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A new two-step selective laser remelting of 316L stainless steel: process, density, surface roughness, mechanical properties, microstructure

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Abstract

A new two-step selective laser remelting (SLR) process was proposed to fabricate 316L stainless steel. The density, surface roughness, and mechanical properties were investigated by a multifunctional density tester, surface roughness meter, and tensile testing machine. Compared with the single-melting selective laser melting (SLM) process, the relative density, surface roughness ($R_a$), ultimate tensile strength, yield strength, elastic modulus, and elongation reached 99.31%, 6.67 $\mu$m, 725 MPa, 643 MPa, 13.95 GPa, and 40.8%, respectively. In addition, the microstructure and fracture characteristics were studied by OM, SEM, and EDS. The results showed little unmelted powder and fewer defects (balling, spatter, and cracks). In addition, a closer and smoother connection between the welds and equiaxed cell were obtained by the SLR process.

1. Introduction

Selective Laser Melting (SLM) is a mature technology in metal Additive Manufacturing (AM) [1], but most research has focused on single-step melting laser scanning [2–9]. Selective laser remelting (SLR) has been applied to scan the same slice two or more times, and offers a solution to improve the quality of parts. The applications and challenges of this technique have been well reviewed [10–15]. Yu et al [10] proposed a remelting strategy in the same and opposite directions to the first scanning routine to fabricate AlSi10Mg parts. Liu et al [11] proposed a new process: powders were premelted using low laser power, and then the powders were melted again by using a high-power laser to realize the remelting process layer by layer. The effects of remelting on the porosity [12], density [13], surface quality [14], and mechanical properties [15] were examined.

However, owing to the closedness of metal 3D printing equipment, researchers cannot autonomously change the remelting strategy. Therefore, the current remelting process is focused on traditional linear reciprocating melting (the angle between first-step scanning and second-step scanning is 0°, and the melt channel is remelted twice). The traditional remelting process helps to reduce the amount of unmelted powder, but remelting in the same melt channel causes overburning and even vaporization of the metal powder.

In this paper, a new two-step SLR process is proposed and applied to metal 3D printing equipment in cooperation with Anhui Top Additive Manufacturing Technology Co., Ltd. The angle between first-step scanning and second-step scanning was 67°, and conventional SLM process parameters were applied for first-step laser scanning melting. However, lower-volume energy densities by changing the laser power and laser scanning speed were applied for second-step laser remelting. The density, surface roughness, microstructure, mechanical properties, and fracture characteristics of 316L stainless steel fabricated by SLR were further investigated, including the stiffness, strength, and plasticity.
2. Materials and methods

2.1. Powder properties and chemical composition
Air-atomized 316L stainless steel powder was selected for SLM and SLR. The average particle size was 22 \( \mu \text{m} \)–55 \( \mu \text{m} \). There was a small amount of satellite powder, irregular powder, and hollow powder. The morphology of the powder is shown in figure 1.

The chemical composition of 316L stainless steel metal powder by EDS is shown in table 1. 316L stainless steel is austenitic stainless steel, and its thermal conductivity is about half of that of low-carbon steel, but the coefficient of linear expansion is about 50% higher than that of low-carbon steel. Thus, the formation process of SLM is more likely to produce defects including bubbles, cracks, spatters, unmelted and partially unmelted powder, and oxide inclusions [16, 17].

All 3D samples were fabricated by a desktop metal printer developed by Anhui Top Additive Manufacturing Technology Co., Ltd, as shown in figure 2. The printer was equipped with an optical fiber device (wavelength 1064 nm, power 250 W). The forming platform was 100 mm \( \times \) 100 mm. The spot diameter was 70–200 um and was continuously adjustable.

2.2. SLR process
As shown in figure 3, a two-step remelting process was applied, and the same layer was reexposed twice. The first step was used to adopt conventional laser process parameters, and various laser process parameters were applied to the second step. Laser remelting has the potential to change the microstructure and improve the mechanical properties of the steel, including its strength and plasticity.

For both first-step scanning and second-step scanning, the hatch space was 0.11 mm, layer thickness was 30 \( \mu \text{m} \), and spot size was 0.08 mm. The angles between layers was 67°, and the angle between first-step scanning and second-step scanning was 67°.

2.3. Experimental data scheme
To study the effects of the new two-step selective laser remelting process on the mechanical properties, five laser process parameters were selected. These are listed in table 2. Scheme 5 is a no-remelting process (single-step SLM process). Three samples for each scheme were fabricated.

