Elimination of turned dendrite in laser multilayer deposition of Rene88DT superalloy on DD3 single crystal

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Received July 20, 2011; accepted October 20, 2011; posted online November 18, 2011

Laser multilayer deposition of Rene88DT superalloy on DD3 single-crystal substrate is conducted. The influences of the crystal orientation of the substrate and the profile of the solid/liquid interface of the molten pool on the deposited microstructure are investigated. A unique strategy is proposed by adjusting the angle between the substrate surface and the substrate crystal orientation. This approach prevents the formation of the turned dendrite, thus obtaining a fully directional microstructure in the deposits.

OCIS codes: 140.3390, 160.3900.

doi: 10.3788/COL201210.041401.

In the past 50 years or so, superalloys have been developed for numerous specialized applications. These high-performance alloys have been used in turbine blades, vanes in aircraft jet engines, and gas turbines in power generators, among others. High-performance alloys are particularly attractive for applications requiring extremely high strengths at elevated temperatures with long exposure times. However, the life of superalloy-manufactured components tends to be limited by defects, such as platform cracks or blade tip erosion. Single-crystal structures do not contain harmful grain boundaries. As such, the fabrication of single-crystal components by directional solidification has gained great attention because the process can improve component mechanical properties.

A promising directional solidification technology, laser multilayer deposition can build three-dimensional (3D) metallic parts directly from computer-aided design models[1−4]. During the process, powders are fed into a molten pool created by a laser beam. These parts are then built by a point-by-point and layer-by-layer approach. Laser multilayer deposition is potentially applied in the deposition or repair of single-crystal structures or directional structures. During the deposition, however, columnar to equiaxed transition (CET) must be avoided and the turned dendrite must be eliminated to realize the deposition or repair of single crystals or directional structures. Previous studies have focused primarily on the prevention of equiaxed crystal growth. Gäumann *et al.* developed a microstructure selection criterion for the CET of complex alloys[5,6]. They also designed a microstructure selection map for the superalloy CMSX-4. However, their research has focused only on eliminating the turned dendrite in the deposited layers. If the turned dendrite is formed and cannot be remelted during laser multilayer deposition or laser repair, the epitaxial microstructure will be interrupted. Ultimately, the directional structure will not be obtained. In this letter, we discussed the influences of the crystal orientation of the substrate, as well as the profile of the solid/liquid interface of the molten pool, on the deposited microstructure. A proposed approach to eliminate the turned dendrite to realize the directional solidification was also presented. This approach lays the foundation for using laser multilayer deposition for the fabrication and repair of single-crystal structures or directional structure parts.

The experiments were conducted on a laser multilayer deposition system composed of a 5-kW continuous wave (CW) CO_2 laser, a numerical control working table, and a powder feeder system with a lateral nozzle. During the laser multilayer deposition, the laser beam was focused on the substrate surface to create a molten pool. The powders were then delivered into the molten pool by the lateral nozzle. The nozzle was placed in the plane of the deposition path and the laser beam. The nozzle was positioned in front of the laser beam and inclined at approximately 30° to the vertical. Argon gas was used as carrier and shield gas to protect the interaction zone. Figure 1 presents the schematic of the experimental procedure.

Rene88DT superalloy powders (74–124 μm in size) were used as deposited materials in the experiments. DD3 single-crystal plates with dimensions of 30×5×5 (mm) were used as substrates. The Rene88DT superalloy and the DD3 single crystal have the same face-centered cubic structure. The chemical compositions of the materials are presented in Table 1. The main processing parameters are given in Table 2. Selection of these parameters was based on previous experimental studies[7]. CET can be avoided during deposition using these processing parameters. The formation and elimination of the turned dendrite without CET will be further discussed in the succeeding sections.

