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ARTICLE

# Gradient Microstructure of K4169 Superalloy Prepared by Low Voltage Pulsed Magnetic Field Combined with Directional Solidification

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**Abstract:** The influence of the low voltage pulsed magnetic field (LVPMF) on the microstructure transition of K4169 superalloy was investigated. The gradient microstructure of K4169 superalloy composed of columnar grains, coarse grains, and fine grains was prepared through the combined method of LVPMF with directional solidification, which provided a new approach for the preparation of superalloy with gradient microstructure. The distribution of the Lorentz force and flow field under LVPMF effect was simulated, and therefore the microstructure transition mechanism was revealed. Results show that the microstructure transition should be attributed to the coupling effects of the Lorentz force and forced convection.

**Key words:** pulsed magnetic field; gradient microstructure; superalloy; Lorentz force; forced convection

Solidification of superalloy melt can lead to different grain structures, and the dendritic structures of columnar grain and equiaxed grain are usually generated after casting. The growth orientation of columnar grain is preferentially perpendicular to the mold walls, and that of equiaxed grain is random[1]. The columnar and equiaxed crystals in superalloy have different applications. For example, the modern superalloy turbine blade is generally made of columnar polycrystal or single crystal materials, because the columnar structure improves the creep resistance of turbine blade at high service temperature[2]. For the applications at ambient temperature, uniform and fine equiaxed grains are beneficial to the strength enhancement and fatigue resistance[3].

With the rapid development of materials and manufacture technologies, structural-gradient materials, especially the gradient materials with different mechanical properties, have attracted more and more attention for their tailor-made features in unique applications, such as the turbine blisk. During the operation of gas turbine engine, the turbine wheel typically rotates at high speeds in high temperature environment. The turbine blisk includes a disk and some blades. Because the operating conditions are different, hubs usually have the qualities of high tensile strength and high resistance to low cycle fatigue, and rims and blades have the qualities of high stress rupture and good creep resistance[4]. Therefore, the fine microstructure is required for the hubs, the coarse grain microstructure is required for the rims, and the columnar polycrystal or single crystal is required for the blades[5–6]. Generally, the blade and disk are manufactured separately, but the integrated structure has better mass reduction effect.

The columnar crystals or single crystals can be prepared by the directional solidification technique[7–8]. In recent years, the low voltage pulsed magnetic field (LVPMF) process provides a new solidification method for structure control. Li[9] and Ma[10] et al investigated the grain refinement of IN718 superalloy after LVPMF treatment and reported that the equiaxed grains were completely refined after LVPMF process, whereas the solidification structure at the sample edge without LVPMF treatment consisted of nearly columnar grains. As a result, the combined method of directional solidification with LVPMF process can prepare gradient

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materials with columnar grains, coarse grains, and fine grains.

In this research, K4169 superalloy was chosen as the experiment material to study the preparation of gradient materials. K4169 superalloy has favorable properties, including excellent corrosion resistance, good oxidation resistance, and high strength properties at elevated temperatures[11–12]. The chemical composition of K4169 superalloy is Cr=18wt%, Co=12wt%, Nb=4wt%, Ti=1.0wt%, Al=0.5wt%, Mo=3wt%, Ta=3wt%, B=0.018wt%, C=0.015wt%, and balanced Ni. In order to investigate the microstructure transition mechanism of K4169 superalloy under LVPMF, numerical simulations were performed to reveal the distribution of Lorentz force and flow field in the melt. The boundary conditions, governing equations, and material parameters are reported in Ref.[13]. The calculation neglected the natural convection in this research.

## 1 Experiment

The directional solidification apparatus consisted of a pulse power, a withdrawal system, and a Bridgman furnace. The pulse voltage ranged from 0 V to 300 V, and the pulse frequency was 5 Hz. The K4169 superalloy samples with dimension of $\Phi$10 mm×100 mm were prepared. The K4169 superalloy in the alundum tube was heated by the heater coil. When the K4169 superalloy was completely melted and the temperature of melt reached 1375 °C, the sample was taken out of the furnace at speed of 0.75 mm/s under LVPMF, as shown in Fig.1. The sample I, sample II, and sample III were taken out of the furnace without LVPMF, with LVPMF of 200 V, and with LVPMF of 300 V, respectively. After solidification, the samples were cut, ground, polished, and etched by the mixed solution of 50 mL HCl, 3.5 mL $H_2SO_4$, and 15 g $CuSO_4$.

