# The Formation Mechanism of Abnormal Grains of Superalloys Used for the Turbine Blade

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**Abstract：** The change of blade size has a significant impact on the solidification microstructures, resulting in the fluctuation mechanical properties of the turbine blade, which would affect its service performance. It is found that the abnormal grains with special grain boundaries were easy to occur in the airfoil of the turbine blade made of K465 alloy, while no abnormal grain was found in the root of the blade. The size of the abnormal grain is in micron scale, which is much smaller than the equiaxed grain with millimeter scale in cast K465 superalloy. The stability of stress rupture properties of the alloys with the abnormal grains decreased. The samples with different thickness were designed to simulate the microstructures at different positions of the turbine blade. The nucleation and growth mechanism of abnormal grains with special grain boundaries were revealed. In addition, the optimization the alloy composition was conducted to reduce the tendency of abnormal grains in cast superalloys and the adverse influence of the size effect on the microstructural stability and mechanical properties, which could provide ideas for improving the stability of mechanical properties of turbine blades.

**Keywords:** nickel based superalloy, size effect, residual stress, abnormal grains

## 1 **Introduction**

In recent years, with the continuous increase of thrust to weight ratio in aeroengines, the service temperature of turbine blades has become higher and higher. The internal cooling structure of turbine blades would be sophisticated, which results in the significant differences in wall thickness at different positions of a turbine blade [1]. Generally, the changes in blade cross-sectional dimensions would affect the heat and cooling rate during the solidification process, and the key parameters have a significant impact on the solidification structure. In addition, during the alloy solidification process, the residual stress in the thin-walled site is relatively high, which can easily lead to significant plastic strain [2]. Some researchers have found that the microstructure with high residual stress are prone to recrystallization during the heat treatment process, resulting in the formation of abnormal grains [3]. While the abnormal grains would cause the decrease of the mechanical properties of blade alloys [4]. It is found that the abnormal grains at the thin-walled part of a K465 alloy blade, which decrease the safety of the blade during service. This study focuses on the formation mechanism of abnormal grain in the K465 alloy. Specimens with different thicknesses were designed to simulate different positions of the blade, revealing the fundamental mechanism of the formation of abnormal grain and providing guidance for the optimization of the alloy.

## 2 Experimental procedure

The samples with different thicknesses (3mm, 5mm, 10mm, and 20mm) were designed to simulate different positions of the blades, with a width of 15mm and a height of 80mm. The K465 master alloy was melted using the VIM-F25 vacuum induction furnace, and the tested alloy is as follow in weight percent: Al 5.41, Co 10.0, Cr 8.6, Mo 2.0, Nb 1.1, Ti 2.5, W 10.3, Zr, 0.03, B 0.024, C 0.17, and the balance of nickel. The liquid alloy was cast into the alumina-silicate mold buried in the sand box to obtain the thin-walled specimens. The specimens were taken out until the mold and sand box were cooled to room temperature. The above specimen preparation method was similar as the method of the cast blade.

## 3 Result and discussion

### Abnormal grains

Fig. 1a shows the typical microstructure of a K465 alloy specimen with a thickness of 20 mm. There are coarse equiaxed grains in the alloy structure, with a grain size of about a few millimeters. The microstructure includes $\gamma'$, $\gamma$ matrix, eutectic and carbide; In addition, the abnormal grain was observed in the alloy, as indicated by the red arrow in Fig. 1a. As the thickness of the specimens decreases, the number of abnormal grains increases (Fig. 1b, c, and d). In addition, abnormal grains are more likely to appear near carbides between dendrites (as indicated by the blue arrow in Fig. 1a). The size of the abnormal grain is about tens of micrometers, much smaller than the equiaxed grains, and contain a large amount of precipitated phases. The abnormal grain is high-angle grain boundaries (HAGBs), as indicated by the inverse pole plot (IPF) and corresponding misorientation.