The samples were cross-sectioned along the laser scanning direction and etched with 10 percent hydrofluoric acid. A comparison was made between the optical photographs of the microstructure of the samples and the

Table 1. Chemical Compositions of the Powders and the Substrates (wt.-%)

	Al	B	C	Co	Cr	Fe	Mo	Ni	Si	Ti	W	Zr	Nb
Rene88DT Superalloy	2.2	0.02	0.04	14.0	17.0	< 0.5	4.0	bal	< 0.2	3.3	4.2	0.04	3.5
DD3 Single Crystal	5.7	trace	0.06	5	9.5	–	4.2	bal	–	2.3	5.2	< 0.005	–

Table 2. Processing Parameters for Laser Multilayer Deposition Process

Laser Power P (W)	Scanning Velocity v_b (mm/min)	Spot Diameter D (mm)	Z Increment ΔZ (mm)	Powder Feed Rate m_p (g/min)
700	150	1.5	0.3	6.82

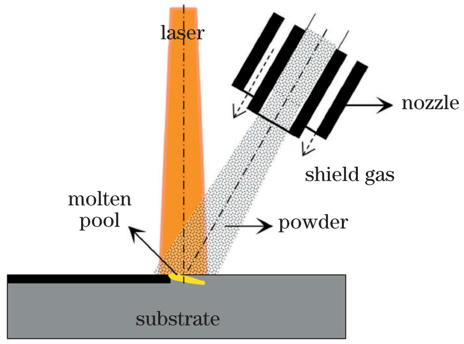

Fig. 1. Schematic of the laser deposition process.

results of the analysis.

Both the preferential orientation of the crystal and the direction of the heat flow control the growth direction of the dendrite. Therefore, the growth velocity of the dendrite tip $v_{[hkl]}$ along the preferential orientation [hkl] in laser multilayer deposition can be given as[8−10]:

$$\left|v_{[\mathrm{hkl}]}\right| = \frac{\left|v_\mathrm{s}\right|}{\cos\psi} = \frac{\left|v_\mathrm{b}\right|\cos\theta}{\cos\psi}, \quad (1)$$

where v_s is the solidification velocity, ψ is the angle between the normal to the solid/liquid interface and the preferential orientation [hkl], v_b is the laser scanning velocity, and θ is the angle between the normal to the solid/liquid interface and the laser scanning direction. The direction and velocity of the dendrite growth can be determined based on the minimum velocity criterion[11].

The experiment was designed and performed based on the above analysis. The laser was scanned along the [100] direction on the (001) crystal face. The central cross-section of the molten pool along the scanning direction was chosen as the subject (Fig. 2). The growth velocity of the dendrite in the preferential growth direction can thereby be obtained from Eq. (1), which can be expressed as

$$v_{[001]} = \frac{v_\mathrm{b}\cos\theta}{\cos\left(\frac{\pi}{2}-\theta\right)}, \quad (2)$$

$$v_{[100]} = \frac{v_\mathrm{b}\cos\theta}{\cos\theta} = v_\mathrm{b}. \quad (3)$$

Equations (2) and (3) are combined with the selection of the growth orientation with the minimum velocity[11]. Thus, when $\theta > \pi/4$, $v_{[001]} < v_{[100]}$, the [001] direction is the preferential growth direction of the dendrite. When $\theta < \pi/4$, $v_{[001]} > v_{[100]}$, the [100] direction is the preferential growth direction of the dendrite. As shown in Fig. 3, the dendrite growth can be obtained on the premise that CET has not occurred. The shape of the molten pool tail has an important effect on the formation of the turned dendrite. Therefore, the steeper the molten pool tail, the easier the turned dendrite formation.

Figure 4 shows the microstructure of the laser multilayer-deposited Rene88DT superalloy along the [100] direction on the (001) crystal face on the DD3 single crystal. The microstructure was obtained by shutting down the laser instantly when the molten pool achieved the steady state. The results suggest that the solid/liquid interface and the boundary between the [001] growth dendrite and the [100] growth dendrite can be identified clearly. The angle between the boundary and the laser scanning direction is about $\pi/4$. This result agrees well with the theoretical prediction. Therefore, the turned dendrite will be formed on top of each deposited layer. Figure 5 shows the microstructure of the laser multilayer deposition along the [100] direction on the (001) crystal face of the DD3 single crystal, with the

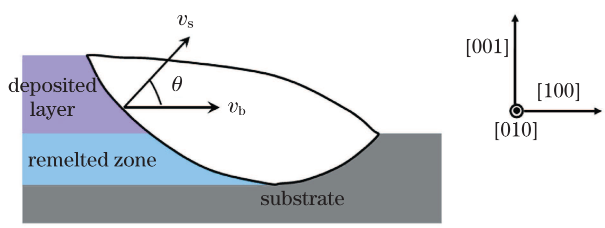

Fig. 2. Schematic of the section of the molten pool center along the laser scanning direction.

