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ARTICLE

Effect of Substrate Preheating, Remelting, In-situ Presintering on Crack Formation of Ti-47Al-2Cr-2Nb Fabricated by Selective Laser Melting

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Abstract: The methods of substrate preheating, remelting and in-situ presintering were proposed to fabricate Ti-47Al-2Cr-2Nb by selective laser melting (SLM). The effects of these approaches on the formation of cracks and surface quality were investigated. The results indicate that substrate preheating, remelting and in-situ presintering powder can reduce the formation of cracks to a certain extent, and the density is increased by 1.71%~4.34%. Remelting contributes to improvement of the surface quality but greatly reduces the productivity. In addition, the combination of substrate preheating and in-situ presintering can effectively prevent the occurrence of cracks, and the density is over 99%.

Key words: substrate preheating; remelting; in-situ presintering; crack; surface; selective laser melting (SLM)

γ-TiAl alloy is considered as one of the promising high-temperature structural materials, and its application in aero-industries will be very beneficial to lightweight of machine parts and the improvement of thrust loading of aero-engine[1-4], e.g. low-pressure turbine blades made of the Ti-48Al-2Cr-2Nb alloy are used in the last two rotor stages of the GEneX jet engine of Boeing's 787 and 747-8[5]. However, due to the poor room temperature ductility and low hot deformability of γ-TiAl, it is still difficult to produce TiAl components by the conventional manufacturing processes, such as precision casting, isothermal forging and thermoplastic forming, with extremely high cost, heterogeneous microstructures and limited structural complexity[6].

Nowadays, selective laser melting (SLM) [7-9], one of the additive manufacturing techniques, has been used to produce TiAl components, which will allow the realization of more complex geometries and material savings. In the past, many researchers have studied the preparation of γ-TiAl alloys by SLM in an attempt to fabricate fully dense and high-performance samples[7,10-12]. Nevertheless, fully dense γ-TiAl sample fabricated by SLM have seldom been reported. This is because during the SLM process, the fast cooling rates and the high thermal gradients induce high residual stresses, in combination with the brittle behavior of γ-TiAl alloys, which leads to the formation of crack inevitably[10-12].

Hence, in order to eliminate cracks, more methods need to be explored. In this study, Ti-47Al-2Cr-2Nb was prepared by SLM. The methods of substrate preheating, remelting and in-situ presintering were proposed, and the improvement effect of these approaches on the formation of crack was investigated.

1 Experiment

The investigations were carried out on a Ti-47Al-2Cr-2Nb alloy powder with a particle size range of 20~70 μm using a laboratory-based SLM system (Fig. 1) equipped with a 500W Nd-YAG fiber laser and two sets of powder laying devices[13]. The original optimal parameters (laser power P, scanning speed v, hatch spacing s) were also selected according to the previous research[14]. On this foundation, some measures were taken to prevent the occurrence of cracks in the formed parts: (1) preheating the substrate to 200 °C, (2) laser in-situ

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presintering powder and then beginning to melt, (3) remelting after completion of the melting process of each layer. Various blocks (S1~S6) were produced using combinations of original optimal parameters, substrate preheating, remelting and in-situ presintering, and the detailed process parameters and combinations are shown in Table 1.

In order to validate the improvement effect of these parameter combinations on the formation of cracks, first, ten-layer samples (10 mm×10 mm×1 mm) were prepared to compare the porosity. Then, samples with different number of layers (1~10 layers) were fabricated to further investigate which layer the cracks initiate from. After fabrication, the surfaces of the samples were observed by optical microscope (OM, Leica DM4000M) and scanning electron microscope (SEM, JEOL JSM6490). The surface roughness of the formed parts was illuminated by a 3D laser scanning microscope (VK-X200, KEYENC). The relative density of SLM samples was examined by analyzing OM images of the vertical cross section of each cube and quantified using Image Pro Plus software. For each sample, three cross sections at different locations were measured and averaged.