As shown in table 2, in this paper, five experimental schemes were applied. Scheme 1 to scheme 4 were two-step SLR processes, and scheme 5 was a single-step SLM process. The first-step laser process of all five experimental schemes was the same:
By comparing schemes 1–4 with scheme 5, the effects of SLR and SLM on the density, mechanical properties, fracture properties, and surface roughness were studied. (2) The volume energy density of scheme 1 and scheme 2 were the same at 87.719 J mm$^{-3}$. The second-step remelting process of scheme 1 reduced the laser power (200 W), and the second step of scheme 2 increased the laser scanning speed (1187 mm s$^{-1}$). (3) The volume energy density of scheme 3 and scheme 4 were the same at 109.64 J mm$^{-3}$. The second-step remelting process of scheme 3 reduced both the laser power (200 W) and scanning speed (760 mm s$^{-1}$), and the second-step remelting process of scheme 4 did not change the characteristics, which is consistent with the first-step melting parameters.

In addition, by comparing schemes 1 and 2 (or schemes 3 and 4), differences between the same volume of energy densities on the mechanical properties and fracture characteristics were investigated. By comparing scheme 1 (2) and scheme 3 (4), differences between volume energy densities on the mechanical properties and fracture characteristics were investigated.

Table 2. Experimental process parameters of five experimental schemes.

| NO. | First step | Second step |
|-----|------------|-------------|
|     | Power/W    | Scanning velocity mm/s | Volume energy density J/mm$^3$ | Power/W | Scanning speed mm/s | Volume energy density J mm$^{-3}$ |
| 1   | 250        | 950         | 109.64 | 200       | 950         | 87.719 |
| 2   | 250        | 1187.5      |        | 200       | 760         | 109.64 |
| 3   | 200        | 760         | 109.64 | 250       | 950         |        |
| 4   | 250        | 950         |        | No-remelting (single-step SLM process) |        |        |

Figure 2. TB-SLM100S desktop metal printer.

Figure 3. Two-step selective laser remelting process.

Table 2. Experimental process parameters of five experimental schemes.
2.4. Tensile test method
A tensile test was carried out according to ASTM E8/E8M-16a. The strain rate was 1 mm min$^{-1}$ using a combined universal testing machine. The tensile specimen is shown in figure 4. The specimen specifications were as follows: parallel length $L_c = 25$ mm, cross-sectional shape was a rectangle, original diameter was 2 mm, and the sample was nonproportional. The sample was not machined and was used directly after formation with SLM.

2.5. Characterization
The 3D parts for microscopic observation were premilled, mechanically polished, and chemically etched. The etchant used for chemical corrosion was FeCl$_3$, and the corrosion time was 1 s.

A Nikon EPIPHOT-300 optical microscope was used for low-fold microstructure observation. The morphology was observed by SEM (Hitachi SU8010), and an Oxford Instruments EDS (AZtec X-Max50) was used for composition analysis. Using a multifunctional density tester (DAHOMETER, ar-300me) to measure the density of printed samples, the precision of the density measurement was found to be 0.001 g cm$^{-3}$. A surface roughness meter (TESA rugosurf 10-G) was used to measure the surface roughness. A tensile testing machine (MTS C45.305) was used to carry out the tensile test at room temperature and a speed of 0.2 mm min$^{-1}$.

3. Results
In order to explore the comprehensive influence of the laser power and scanning speed on the density, surface roughness, microstructure, mechanical properties, and fracture characteristics, the volume energy density was selected as the research object to represent the input energy per unit volume.

Volume energy density: $E = \frac{P}{V_{\text{h} \cdot t}}$

with the following symbols: laser power $P$ (W), scanning velocity $v$ (mm s$^{-1}$), hatch space $h$ (mm), and layer thickness $t$ (mm).

3.1. Relative density
In general, the density of samples fabricated by SLM and SLR directly reflects the internal quality and defects such as pores and bubbles, and also affects the mechanical properties. Therefore, density is one of the important parameters of SLM formation. The theoretical bulk density of the 316L stainless steel alloys was 7.98 kg cm$^{-3}$. After SLM and SLR, the relative density of the as-fabricated samples reached 99.19% and 99.31%, respectively, as shown in figure 5.

Compared with the SLM process (sample 5, 7.916 Kg cm$^{-3}$), the density of sample 1 increased to 7.925 kg cm$^{-3}$. This is mainly owing to the second-step remelting, which reduced the amount of unmelted powder and the porosity.