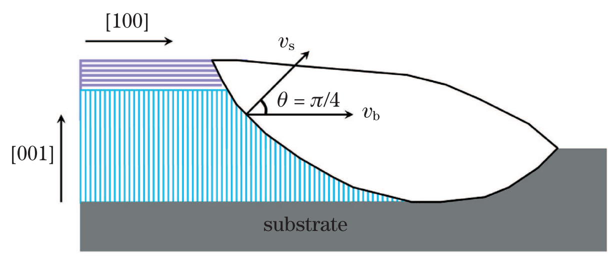

Fig. 3. Schematic of the formation of the microstructure in the laser multilayer-deposited Rene88DT on the DD3 single crystal.

processing parameters in Table 2. The directional growth is obtained in the bottom and middle regions of the deposited sample. However, a large region of turned dendrite growth along the [100] direction is retained on top. Since a small residue of the turned dendrite will have harmful effects on the formation and properties of the single crystal laser deposits, the remelted depth must be larger than the thickness of the turned dendrite in the following deposition to obtain the directional structure. However, it is difficult to ensure that the turned dendrite in each deposited layer can be remelted completely by the following deposition. So reducing or eliminating the turned dendrite on the top of each deposited layer will be helpful to obtain the single crystal laser deposits.

Previous studies have suggested that completely eliminating the turned dendrite by optimizing the processing parameters is difficult. The crystal orientation of the substrate has an important effect on the microstructure. Thus, changing the angle between the substrate surface and the substrate crystal orientation may be an effective way to eliminate the turned dendrite.

When the (001) crystal face rotates clockwise at angle ω around the [010] orientation, i.e., the substrate surface does not coincide with the (001) crystal face (Fig. 6), the solidification velocities in the two preferential growth directions can be expressed as

$$|v_{[001]}| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos\psi_{[001]}}\right| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos\left(\frac{\pi}{2}-\theta-\omega\right)}\right| = \frac{v_\mathrm{b}\cos\theta}{|\sin(\theta+\omega)|}, \tag{4}$$

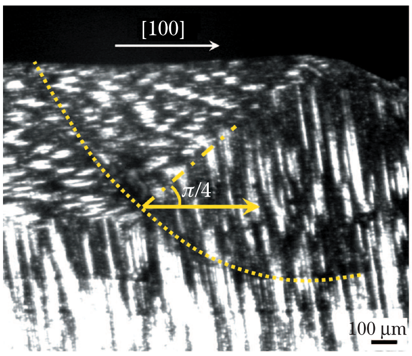

Fig. 4. Microstructure obtained by shutting down the laser instantly during laser deposition.

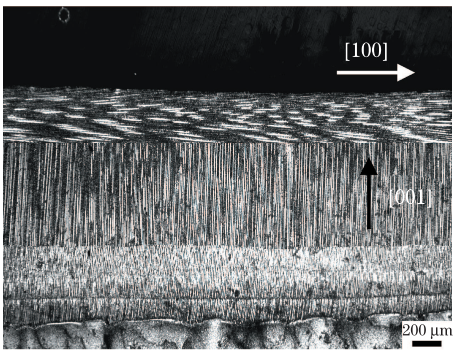

Fig. 5. Cross-section of the solidification microstructure of the laser multilayer-deposited Rene88DT on the DD3 single crystal.

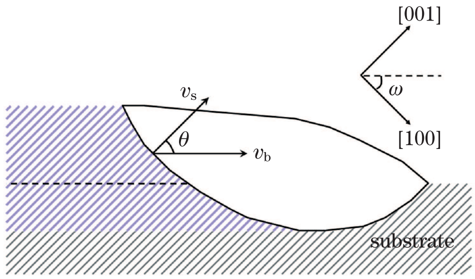

Fig. 6. Schematic of the microstructure formation with ω=$\pi/4$ during laser deposition.

$$|v_{[100]}| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos\psi_{[100]}}\right| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos(\theta+\omega)}\right| = \frac{v_\mathrm{b}\cos\theta}{|\cos(\theta+\omega)|}. \tag{5}$$