2 Results and Discussion

2.1 Density

Fig. 2 shows the density of the SLM samples that were fabricated under different treatment measures. It can be observed that S1 sample has the lowest density of 94.80%, which means that only optimizing the process parameters such as laser power (*P*), scanning speed (*v*) and hatch spacing (*s*) cannot completely eliminate the cracks. As for S2, S3 and S4, the density values are 96.51%, 96.65% and 97.24%, respectively; compared with S1, the increments are 1.71%, 1.85% and 2.44%, respectively, which show an increasing trend. The experimental findings indicate that substrate preheating, remelting and in-situ presintering powder can prevent the occurrence of cracks to a certain extent. This is mainly because preheating the substrate to 200 °C can reduce the temperature gradient between the solidifying layers and the lower parts of the formed specimens[15], remelting can slow the cooling rate after completion of the deposition process[16], and in-situ presintering powder can increase the initial temperature of powder in the forming area to decrease the temperature gradients of forming parts[17].

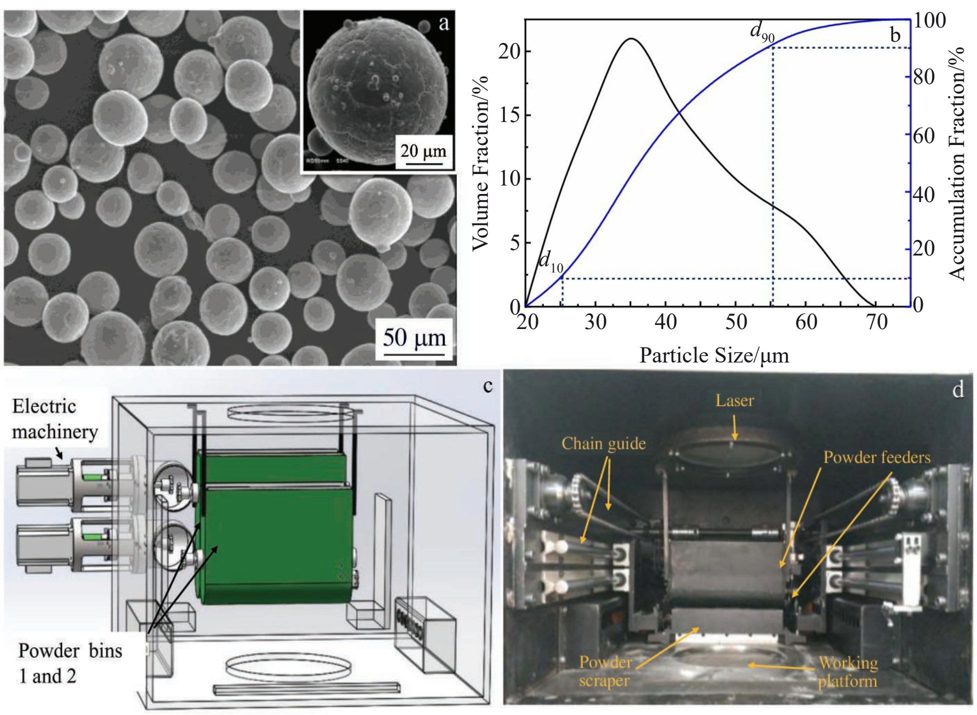

Fig.1 Ti-47Al-2Cr-2Nb powder morphology (a) and particle size distribution (b) [14], laboratory-based selective laser melting system three-dimensional model (c) and physical equipment (d)[13]

Table 1 Process parameters and combinations of fabricated samples

Solution	Process parameter	S1	S2	S3	S4	S5	S6
Optimal parameters	*P*=200 W, *v*=20 mm/s, *s*=0.4 mm	√	√	√	√	√	√
Substrate preheating	200 °C		√			√	√
Remelting	*P*=200 W, *v*=1000 mm/s, *s*=0.15 mm			√		√	
In-situ presintering	*P*=125 W, *v*=2000 mm/s, *s*=0.1 mm				√		√