However, not every SLR experimental scheme was capable of increasing the density. The density of samples 2–4 fabricated by SLR were lower than that of sample 5 fabricated by SLM. Comparing sample 1 (3) with sample 2 (4), it can be seen that the volume energy of the second step is the same, but owing to the increasing laser power and laser scanning speed, the splashing of metal powder and liquid was significant, so the density decreased.

According to the above analysis, a low second-step volume energy density for SLR could not determine the density, and only a low volume energy density with low laser power helped to increase the density. By contrast, a low volume energy density and high scanning speed decreased the density.

3.2. Mechanical properties
Figure 6 shows a macrophysical diagram of the 3D parts after breaking. The fracture position fluctuated randomly, the fracture surface was 45°, and the fracture was instantaneous.
3.2.1. Stress-strain diagram
The stress-strain diagrams of 316L stainless steel prepared by SLM and SLR are shown in figure 7. The average value of the elastic modulus (E), yield strength, ultimate tensile strength (UTS), and elongation for both single-melting SLM and two-step SLR are shown in figure 8.

(1) Elastic modulus: As shown in figure 7, the elastic deformations (below 4.5 ± 15% strain) for the five samples were similar to each other. The elastic modulus for SLR fluctuated between 12.93 ± 0.1 GPa and 13.95 ± 0.1 GPa, which was lower than that of SLM at 14.29 ± 0.1 GPa.

(2) Yield strength: As shown in figure 7, there was no obvious yield stage in the stress-strain curve. The yield strength fluctuated between 590 ± 15 MPa and 643 ± 15 MPa for SLR. Compared with single-melting SLM at 591 ± 10 MPa, the effect of remelting on the yield strength of the metal 3D printing parts was obvious and improved by up to 8.79%.

(3) Ultimate tensile strength (UTS): Compared with the SLM process, the UTS of two-step SLR improved from 674 MPa ± 15 MPa to 725 MPa ± 15 MPa, a 7.57% improvement. Considering that the two-step
remelting of 3D parts did not undergo isostatic pressure or other heat treatments, it was possible to further improve the UTS.

(4) Elongation after break: As shown in figure 8, the elongation of two-step SLR fluctuated between 34.9 ± 1.5% and 40.8 ± 1.5%. Compared with single-melting SLM at 39.4%, the elongation improved to 40.8%. Therefore, suitable two-step SLR process parameters can improve the both the strength and plasticity of 316L.

Compared with SLM, the SLR process changed the mechanical properties of the samples. NO.1 by SLR increased the strength, plasticity, and elasticity, while NO. 2 and NO.4 decreased the strength and plasticity. Thus, only the use of both low volume energy density and low laser power for second-step remelting by SLR could improve the mechanical properties.
3.2.2. Surface roughness

The surface roughness was measured by a surface roughness meter (TESA rugosurf 10-G), as shown in figure 9. The surface roughness Ra of the as-fabricated samples by SLM and SLR reached 6.667 μm and 11.289 μm, respectively; and Rz reached 41.96 μm and 66.707 μm, respectively. Thus, two-step remelting improved the surface roughness significantly by 40.9% for RZ and 37.09% for Ra.

(1) Surface roughness Ra: As shown in figure 9, surface roughness Ra of sample 2 was higher than that of sample 5. This was mainly a result of the high speed for sample 2. A high laser scanning speed aggravated the impact of metal gas on the liquid metal, forming significant liquid spatter.

(2) Surface roughness Rz: As shown in figure 9, Rz of every sample by SLR was lower than that of SLM owing to the second-step remelting. Second-step remelting helped to reduce the amount of unmelted powder and balling, and thus Rz for SLR decreased.

Figure 9. Surface roughness of five as-fabricated samples.

Figure 10. Upper-surface morphology of sample parts by SLR and SLM: (a) No. 1; (b) No. 2; (c) No. 5.
In addition, comparing sample 2 with samples 3–4, it can be seen that the high-volume energy of the second step helped to decrease both $R_a$ and $R_z$. This was mainly because increasing the volume energy density helped to melt the powder, which reduced the amount of unmelted powder and made the laps between the welds smoother. Thus, the second-step remelting process could decrease $R_z$, but a low scanning speed helped to decrease both $R_a$ and $R_z$.