By combining the minimum velocity criterion[11] with Eqs. (4) and (5), when ω increases from 0 to $\pi/4$, the thickness of the turned dendrite decreases gradually because $0< \theta \leqslant \pi/2$. As shown in Fig. 6, a complete epitaxial dendrite growth can actually be obtained when ω=$\pi/4$ from theoretical predication. Under this condition, the growth velocities in the [001] and [100] directions on the solid/liquid interface of the molten pool are given as

$$|v_{[001]}| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos\psi_{[001]}}\right| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos\left(\theta-\frac{\pi}{4}\right)}\right| = \frac{v_\mathrm{b}\cos\theta}{\left|\cos\left(\theta-\frac{\pi}{4}\right)\right|}, \tag{6}$$

$$|v_{[100]}| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos\psi_{[100]}}\right| = \left|\frac{v_\mathrm{b}\cos\theta}{\cos\left(\theta+\frac{\pi}{4}\right)}\right| = \frac{v_\mathrm{b}\cos\theta}{\left|\cos\left(\theta+\frac{\pi}{4}\right)\right|}. \tag{7}$$

However, when ω=$\pi/4$, the dendrite at the bottom of the molten pool growing in the [001] and [100] directions are at critical positions. Any small disturbance in the laser deposition process may change the growth direction of the dendrite. Thus, $\omega < \pi/4$ should be set to restrain the formation of the turned dendrite in the deposited layers during the deposition process.

Figure 7 presents the microstructure obtained by adjusting ω=$\pi/12$ with the processing parameters (Table 2). The directional solidification dendrite along the [001] direction was obtained from the bottom and from the middle of the laser deposits. However, the turned dendrite along [100] was partially retained at the top region. The thickness of the turned dendrite was much smaller than that in the deposits obtained with ω=0. Figure 8 shows the microstructure obtained with ω=$\pi/6$ under the same processing parameters. An almost full directional microstructure along the [001] direction was obtained. Therefore, adjusting the angle between the substrate surface and the substrate crystal orientations can help prevent the turning of the dendrite and can yield a microstructure with continuous epitaxial growth.

In conclusion, we investigate the laser multilayer deposition of Rene88DT superalloy on DD3 single-crystal substrate. The influences of the crystal orientation of the substrate and the profile of the solid/liquid interface

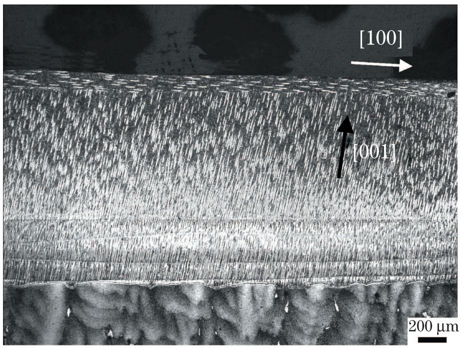

Fig. 7. Cross-section of the solidification microstructure of the laser multilayer-deposited Rene88DT on the DD3 single crystal obtained at $\omega=\pi/12$.

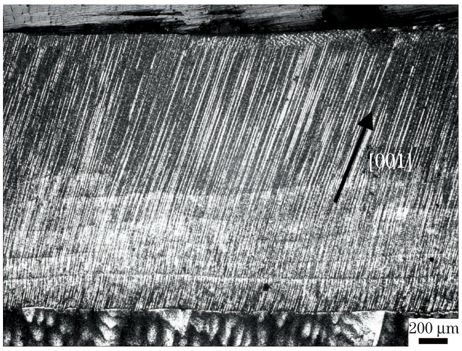

Fig. 8. Cross-section of the solidification microstructure of the laser multilayer-deposited Rene88DT on the DD3 single crystal obtained at $\omega=\pi/6$.

of the molten pool on the deposited microstructure are discussed. When the laser scans along the [100] direction on the (001) crystal face, the directional dendrite growth is obtained in the bottom and middle regions of the deposited layer. A large region of turned dendrite growth along the [100] direction is also obtained in the top of the deposited layer. The theoretical analysis agrees well with the experimental results. Further, the influence of the angle between the substrate surface and the preferential orientations of the substrate on the formation of the microstructure is also discussed. The turned dendrite can be eliminated by adjusting the angle ω between the substrate surface and the substrate crystal orientations. A microstructure with almost full epitaxial growth is obtained with $\omega=\pi/6$.

This work was supported by the National Natural Science Foundation of China (Nos. 51105311 and 50871089), the State Key Laboratory of Solidification Processing in Northwestern Polytechnical University (No. SKLSP201102), and the China Postdoctoral Science Foundation (No. 201104679).

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