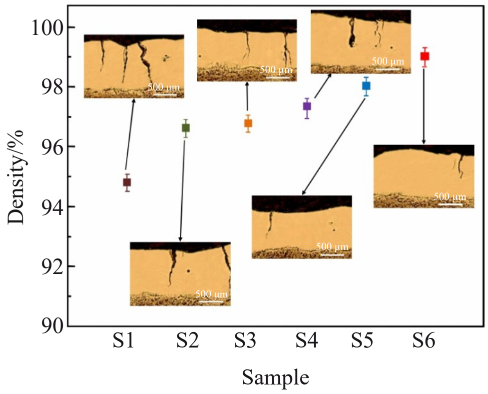

Fig.2 Density of ten-layer samples fabricated under different treatment measures

In addition, the density of S5 and S6 is 98.26% and 99.14%, the increments are 3.46% and 4.34% compared with that of S1, respectively, which reveal additive effects of the combination. The combinations of substrate preheating, remelting and in-situ presintering make it more effective to decrease the thermal gradients and cooling rates, and then further reduce the formation of cracks.

2.2 Surface roughness

Fig. 3 shows the top surface morphologies of the samples S1~S6. All of the TiAl samples possess relatively rough surfaces, because γ-TiAl alloy is a typical hard-to-fabricate material with a very narrow process window, which is liable to cause severe material evaporation and process instability, leading to balling and an uneven surface. It is apparent that remelting can improve the top surface quality. For S1 and S3, initial surface and re-melted surfaces are significantly different, and large-sized balls and undulating surface can be observed on the surface of S1 (Fig. 3a), causing a relatively coarse surface with a roughness S_a value of 135 μm (Fig. 4a and 4b). After remelting scanning, large-sized particles become smaller and even striated surface texture can be observed on the re-melted surface of S3 (Fig. 3c), and the roughness S_a is reduced to 63 μm (Fig.4c and 4d).

As for the surface roughness, as shown in Fig.4, the surface roughness values range from 56 to 135 μm (as seen in Table 2), which are worse than those of samples fabricated using Ti6Al4V and AlSi10Mg in Ref.[18-20]. In summary, substrate preheating and in-situ presintering slightly affect the surface roughness, while remelting contributes to improvement of the quality of the surface, but greatly reduces the productivity.

2.3 Crack initiation layer

Fig.5 presents which layer the cracks initiate from. It can be observed that cracks occur and increase with increasing the deposition thickness because of the accumulated residual stress. It can also be seen that cracks originate from the third layer under original optimal parameters. Compared with S1, there is no macro-crack in three-layer samples of S2 and S3, and the initial layer of the cracks increases from the third layer to the fourth layer. For S4 and S5, cracks are generated when the deposition thickness exceeds four layers. For S6, few micro-cracks are formed in the five-layer sample. Although substrate preheating is an effective approach to reduce the formation of crack, preheating to 200 °C is insufficient to reduce the temperature gradient and fully mitigate the thermal stress, while further increasing the preheating temperature is restricted by the current commercial SLM machines. Hence, the achieved improvement effect of substrate preheating on the initiation of crack is not as good as that of in-situ presintering powder.

Fig. 6 shows the cross-section of five-layer samples under different treatment conditions. Cracks spread from the top surface to the substrate, and the propagation depth of cracks varies from 82 μm to 458 μm. Obviously, the depth of crack in

