Postprint: Investigation of Dendritic Structure Uniformity in Directionally Solidified DD6 Single-Crystal Superalloy

Authors: Wang Yumin, Li Shuangming, Zhong Hong, Fu Hengzhi

Date: 2023-03-19T00:00:00+00:00

Abstract

The uniformity of dendrite distribution in DD6 single crystal superalloy was investigated using primary dendrite spacing, minimum spanning tree (MST), Voronoi polygons, FFT, RO-XRD, and EBSD methods. The results show that the average primary dendrite spacing in DD6 single crystal superalloy is 325.7 mm with a variation rate of 7.38%. The number of nearest-neighbor dendrites obtained by the Voronoi polygon method ranges from 5.87 to 5.93, with the proportion variation rate exceeding 30%; in addition, the variation in branch length of MST is also significant, reaching 26.95%, and the FFT spectra differ at different locations, indicating that the microstructural uniformity of the DD6 single crystal superalloy obtained by the grain selection method in the experiment needs further improvement. These results also indicate that dendrite growth in directionally solidified single crystal superalloys is a dynamic adjustment process; the degree of variation in the dendrite growth process can be quantified by measuring primary dendrite spacing combined with Voronoi polygons and MST methods, whereas using average primary dendrite spacing alone to evaluate the stability of the solidification process is insufficient. The deviation angle between the preferred orientation and the axial direction (Z-axis) of the DD6 single crystal superalloy obtained by the grain selection method was measured, and it was found to be within 10°. The EBSD test results are larger than the corresponding ROXRD results, which is due to the fact that RO-XRD selects the diffraction peak corresponding to the maximum intensity when calculating the deviation angle.

Full Text

Evaluation of the Uniform Distribution of Dendritic Microstructure in Directionally Solidified Single-Crystal DD6 Superalloy

WANG Yumin, LI Shuangming, ZHONG Hong, FU Hengzhi
State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072

Correspondent: LI Shuangming, professor, Tel: (029)88493264, E-mail: lsm@nwpu.edu.cn

Supported by National Natural Science Foundation of China (No.51323008), Fundamental Research Funds for the Central Universities (No.3102014JCQ01021) and Fund of State Key Laboratory of Solidification Processing in NWPU (No.101-QP-2014)

Abstract

Homogeneous distribution of primary dendritic arm spacing (PDAS) is required to achieve uniform mechanical properties in the final product of single-crystal superalloys. In this work, the dendrite characterization and orientation of Ni-based single-crystal DD6 superalloy have been deeply investigated using different methods, which include minimum spanning tree (MST), Voronoi polygon-based approach, fast Fourier transform (FFT), as well as EBSD and RO-XRD. The investigation results indicate that the mean PDAS of DD6 superalloy is about 325.7 m and its variation ratio is 7.38%. The measured Voronoi polygon parameters suggest that the number of nearest-neighbor dendrites ranges from 5.87 to 5.93, approximating six nearest neighbors in the spatial distribution of dendrite microstructures. However, the change in ratio of six nearest neighbor proportion has exceeded 30% for the twenty specimens. The MST method shows that the change in branch length measured from the twenty specimens achieves 26.95%. Also, the analysis results of FFT imply that the dendrite microstructures of DD6 superalloy evolve apparently. These results provide proof that the dendrite microstructures of DD6 superalloy vary with the solidified distance. Additionally, the deviation angles between preferential orientations of DD6 with the axial direction of specimen were measured by EBSD and RO-XRD, respectively. The deviation angle values of DD6 superalloy in this experiment are both within 10°. The reason for the deviation angle measured by RO-XRD being smaller is well explained due to the fact of selecting the diffraction intensity maximum angles. Furthermore, the EBSD results indicate that the orientations of DD6 superalloy prepared by grain selector can be well controlled along the Z-axial direction, but do not work in other two X and Y directions.

