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Origin of stray-grain formation and epitaxy loss at substrate during laser surface remelting of single-crystal nickel-base superalloys

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ABSTRACT

The stray-grain formation and epitaxy loss at the substrate during laser surface remelting of single-crystal nickel-base superalloys, which immediately lead to the break of the single-crystal growth, were investigated by means of modeling and experiments. Results indicate that the stray-grain formation and epitaxy loss at the substrate are attributed to the increased trend of the formation of equiaxed grains resulting from the composition segregation at the substrate interdendritic region. Accordingly, a solution treatment for the substrates prior to laser processing can effectively avoid the SG formation and epitaxy loss, which reveals a basic precondition, homogenized solution treatment of substrates, for successful single-crystal laser processing.

1. Introduction

Nickel-base single-crystal (SX) superalloys are unique high-temperature materials used as turbine blades and vanes due to their excellent mechanical properties at elevated temperatures [1,2]. Nevertheless, many types of damage, *e.g.*, blade tip erosion, are unavoidable under high temperature conditions. This means that the repair of damaged SX components is necessary because of the extremely high replacement costs. In addition, it is also necessary to repair the casting defects (such as surface pores) and crystalline imperfections within the single-crystal components resulting from the casting process [3–5]. Recently, the laser additive manufacturing (LAM) process, a near-net-shaping laser-deposited process, has exhibited a significant impact on the fabrication of a variety of alloys such as Ni-base superalloys [6–10]. Furthermore, since the LAM process allows rapid and accurate addition of controlled amounts of material to required locations with a low heat input, it also has potential for rapid forming and precision repair of SX components [4,5,11–19].

Successful SX LAM needs to ensure that the columnar dendrites epitaxially grow from the SX substrate along one of the six ⟨001⟩ preferred crystal directions [20]. However, the SX growth may be broken by the stray grain (SG) formation in the constitutional supercooling (CS) region ahead of the solid/liquid interface, *i.e.* columnar-to-equiaxed transition (CET), especially when the solidification is close to the top of melt pool. Therefore, many researchers have focused on the understanding of the CET [4,5,13–19]. However, in addition to the CET at the melt-pool top, there exists a remarkable phenomenon, epitaxy loss at the substrate, which immediately results in the break of the SX nature. In previous research, the epitaxy loss at substrate is generally attributed to the SG formation resulting from (1) the difference of crystallographic structures between deposit and substrate [18,21,22] and (2) certain undesirable particles, *e.g.*, topologically closed-packed (TCP) phases, in substrate [21–23]. However, the mechanism of SG formation and resulting epitaxy loss at the substrate has not yet been taken into account seriously because these misoriented grains will be suppressed by other dendrites growing with a preferred crystal direction [21,22]. More importantly, SGs forming at the substrate and resulting epitaxy loss will be retained in the repaired components because such SGs cannot be fully remelted. Therefore, in-depth understanding regarding the origin of the SG formation at the substrate is necessary for successful SX laser processing.

The aim of this paper is to elucidate the mechanism of the SG formation at the substrate, which immediately leads to the break of the SX growth. For this purpose, the microstructures produced on the substrates with different conditions were compared with those calculated by microstructure selection model to reveal the origin of SG formation at substrate.

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Table 1
Chemical compositions (in wt.%) of the roots of the dendrites growing from the interdendritic region and epitaxially from the dendritic core.

	Al	Cr	Co	Ta	Ti	W
Mean	5.2 ± 0.2	9.0 ± 0.3	5.5 ± 0.1	2.5 ± 0.4	2.1 ± 0.4	9.3 ± 0.7
Interdendritic region	6.0 ± 0.2	8.7 ± 1.0	4.7 ± 0.2	3.5 ± 0.1	3.8 ± 0.3	5.3 ± 0.8
Dendritic core	4.6 ± 0.2	9.2 ± 0.4	5.7 ± 0.2	1.3 ± 0.5	1.5 ± 0.1	12.6 ± 0.9

2. Experimental

In this paper, laser remelting experiments were performed on the different SX substrates with or without standard solution treatment to reveal the origin of SG formation at substrate for following several reasons. Firstly, because the LAM and laser remelting possess a similar solidification process, which is especially true at melt-pool bottom, the latter can be regarded as the LAM process without powder feeding, *i.e.*, a simplification of the LAM process [19]. Secondly, experiments by a process without powder feeding contribute to exclude the effect of heterogeneous nuclei resulting from unmelted powders and improve the reliability of analyses. In addition, laser remelting process is easy to be numerically modelled to rapidly evaluate the solidification conditions for theoretically analyzing and comparing with experiments. Therefore, the conclusions deduced based on the experiments and modeling of laser remelting possess, a simplification of the LAM process, can be reasonably applied to actual LAM process for the reference.