### 3.3. Microstructure analysis

#### 3.3.1. Morphology of metal 3D samples

Figure 10 shows the upper-surface morphology of samples by SLR and SLM. Little unmelted powder and less spatter appeared in sample 1 by the SLR process, which was why SLR was able to improve the mechanical properties.

In addition, comparing sample 1 with sample 2, a higher laser scanning speed of the second-step remelting process increased both the liquid spatter and powder spatter, leading to a decrease in the mechanical properties.

Figure 11 shows the upper-surface morphology after corrosion. Thanks to second-step scanning at 67°, interlaps between melt pools presented a cross shape, which improved the strength of the interlaps. Figure 11 shows that compared with the SLM process, there was almost no gap between melt pools after corrosion. In addition, few pores appeared in sample 1 by the SLR process, so the remelting strategies induced a significant decrease in porosity.

Figure 12 shows the side-surface morphology of samples by SLR and SLM. Figures 12(a) and (b) show that the arc of SLR was close to the level, and the radian between the molten pools showed a process smoother than SLM. Second-step scanning reduced the amount of unmelted powder, which made the molten pools smoother and the interlaps between welds not obvious. Thus, the connections between welds were more stable.

#### 3.3.2. Microstructure of metal 3D parts

For both the SLR and SLM processes, at the beginning of laser scanning, temperature gradient $G$ at the bottom of the melt pool was very large, and the solidification rate $R$ was very small. The ratio $G/R$ tended to infinity and planar structure forms. When the laser spot leaves, the ratio of $G/R$ decreased, and the crystal changed from
planar crystal to cellular crystal growth. With an increase in the substrate temperature, the melt powder was in contact with fine higher-temperature crystal planar crystals, and the melt powder grew like dendrites [19–21].

Figure 13 shows that compared with SLM, the columnar cell zone of samples by SLR was significantly reduced, and most of them were equiaxed cells. As a result, second-step remelting destroyed the original columnar cell of first-step melting and reduced the grain size, resulting in almost all equiaxed cells. This is why the remelting process improved both the strength and plasticity.

3.3.3. Fracture morphology of 3D parts

Figure 14 shows the cross-section macromorphology of the fracture surfaces. Samples fabricated by both SLR and SLM were broken along 45° at the cutoff port and belonged to a typical ductile fracture.

Figure 15 shows that the tensile fractures of samples by SLR and SLM were dimple fractures. There was little unmelted powder, liquid spatter, or cracks in the fracture. As shown in figures 11 and 12, defects such as pores appeared in samples by SLM, and fewer defects appeared in samples by SLR. Thus, second-step remelting of SLR reduced the amount of unmelted powder, which helped to decrease the number of internal defects such as balling and pores.

4. Conclusions

Several interesting results in this investigation were found, even though some were not consistent with expectations.

(1) Two-step selective laser remelting was a promising method to enhance the density, surface quality and mechanical properties (strength and plasticity). However, the process parameters of second-step remelting affected the results significantly.
Nowadays, the volume energy density is generally introduced as a comprehensive characterization parameter of the laser power, laser scanning speed, and hatch space layer thickness when studying the effects of mechanical properties. The results in this paper showed that the same volume density (high laser power/high scanning speed, and low laser power/low speed) exhibited different properties including mechanical characteristics, densities, and surface roughness. A high scanning speed increased the spatter and other defects, and high laser power reduced the amount of unmelted powder and decreased the number of defects such as balling and pores. Therefore, under the premise of melting, high laser power/low laser scanning speed should be adopted as much as possible.

Figure 13. Side and cross-section microstructure morphology of samples by SLR and SLM: (a) No. 1; (b) No. 5.

Figure 14. Macromorphology of fracture surfaces of typical tensile parts.

(2) Nowadays, the volume energy density is generally introduced as a comprehensive characterization parameter of the laser power, laser scanning speed, and hatch space layer thickness when studying the effects of mechanical properties. The results in this paper showed that the same volume density (high laser power/high scanning speed, and low laser power/low speed) exhibited different properties including mechanical characteristics, densities, and surface roughness. A high scanning speed increased the spatter and other defects, and high laser power reduced the amount of unmelted powder and decreased the number of defects such as balling and pores. Therefore, under the premise of melting, high laser power/low laser scanning speed should be adopted as much as possible.
In future work, the remelting mechanism needs to be studied, mainly with regard to the mechanism and control of defect formation including spatter and pores. On the other hand, the strengthening research of posttreatment by heat treatment should be carried out.

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Author contributions

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Conflicts of interest

The authors declare no conflict of interest.
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