Keywords: Ni-based single-crystal superalloy, microstructure uniformity, primary dendrite, deviation angle

Superalloys have become critical materials for high-temperature components in aeroengines and rocket engines due to their excellent room-temperature and high-temperature strength, good microstructural stability, oxidation and hot corrosion resistance, and superior fatigue and creep properties [1]. Research on superalloys is not only closely related to national defense technologies such as aerospace engines but also concerns the development of national economy industries including energy power, transportation, and nuclear industry. Consequently, superalloys have become one of the important indicators measuring a country's materials development level [2,3]. Meanwhile, the development of superalloys is closely related to the progress of aeroengines, and single-crystal superalloys are currently used for working blades in advanced aeroengines both domestically and internationally.

DD6 single-crystal superalloy is a second-generation Ni-based single-crystal superalloy independently developed in China. It offers cost advantages due to its low Re content while exhibiting tensile properties and creep rupture performance comparable to foreign second-generation single-crystal superalloys [4]. During directional solidification of DD6 single-crystal superalloy, the solidification microstructure generally consists of dendrites, which result from solid/liquid interface instability during non-equilibrium solidification and are controlled by solidification processes. Therefore, evaluating the uniformity of alloy solidification dendritic microstructure also evaluates the stability and reliability of the solidification process.

Current research on dendritic microstructure uniformity in single-crystal superalloys has primarily focused on dendrite spacing [5,6], because dendrite spacing in superalloys has a strong correlation with properties and has become an indispensable bridge linking process, microstructure, and performance. For instance, Lamm and Singer [7] demonstrated that reducing primary dendrite spacing can improve the fatigue life of superalloys. Dendrite spacing also significantly influences element segregation, shrinkage porosity, and freckle formation [8]. Additionally, single-crystal superalloys exhibit significant anisotropy, with elastic moduli differing among alloys with [100], [110], and [111] orientations, among which the [100] orientation demonstrates the best comprehensive performance [9].

Conventionally, dendrite spacing is measured using the line intercept method or area method [10,11] to obtain average dendrite spacing. If the average spacing from multiple measurements is more concentrated, the dendrite distribution is considered more uniform. This measurement method has its rationality, providing the average dendrite spacing magnitude and approximate distribution range. However, its disadvantages are also evident. First, it filters out the maximum dendrite spacing, which provides sites for solute element segregation, interdendritic second phases, eutectic phases, and shrinkage porosity, and is also where fatigue cracks most easily initiate [12]. Second, average dendrite spacing cannot provide useful information about dendrite arrangement in the alloy. Therefore, using average dendrite spacing to judge and evaluate dendritic

microstructure uniformity is insufficient, raising the question of how to judge dendritic microstructure uniformity and what methods to employ for evaluation.

To address the limitations of conventional dendrite average spacing measurement methods, this work employs additional research methods such as minimum spanning tree (MST), Voronoi polygons, and fast Fourier transform (FFT) to comprehensively investigate the uniformity of dendritic microstructure distribution in single-crystal superalloys. Additionally, rotation orientation X-ray diffraction (RO-XRD) and electron backscatter diffraction (EBSD) were used to study the orientation distribution of DD6 dendrites, aiming to establish approaches for evaluating uniformity in both dendritic growth direction and crystal orientation. Single-crystal superalloy was selected as the research subject for two reasons: first, to avoid the influence of different grain orientations on dendrite spacing; second, because single-crystal superalloys have high requirements for microstructural uniformity [13]. This research is not only significant for controlling the solidification microstructure of single-crystal superalloys but also contributes to a deeper understanding of the directional solidification process.