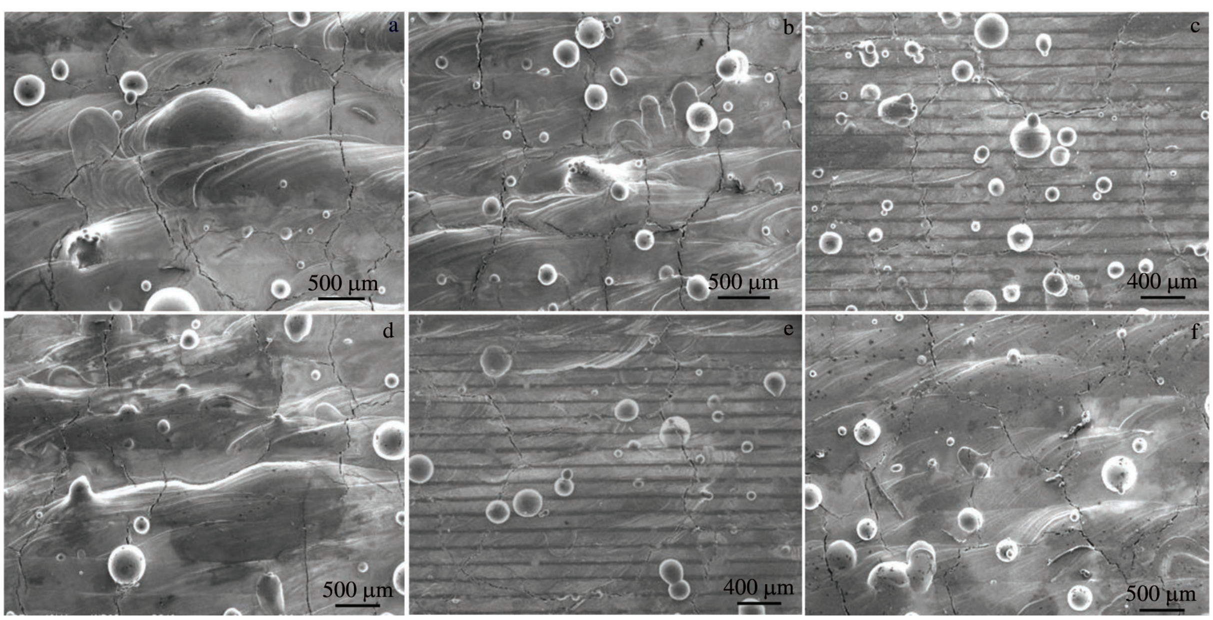

Fig.3 SEM morphologies of top surface of different samples: (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, and (f) S6

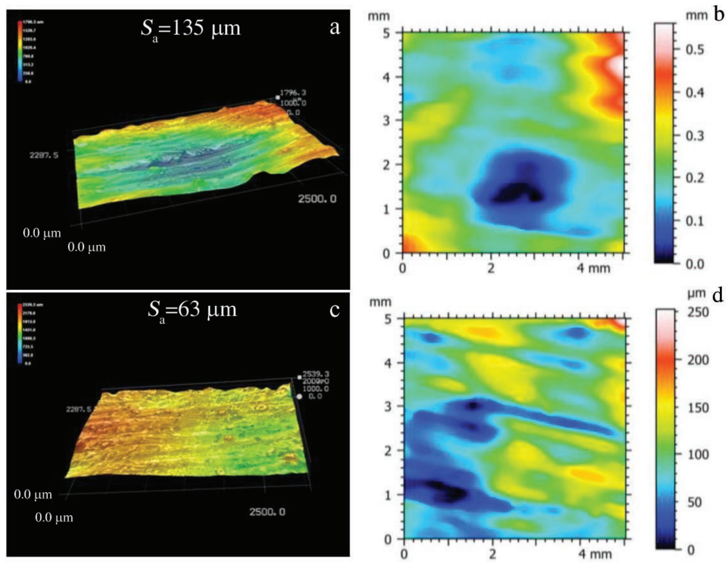

Fig.4 3D morphologies of initial sample S1 (a) and remelted sample S3 (c); surface roughness of S1 (b) and S3 (d)

