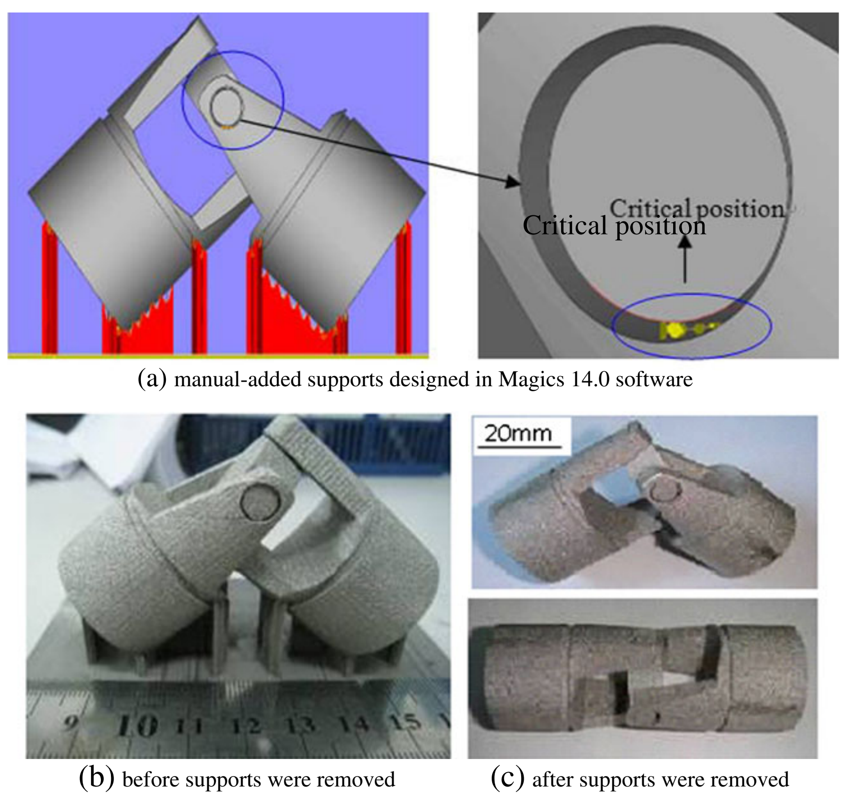
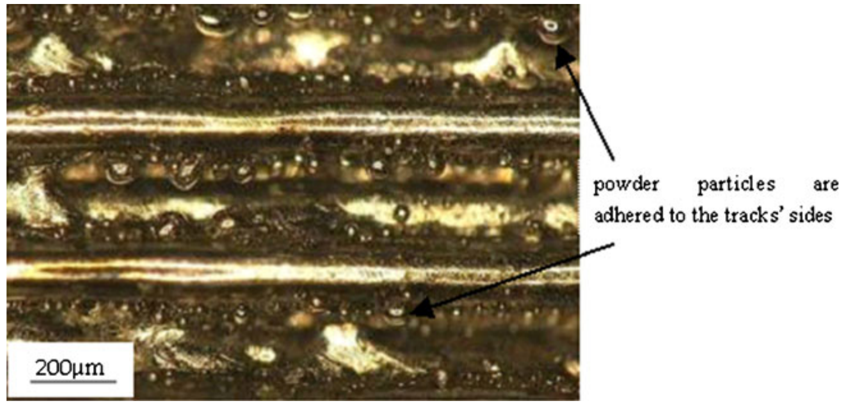



**Fig. 14** Non-assembly mechanisms was manufactured by SLM. **a** Manual-added supports designed in Magics 14.0 software; **b** before supports were removed; **c** after supports were removed

Fig. 15 Stainless steel powder particles were adhered to the both sides of the tracks




hard to escape from the key positions. In principle, the clearance of the non-assembly mechanisms should be designed as small as the size of the biggest powder particles (it was 30 μm in this experiment), but for the powder adhering phenomenon happened in heat affected zone, the clearance size must be designed much bigger than the theoretical size, only in this way that the freely moved non-assembly mechanisms can be directly manufactured by SLM.

The smallest clearance of the non-assembly mechanisms that can be manufactured was 0.2 mm [20], which was much bigger than the biggest powder particle size 30 μm. The fabrication of the non-assembly mechanisms was a typical example of overhanging surface optimization.