Experimental Methods

The material selected for this study was the second-generation Ni-based single-crystal superalloy DD6 [14], with chemical composition (mass fraction, %) of: Cr 4.3, Co 9.0, Mo 2.0, W 8.0, Ta 7.5, Re 2.0, Hf 0.1, Al 5.6, Nb 0.5, Ni balance. DD6 was prepared using the grain selector method with a pouring temperature of 1560 °C and a withdrawal rate of 6 mm/min. The prepared cylindrical ingot (length 120 mm, diameter 16 mm) was cut longitudinally into 20 equal sections and labeled No.1 to No.20, as shown in [Figure 1: see original paper]. The specimens were then ground and polished, etched with a solution of 5 mL HNO_3 + 10 mL HF + 15 mL $C_3H_8O_3$, and observed using a Lecia DM4000M optical microscope (OM) for cross-sectional microstructure examination. Dendrite spacing was measured using OLS4000 control software. After cutting, grinding, and mechanical polishing, the specimens were electropolished using an electrolyte of 72% C_2H_5OH + 8% $HClO_4$ + 20% $C_4H_9OCH_2CH_2OH$, and orientation testing was performed using the EBSD attachment on a SUPRA 55 scanning electron microscope (SEM). Orientation analysis was subsequently conducted using Channel 5 software. Additionally, the deviation angles were measured by RO-XRD using a modified D/max2400 X-ray diffractometer.

Since dendrite spacing measurements were performed on cross-sections, the study of dendritic microstructure uniformity in DD6 single-crystal superalloy was also conducted on cross-sections. Determining dendrite centers on the cross-section was crucial for this research. This experiment used Image J software to manually determine the coordinate positions (x, y) of dendrite centers on cross-sections, as this approach is more accurate than automatic image processing software [15]. The number of dendrites on the entire cross-section of DD6 single-crystal superalloy was approximately 1700, providing a sufficient quantity to reflect the overall dendrite distribution on the cross-section. Gaussian fitting

was employed for subsequent data processing, where the Gaussian function distribution [16] can be described as:

$$f(x) = A_0 \exp\{-[(x - A_1)/A_2]^2\}$$

where x_i and y_i represent the horizontal and vertical coordinate values of the fitted model points, respectively; the estimated parameters A_0, A_1, and A_2 correspond to the peak height, position, and width information of the Gaussian curve, respectively. These three parameters are important for later microstructure uniformity determination.

To analyze the dendritic microstructure uniformity in DD6 single-crystal superalloy specimens, the area method was first applied to measure primary dendrite spacing on cross-sections. The average primary dendrite spacing measured by the area method only reflects local features and cannot completely represent the overall microstructure distribution of the specimen, necessitating additional analytical methods. Therefore, Voronoi polygons [17], MST [18], and FFT [19] methods were also employed for comparative analysis of dendritic microstructure uniformity. A Voronoi polygon is formed by connecting any point to multiple surrounding discrete points with straight lines and then constructing perpendicular bisectors of these lines; the polygon formed by the intersection of these bisectors can be used for nearest-neighbor analysis to determine the number of nearest-neighbor dendrites around any dendrite center point, thereby establishing dendrite concentration. MST refers to a non-closed figure connecting all points while ensuring the minimum total path length, thus representing the minimum total length required to connect all points. FFT is a process that converts a function into a series of periodic functions for processing.

Primary dendrite spacing provides the average interval between dendrites, Voronoi polygons reflect useful information about dendrite arrangement, while MST and FFT can determine whether dendritic microstructure has reached stable growth during directional solidification. These methods can only evaluate the macroscopic uniformity of dendritic microstructure but cannot analyze microscopic crystal orientation. Currently, EBSD and RO-XRD are the two main methods for studying microscopic dendrite crystal orientation uniformity [20]. Through EBSD technology, the preferred orientation of DD6 superalloy dendrites on cross-sections and the angle between the preferred orientation and the cross-section axial direction can be obtained. However, EBSD measurement range is very small, mainly for microzone texture determination, whereas RO-XRD provides larger measurement range and better statistics.