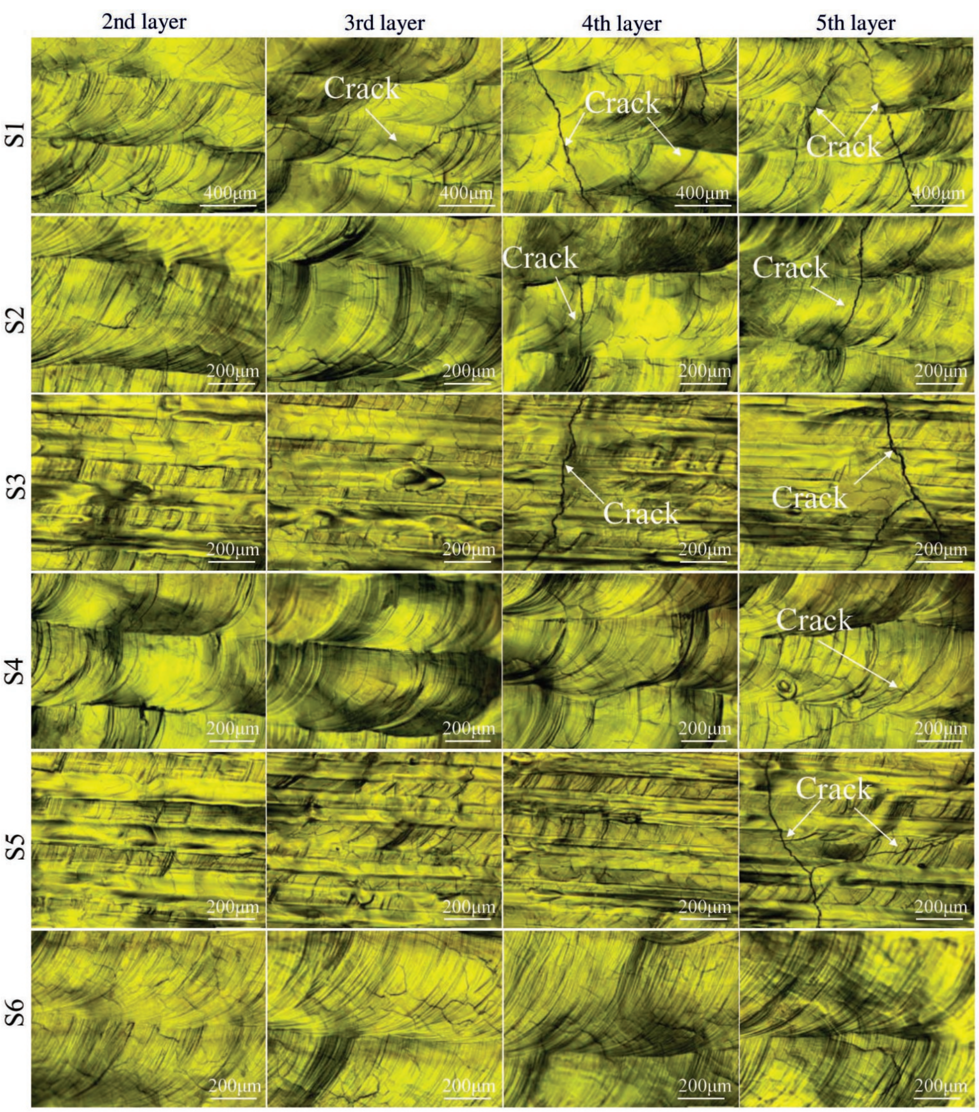

Fig.5 Top surface morphologies of two-layer, three-layer, four-layer, and five-layer samples

Table 2 Summary of the effects for sample S_1~S_6 under different treatment conditions

Sample	Solution	Density/%	Roughness, S_a/μm	Crack initiation layer
S1	Optimal parameters (OP)	94.80±0.33	135	2
S2	OP+substrate preheating	96.51±0.41	128	3
S3	OP+remelting	96.65±0.35	63	3
S4	OP+in-situ presintering	97.24±0.48	141	4
S5	OP+ Substrate preheating+remelting	98.26±0.33	56	4
S6	OP+substrate preheating+in-situ presintering	99.14±0.24	129	5