All laser remelting experiments were conducted using a 6 kWLAM system with a laser power of 1000 W, a scanning velocity of 5 mm/s, a beam diameter of 2 mm, and a preheating temperature of 20 °C. A commercial Ni-base SX superalloy, SRR99, was chosen for laser remelting. All the substrates were machined from SX cast ingots with the [001] orientation normal to the remelted surfaces. The substrate surfaces were ground with 600-grit SiC paper and cleaned in methanol prior to the laser processing. A standard solution treatment for SRR99 alloy (1300 °C, 4 h) was selected to homogenize some substrates. For confirming the universality of the conclusion for laser processing, the single-layer LAM experiments with powder feeding, *i.e.*, laser cladding, in the substrates without and with the solution treatment were also performed under the same conditions. The microstructure was characterized by a Leica DM-4000 optical microscope (OM) and a JEOL JEM-6010 scanning electron microscope (SEM), and the element distribution was analyzed by a JEOL JXA-8100 electro probe micro-analyzer (EPMA). The chemical compositions (in wt.%) of the SRR99 alloy are tabulated in Table 1.

3. Results and discussion

Fig. 1 shows the microstructures of the different SRR99 SX substrates. In Fig. 1a, the dendritic morphology of the as-cast substrate (without standard solution treatment) is clearly visible due to the composition segregation. In addition, a limited amount of γ-γ′ eutectic islands occurs in some interdendritic regions. For presenting the phases in the as-cast substrate more clearly, the high-magnification SEM image of the microstructure is shown in Fig. 1c. One can see that numerous cubical γ′ phases precipitate within coarse dendrites whereas those in interdendritic regions are coarse and irregular. In comparison, for the substrate with the standard solution treatment the dendritic morphology at the substrate is indistinct because of an effective decrease in the element segregation. Also, these γ-γ′ eutectic phases and γ′

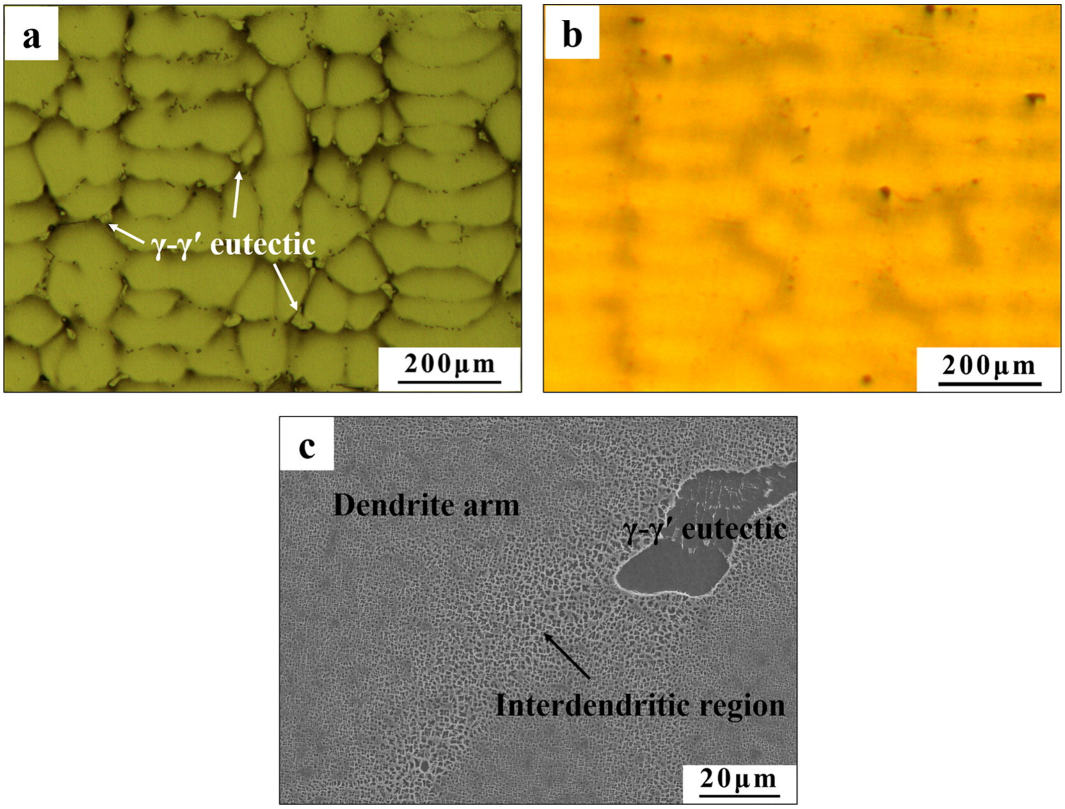

Fig. 1. OM images showing the microstructures of the different substrates (a) without standard solution treatment and (b) with standard solution treatment. (c) SEM image showing the high-magnification microstructure of the substrate without standard solution treatment.