2. Experimental Results and Analysis

[Figure 2: see original paper] shows the cross-sectional microstructures and corresponding local magnified images of specimens No.5, No.10, and No.15. The cross-sectional microstructure consists of dendrites densely distributed across

the entire cross-section, with more regular arrangement at the edges than in the interior. Dendrites at different positions show almost no visible difference. In the magnified images, however, variations in dendrite size and arrangement become apparent. Some dendrites exhibit asymmetric secondary dendrite arms due to the misalignment between the dendrite preferred orientation and heat flow direction during actual alloy solidification, causing dendrite growth direction to lie between heat flow and preferred orientation. This results in asymmetric dendrite growth, where secondary dendrite growth on the side of the dendrite axis facing away from the solid/liquid interface front is suppressed by secondary dendrite growth from adjacent dendrites toward the liquid/solid interface front, creating secondary dendrite asymmetry [21].

2.1 Area Method Measurement of Primary Dendrite Spacing and Study of Dendritic Microstructure Uniformity

The formula for measuring primary dendrite spacing (l) using the area method is:

$$l = c\sqrt{A/N}$$

where N represents the number of dendrites within area A; c is a constant, typically taken as 1 [10]. To reduce experimental error, primary dendrite spacing was measured at five different positions on the cross-section, and the average value was calculated. The measured primary dendrite spacing values for the 20 specimens are shown in [Figure 3: see original paper]. The results indicate that the variation ratio of primary dendrite spacing for the 20 specimens is 7.38%, where the variation ratio (δ) is calculated as:

$$\delta = [\max(x_n) - \min(x_n)]/\bar{x} \times 100\%$$

where $\bar{x}$ represents the mean value; x_n $(n = 1, 2, \cdots, 20)$ represents the primary dendrite spacing of each specimen.

Determination of average primary dendrite spacing is crucial for directional solidification microstructure. In alloy solidification theory, process parameters (solidification rate and temperature gradient) are correlated with microstructure through primary dendrite spacing, which can quantify the influence of preparation processes on microstructure to achieve property control. From the primary dendrite average spacing measurement results in [Figure 3: see original paper], the average primary dendrite spacing of DD6 single-crystal superalloy is 325.7 m with a variation ratio of 7.38%, which is less than 10%. This suggests that the primary dendrite spacing of DD6 single-crystal superalloy solidification microstructure in this experiment is uniform, as the variation ratio is one order of magnitude smaller than the measured values and can therefore be considered approximately small. This microstructural uniformity has a positive effect on alloy properties [11].

2.2 Voronoi Polygon Analysis of Dendritic Microstructure Uniformity in DD6 Single-Crystal Superalloy

[Figure 4: see original paper] shows the cross-sectional dendrite center distribution maps of specimens No.5 and No.10, with corresponding microstructures shown in [Figure 2: see original paper]b and d. The primary dendrite spacing measured by the area method is 317.3 m and 326.2 m, respectively, with a difference of only 8.9 m, indicating very small variation and suggesting uniform solidification microstructure. Based on the dendrite center points in [Figure 4: see original paper], corresponding Voronoi polygon maps were constructed, as shown in [Figure 5: see original paper], where the insets show magnified Voronoi polygons. The number of edges for each closed polygon is labeled, representing the number of nearest-neighbor dendrites around the dendrite center within the closed figure.

Statistical analysis of the nearest-neighbor dendrite numbers from [Figure 5: see original paper] yielded the histograms shown in [Figure 6: see original paper], which were fitted using Equation (1) with Gaussian curves shown in the figures. The peak position of the Gaussian fitting curve represents the number of nearest-neighbor dendrites with the largest proportion across the entire cross-section. The results show that the average number of nearest-neighbor dendrites is 5.91 for specimen No.5 ([Figure 6: see original paper]a) and 5.92 for specimen No.10 ([Figure 6: see original paper]b), with a small difference. Additionally, the peak height in the Gaussian distribution represents the proportion magnitude—higher peaks indicate higher proportions of nearest-neighbor numbers—while peak width represents the concentration distribution of nearest-neighbor dendrite numbers; wider peaks indicate more dispersed distribution of nearest-neighbor dendrite numbers. The proportion of nearest-neighbor dendrites is 41.11% for specimen No.5 and 45.05% for specimen No.10, showing little difference. When comprehensively comparing all 20 specimen groups by contrasting the peak center positions, peak heights, and peak widths, the distributions of nearest-neighbor dendrite numbers, Voronoi polygon peak heights, and peak widths for each specimen are obtained, as shown in [Figure 7: see original paper].