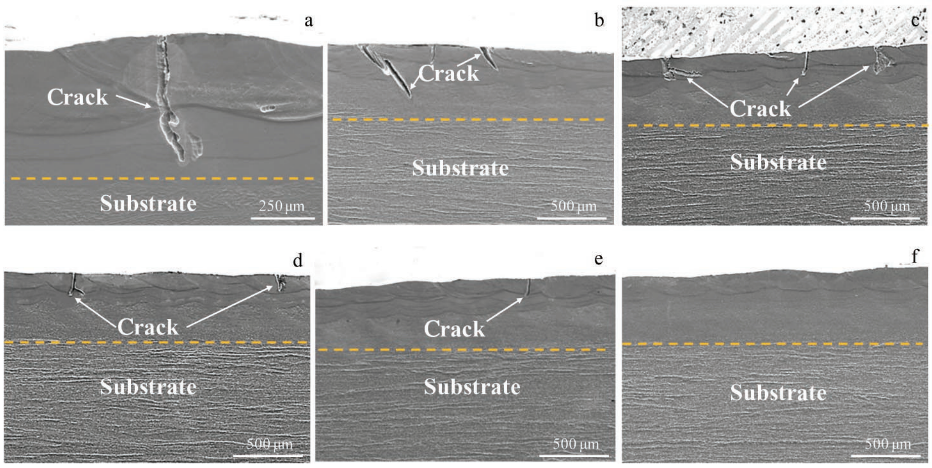

Fig.6 Cross-sections of five-layer samples under different treatment conditions: (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, and (f) S6

S1 is 458 μm, which is larger and deeper than cracks in S2~S6. Through the measures of substrate preheating, remelting and in-situ presintering, the number and propagation depth of cracks are decreased, and its change trend is consistent with the surface crack change (Fig. 5) and density change (Fig.2).

In summary, as shown in Table 2, the combination of substrate preheating and in-situ presintering (S6) has the best effect on preventing the occurrence of cracks, the density of ten-layer samples is 99.14% and there is no crack in five-layer sample. However, fully dense γ-TiAl sample is still hard to fabricate, and reducing the layer thickness is undoubtedly a good way to further eliminate cracks.

3 Conclusions

1) The ten-layer TiAl sample fabricated under original optimal parameters possesses the lowest density of 94.80%, and cracks appear from the third layer. Substrate preheating, remelting and in-situ presintering powder can reduce the formation of cracks and increase the density by 1.71%~4.34%, and the initial layer of the cracks increases from the third layer to the fourth layer.

2) The substrate preheating and in-situ presintering slightly affect the surface roughness, and remelting can reduce the surface roughness from 135 μm to 63 μm but greatly reduce the productivity.

3) The combination of substrate preheating and in-situ presintering makes it more effective to prevent the occurrence of cracks, the density of ten-layer sample (S6) is over 99% and the five-layer samples has no cracks.

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基板预热、重熔、预烧结对激光选区熔化 Ti-47Al-2Cr-2Nb 裂纹形成的影响

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摘 要：为了抑制激光选区熔化（SLM）制备 Ti-47Al-2Cr-2Nb 合金时裂纹的形成，研究了基板预热、重熔和预烧结等方法对裂纹形成和表面质量的影响。结果表明，基板预热、重熔和预烧结可以在一定程度上减少裂纹的形成，致密度提高了 1.71%~4.34%；重熔有助于改善表面质量，但会明显降低生产效率；另外，基板预热与预烧结相结合，能更有效地防止裂纹的产生，致密度超过 99%。

关键词：基板预热；重熔；预烧结；裂纹；表面；激光选区熔化（SLM）

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