### 5.2 Controlling local energy input

Almost all rapid prototyping technologies (such as SLS/SLM) have multiple groups of parameters based on processing quality. These parameters are generally obtained through a large number of experiments. In general, fixed parameters (scanning speed, laser power, spot size, etc.)are used during single manufacturing process. However, when the parameters of solid-supported zone (Fig. 1b) are used in power-supported zone (Fig. 1b), the heat input should be too large, leading to a large melting pool and sinks into the supporting powder as the result of gravity and capillary force, all of which will make the fabricating quality of overhanging surface worse. Therefore, it is necessary to change the laser energy input in real time to optimize the fabricating quality of overhanging surface according to its inclined angle value. Currently, the "skin and core" scanning strategy used by EOS Company is a typical example of using different parameters at different positions of the part. Skin refers to the outer part of the layer, and core refers to the inner part the layer. Finding the appropriate process parameters for skin and core zones are respectively needed. In order to define the feasible process window, labor intensive trial and error are necessary. However, "skin and core" scanning strategy is only used to improve the fabricating efficiency and cannot solve the fabricating defects of the overhanging surface. Therefore, it is suggested that controlling local energy input could be used to optimize the overhanging surface's fabricating quality according to the value of the inclined angle. When overhanging surface started to be formed (especially at the first layer), according to the relationships in Fig. 9, the scanning speed should be increased or the laser power should be reduced to reduce energy input, only in this way then warping trend and the amount of dross could be reduced. Figure 16 is the typical circular overhanging surfaces, on which at ($h_1$+$h_2$) zone, it only need the typical processing parameters; but at $h_3$ zone, it will need to reduce energy input (generally by increasing the scanning speed) to reduce warp and dross. The key for well fabricating the circular type overhanging surface by SLM is how to determine the boundary between $h_2$ and $h_3$ zones, which should be estimated by the chamfer angle $\alpha$ at the boundary. The chamfer angle at the boundary can be got according to the relationships in Fig. 9. When manufacturing metal parts with overhanging surface on very low inclined angle, it is important to produce the first layer without distortion on the powder bed, because the underlying powder will not restrict the distortion.

Figure 17 shows the fabricating results comparison of circular-type overhanging surface between whether they were imposed local energy input controlling. In Fig. 17, it can be seen that the fabricating quality of the overhanging

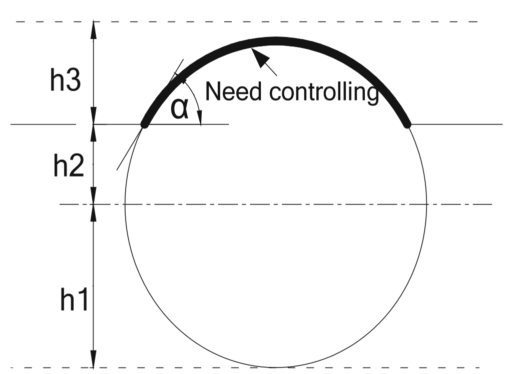
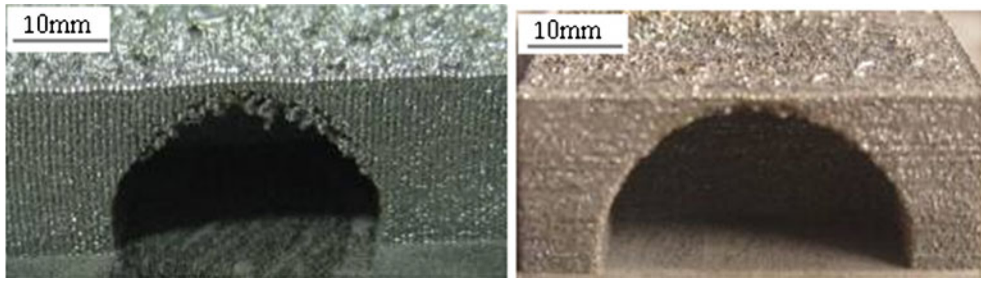



Fig. 16 The schematic diagram of circular overhanging surfaces




(a) scanning speed at h3 zone was 200mm/s (b) scanning speed at h3 zone was 600mm/s

**Fig. 17** Fabricating effects comparison of circular-type overhanging surface between whether they were imposed local energy input controlling. **a** Scanning speed at $h_3$ zone was 200 mm/s. **b** Scanning speed at $h_3$ zone was 600 mm/s

surfaces were improved significantly by controlling local energy input.