[Figure 7: see original paper]a shows that the Gaussian peak nearest-neighbor dendrite numbers range from 5.87 to 5.93, with a variation of only 1.2%, indicating very concentrated distribution and stable nearest-neighbor dendrite numbers. However, [Figure 7: see original paper]b reveals that peak height varies from 53.32 to 40.39, reaching a variation ratio of 31.37%, while peak width varies from 1.00 to 1.40, also achieving a variation ratio of 32.03%, far exceeding 10%. This indicates that the proportion of nearest-neighbor dendrites and the concentration distribution of nearest-neighbor dendrite numbers are relatively dispersed, suggesting that the microstructural uniformity needs further improvement.

2.3 MST Analysis of Dendritic Microstructure Uniformity in DD6 Single-Crystal Superalloy

[Figure 8: see original paper] shows the MST branch length distribution maps for specimens No.5 and No.10, with curves representing Gaussian fitting results where the fitting regression coefficients R^2 equal 0.987 and 0.992, respectively, indicating good fitting quality. Based on the Gaussian fitting results, the peak position, peak width, and peak height values were obtained, as shown in [Figure 9: see original paper]. [Figure 9: see original paper]a shows the distribution of Gaussian peak center positions and average branch lengths, while [Figure 9: see original paper]b shows the peak height and peak width values.

[Figure 9: see original paper]a reveals that the variation ratio of average MST branch length for the 20 specimen groups is 9.25%, indicating relatively uniform distribution. However, [Figure 9: see original paper]b shows that the Gaussian fitting peak width variation is large, reaching 27.54%, meaning the MST branch length distribution is not concentrated. Moreover, both the peak center position and peak height variations exceed 10%, indicating large variation ranges for both the branch length concentration region and the number of lengths. Furthermore, MST branch lengths were sorted from shortest to longest, with the 95th and 5th percentile branch lengths defined as longest and shortest [22], respectively. The ratio of longest to shortest branch length was compared to analyze microstructural uniformity, revealing large variation amplitude. The ratios for specimens No.5 and No.10 are 2.18 and 2.46, respectively. The theoretical numerical model established by Hunt and Lu [23] indicates that when directional solidification dendritic microstructure reaches steady-state growth, the ratio of longest to shortest primary dendrite spacing should be less than or equal to 2. This demonstrates that the solidification dendritic microstructure of the prepared DD6 superalloy has not reached a stable state, which is detrimental to dendritic microstructure uniformity, and the cross-sectional microstructural uniformity of DD6 is suboptimal.

2.4 FFT Analysis of Dendritic Microstructure Uniformity in DD6 Single-Crystal Superalloy

When superalloy microstructure achieves uniform distribution, dendrite positions, spacing, and size should show little variation (<10%). Therefore, microstructural uniformity can also be studied using FFT, a method that reflects gradient changes. [Figure 10: see original paper] shows the frequency spectra obtained by FFT for specimens Nos.1, 5, 10, 15, and 20. The spectra evolve from a single central bright spot to additional bright spots appearing around the center. Different FFT spectra at different cross-sectional positions indicate that microstructure varies at different positions along the specimen. Based on this observation, [Figure 10: see original paper] shows variations in both the number and orientation of surrounding bright spots. FFT results further demonstrate that DD6 single-crystal superalloy dendritic microstructure adjusts along the growth direction during directional solidification.