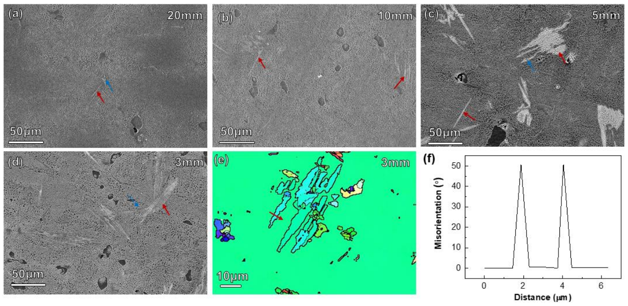


**Fig. 1 (a-d) SEM images of abnormal grains of the specimens with different thickness; (e) IPF images of the 3 mm-specimen; (f) corresponding misorientation of the arrow in (e)**

**Residual stress**

The GND values of regions containing several carbides in samples of different thicknesses were calculated, and the results are shown in Fig. 2. It can be clearly seen that the GND density in the sample increases with the decrease of specimen thickness, indicating that the residual stress in the specimen increases with the decrease of sample thickness. The thermal stress that occurs in the casting during alloy solidification can lead to residual stress, and numerical simulation of thermal stress during solidification is an important method for predicting residual stress in castings. This article conducted residual stress simulations on samples of different thicknesses using ProCAST commercial software, and the results are shown in Fig. 2b. It can be seen that residual stress increases with the decrease of sample thickness. The residual stress of the 20mm thick specimen was about 50 MPa, and as the thickness decreases to 3mm, the stress increased to about 250 MPa. The trend of increasing macroscopic residual stress of the sample with decreasing sample thickness is consistent with the trend of increasing GND density with decreasing sample thickness.

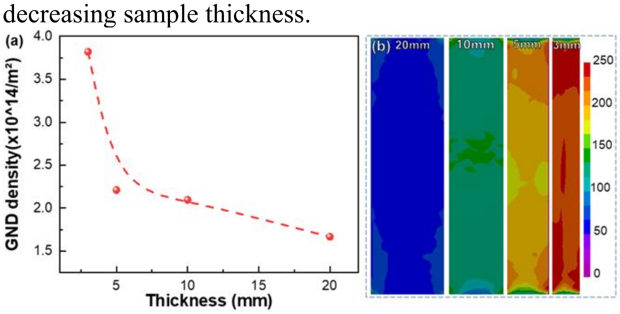


**Fig.2 GND density distribution of in the specimens with different thickness; (b) the residual stress distribution of the specimens with different thickness**

**Size effect induced abnormal grains**

During solidification and subsequent cooling process, residual plastic strain was induced in the microstructures of the K465 superalloy, which was due to the different thermal expansion coefficients of the metal, mold and core. In general, the non-deforming particle (such as a carbide) could be as a site for the development of a recrystallized grain due to that the region surrounding the particle contains a high dislocation density [5]. In this work, the carbides with high dislocation density in the vicinity could serve as the nucleation site, which induce the onset of the recrystallized grain. Hence, it is found that abnormal grains exist around block carbides in the interdendritic region. In addition, the macroscopic residual stress increases with the decreases of the specimen thickness. Therefore, the quantity of the feather-like grains increases with the decrease of the specimen thickness. Moreover, it is reported that the thin-walled sites in single crystal superalloys have an increased propensity for recrystallization [2]. In addition, due to the thin-walled samples prepared by the sand embedding process, the sand box has a high temperature after the solidification, and the sand box with a high temperature in the subsequent cooling process would have a heat treatment effect on the samples. It is speculated that recrystallization would occur near carbides in thin-walled samples due to the heat treatment effect of high-temperature sandbox.

## 4 Conclusion

The abnormal grains with HAGBs were detected in the thin-walled specimens. The experimental results show the cooling rate and the residual stress increases with the decrease of the specimen thickness. The appearance of feather-like recrystallized grains is due to the residual stress generated during the solidification process and the subsequent heat treatment resulted from the sand box with high temperature.

## 5 Acknowledgments

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