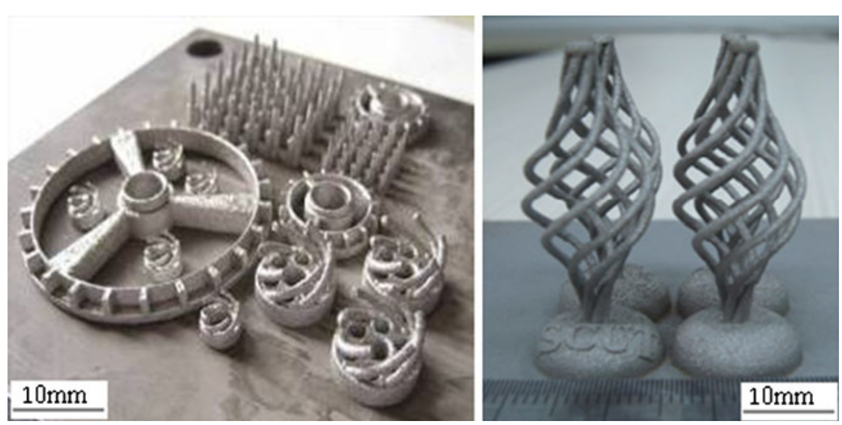
### 5.3 SLM fabricate complex metal parts with overhanging surface

Through above experiments and theoretical analysis, we can see that as long as reasonable technical measures and designing methods were adopted, metal parts with overhanging surfaces can be well fabricated by SLM. The key points is summarized as follow: when the inclined angle of the overhanging surface was a bit low and cannot be changed, then only energy input could be adjusted to optimize the fabricating quality of overhanging surface, while the overhanging surface's density was required to be high, so laser energy input must be high, then only the inclined angle of the overhanging surface should be re-designed. Figure 18 shows the manufacturing examples of complex parts with typical overhanging surfaces, which were optimized by designing. It could be seen from the manufacturing effects that complex parts with overhanging surfaces can be well optimized by above solutions.

## 6 Conclusions

Overhanging surface is the biggest geometrical restraint for SLM technique, as which would have fabricating defects, such as warp and dross. These defects usually lead to the consequence that dimensional accuracy and the shape of the SLM parts could not meet the demands. This paper had investigated several important factors affecting the fabricating quality on overhanging surface, including the inclined angle, scanning speed, laser power, the stress accumulation, and scanning vector length. The analysis found that: (1) the smaller the inclined angle, and the smaller the scanning speed, the warping defect will happen more easily for overhanging surface; (2) the greater the laser power, the warping trend was more greater for overhanging surface; (3) energy input (laser power, scanning speed) and critical building angle were mutually restrained, and the critical building angle included reliable building angle and minimum building angle. If the inclined angle of the overhanging surface was low and cannot be altered in the designing stage, then only the energy input can be adjusted to improve the fabricating quality of overhanging surface; if the processing parameters were established to ensure the parts' density, then only the inclined angle of the overhanging surface can be changed during the designing stage; (4) as the manufactured layers increasing, the residual stress increased cumulatively, causing the warping trend more serious; and (5) the overhanging surface with longer scanning vector will warp more easily, because longer scanning vector was beneficial for residual tress accumulating.

Two effective methods were adopted to improve overhanging surface fabrication, including: (1) adjusting part's




(a) space-curved wheels (b) complex component

**Fig. 18** Complex parts with overhanging surfaces were fabricated by SLM. **a** space-curved wheels. **b** Complex component orientation, the inclined angles at the critical positions of the overhanging part can be changed; and (2) controlling the local energy input. By adopting the above two methods, the fabricating quality of most the overhanging surface can obviously be improved.

This paper provides preliminary design rules for the SLM process, especially for production of complex parts with no need of manual-added support. During SLM process, the relationships between the critical building angles and energy input (scanning speed and laser power) must be considered. When SLM fabricates overhanging surface with the inclined angle $\theta=0°$, even if abundant metal supports were added, the fabricating quality still cannot be guaranteed. Some other factors that also affect the fabricating quality on overhanging surface were not discussed in this article, such as the pattern of manual-added structure, scanning strategy, powdery properties, and so on, these factors may equally be of importance. In order to manufacture complex parts with overhanging surfaces precisely, most of the affecting factors should be pre-considered and optimized before SLM experiment.

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