The evolution of dendritic microstructure along the growth direction can be reflected by the degree of FFT amplitude variation. [Figure 11: see original paper] presents statistical data of amplitudes obtained from FFT analysis of 20 specimen groups, with a variation ratio of 7.93%. Comprehensive FFT results indicate that the degree of dendritic microstructure variation along the growth direction during the entire directional solidification process is not significant. Additionally, the FFT method primarily judges dendrite arrangement order, equivalent to the average analysis of nearest and next-nearest neighbor dendrite numbers in the Voronoi polygon method, and also serves as a judgment of the variation ratio degree of average branch length in MST analysis. Its value (7.93%) is relatively consistent with MST analysis results (9.25%). summarizes the analysis results of dendritic microstructure uniformity using different methods.

2.5 Study of Dendritic Orientation Uniformity in DD6 Single-Crystal Superalloy

[Figure 12: see original paper] shows the EBSD pole figures and corresponding inverse pole figures for the cross-sections of specimens Nos.1, 3, and 15, where [Figure 12: see original paper]a, e, and i are {001} pole figures with the pole figure center representing the macroscopic surface axial direction (Z-axis). The {001} pole figures reveal that (001) pole density projections are located near the pole figure center, while (100) and (010) pole density projections are at the pole figure edges. Comparing the {001} pole figures of Nos.1, 3, and 15 comprehensively, the (001) pole density projections are all located near the pole figure center, indicating that although there is a certain angle between the [001] orientation and the macroscopic axial direction throughout the specimen, they remain consistently aligned. The (100) and (010) pole density projections are at the figure edges, but their positions differ at different locations. According to pole figure projection principles, the specimen [001] orientation is controlled relative to the macroscopic Z-axis, but [100] and [010] orientations are not controlled and exhibit some form of rotation, causing different positions of (100) and (010) pole density projections at the edges.

The inverse pole figures of specimens Nos.1, 3, and 15 further illustrate this issue. The preferred orientation of the specimen macroscopic ZO direction is consistently [001], while the preferred orientations of the other two directions are not consistent. This result occurs because the grain selector method for preparing single crystals can only control one-dimensional orientation, while orientations in other directions cannot be effectively controlled [24].

Based on the {001} pole figures at different cross-sections, the angles between the dendrite preferred orientation [001] direction and the macroscopic axial direction were calculated for specimens Nos.1, 3, and 15, yielding values of 7.4°, 9.2°, and 6.5°, respectively. Since dendrite growth in Ni-based single-crystal superalloys shows obvious anisotropy, deviation between preferred orientation and axial direction within 10° is acceptable in engineering practice [25]. Therefore, within

this angular range, dendrite orientation can be considered relatively uniform.

As shown in [Figure 13: see original paper], RO-XRD results display a pair of diffraction peaks, further confirming the single-crystal microstructure [26]. The deviation angle (ϕ) between the [001] orientation and the macroscopic specimen cross-section normal in [Figure 13: see original paper] is calculated as [26]:

$$\phi = (\theta_2 - \theta_1)/2$$

where θ_1 and θ_2 represent the diffraction angles corresponding to the highest diffraction intensity points. The measured deviation angle ϕ values are presented in .

RO-XRD measurement results show that the deviation angle ϕ between the [001] orientation and the macroscopic specimen cross-section normal is within 10°, which agrees with EBSD calculation results. Comparing the EBSD results in [Figure 12: see original paper] for Nos.1, 3, and 15, the deviation angles measured by EBSD are slightly larger than RO-XRD results. This discrepancy is related to RO-XRD's use of diffraction angles corresponding to maximum intensity when calculating deviation angles. The RO-XRD diffraction patterns show broad envelope peaks, indicating a variation range of crystal orientations—microscopic crystal plane arrangements are not completely consistent. When the detector rotates around the crystal, a certain range of crystal planes participates in diffraction. Additionally, single-crystal diffraction lines are very strong, and diffraction lines can appear not only when the diffraction crystal plane normal is exactly in the diffraction plane but also when it is near the diffraction plane, albeit with lower intensity, which causes peak broadening in the spectrum. To better explain this phenomenon, Gauss fitting was applied to the RO-XRD diffraction peaks. Each diffraction pattern shows a pair of diffraction peaks, so the Gauss fitting formula was selected as:

$$f(x) = a_1 \exp\{-[(x - b_1)/c_1]^2\} + a_2 \exp\{-[(x - b_2)/c_2]^2\}$$

where x and $f(x)$ represent the diffraction angle and corresponding relative intensity from RO-XRD test results, respectively; a_1 and a_2 represent the peak heights of the Gauss fitting curves; b_1 and b_2 correspond to the peak positions (center points); and c_1 and c_2 represent peak widths. Gauss fitting was applied to the RO-XRD diffraction peak envelope of specimen No.1, with results shown by the curve in [Figure 14: see original paper], yielding the fitted Gauss function:

$$f(x) = 1.1 \times 10^4 \exp\{-[(x - 22.5)/1.9]^2\} + 6.841 \times 10^3 \exp\{-[(x - 29.3)/2.3]^2\}$$

where the fitting regression coefficient $R^2 = 0.9122$.

Based on the Gauss fitting results, the diffraction angle range of the first envelope peak in the diffraction spectrum is 18.7°–26.3°, and the second envelope peak is 24.7°–33.9°. From these two envelope peak diffraction angle ranges, the deviation angle is calculated as (33.9 - 18.7)/2, approximately 7.6°, which is consistent with the deviation angle measured by EBSD for No.1 (7.4°). Therefore, using only the diffraction angle corresponding to maximum intensity in RO-XRD deviation angle calculations leads to slightly smaller RO-XRD test results compared to EBSD, a point worthy of researchers' attention.

Comprehensive EBSD and RO-XRD results indicate that the deviation angle between the preferred orientation of Ni-based single-crystal superalloy DD6 and the macroscopic surface axial direction (Z-axis) is within 10°, with consistent results from both test methods. Therefore, the dendrite orientation of DD6 single-crystal superalloy obtained in this experiment can be considered reliable. However, EBSD results still show that while the grain selector method can effectively control the Z-axis orientation of DD6 single-crystal superalloy, orientation variations exist in the X and Y directions, which still influence subsequent microstructure and material properties.

Conclusions

(1) The variation ratio of average primary dendrite spacing in DD6 single-crystal superalloy obtained by the grain selector method is less than 10%. Voronoi polygon analysis indicates that the number of nearest-neighbor dendrites ranges from 5.87 to 5.93 with a variation of only 1.2%, but the proportion variation ratio exceeds 30%. Meanwhile, MST branch length variation is also significant, reaching 26.95%, and FFT spectra differ at different positions. These results demonstrate that the microstructural uniformity of DD6 single-crystal superalloy obtained by the grain selector method in this experiment needs further improvement.

(2) Dendritic growth in directionally solidified single-crystal superalloys is a dynamic adjustment process. Combining primary dendrite spacing measurement with Voronoi polygon and MST methods can quantitatively characterize the degree of variation during dendritic growth, whereas using average primary dendrite spacing alone to measure solidification process stability is insufficient.

(3) The deviation angle between the preferred orientation and axial direction (Z-axis) of DD6 single-crystal superalloy obtained by the grain selector method is within 10°. EBSD results are larger than RO-XRD measurements because RO-XRD uses diffraction angles corresponding to maximum intensity when calculating deviation angles. Additionally, EBSD results indicate that the crystal orientation of DD6 single-crystal superalloy obtained by the grain selector method is well controlled only along the Z-axis direction, with variations existing in the X and Y directions.

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Note: Figure translations are in progress. See original paper for figures.