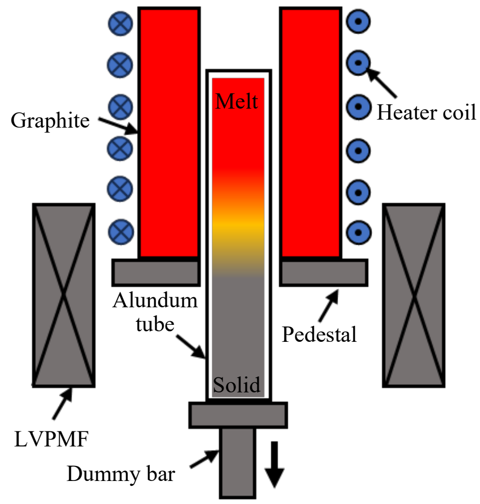


Fig.1 Schematic diagram of experiment equipment

## 2 Results and Discussion

### 2.1 Gradient structure preparation

The preparation of gradient structure with fine crystal, coarse crystal, and columnar crystal is realized. The longitudinal section and transverse section structures of solidified K4169 superalloy are shown in Fig. 2. The solidification structure of sample I is composed of columnar grains. Coarse equiaxed and fine equiaxed grains exist in sample II and sample III, respectively. Besides, the grain size of different samples is calculated, and the results are shown in Fig.3. It can be seen that the grain size is gradually decreased with the increase in pulse voltage of LVPMF treatment.

### 2.2 Gradient structure control mechanism

The Lorentz force is generated in the melt by the coupling effects of the induced current and the magnetic field when the LVPMF is applied. The distribution of Lorentz force in the melt in different pulse periods with different pulse voltages is shown in Fig.4. During the pulse upward period, the melt is subjected to electromagnetic pressure force, and the direction of Lorentz force is from the surface to the sample center (Fig.4a). During the pulse falling period, the melt is subjected

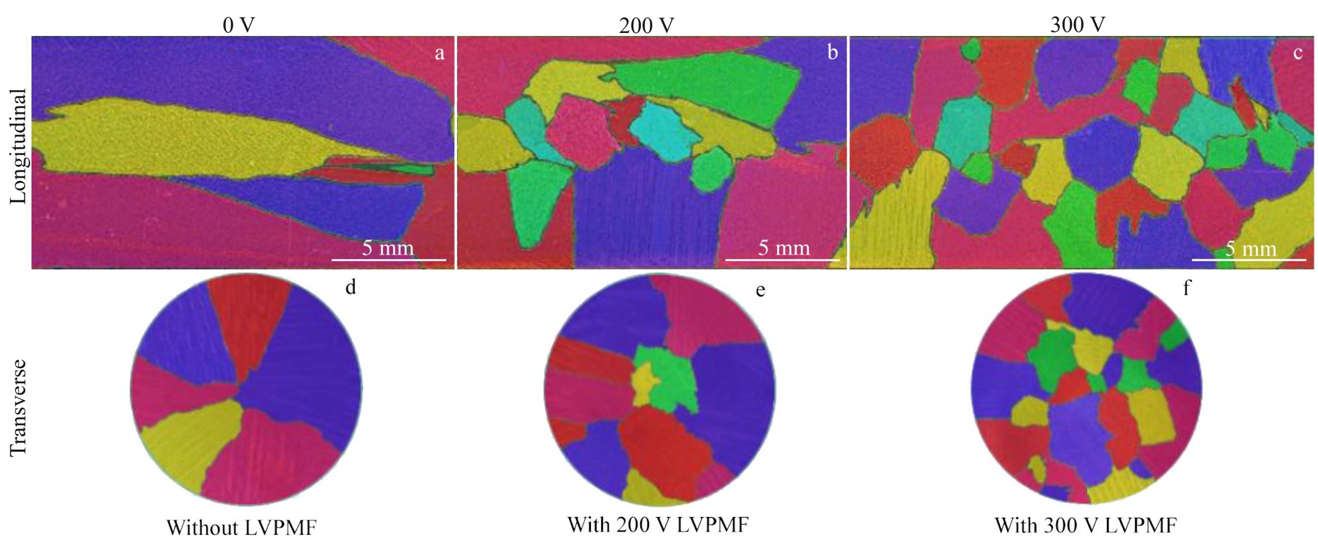


Fig.2 Longitudinal section (a–c) and transverse section (d–f) structures of solidified K4169 superalloy without (a, d) and with LVPMF treatment at pulse voltage of 200 V (b, e) and 300 V (c, f)

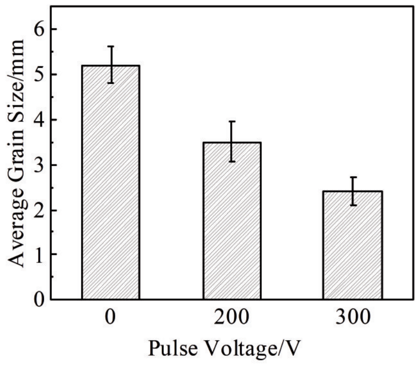


Fig.3 Average grain sizes of solidified K4169 superalloy without and with LVPMF treatment at different pulse voltages

to electromagnetic pull force (Fig. 4b). The simulation results reveal that the direction of Lorentz force changes periodically and the periodic changing of Lorentz force causes melt vibration. Because the electrical conductivity of solid is much better than that of liquid, the induced current in solid is higher than that in liquid[14]. The higher the induced current, the higher the magnetic induction strength. Thus, the magnetic force acting on dendrites is larger than that acting on liquid. The magnetic vibration effect mainly depends on the Lorentz force, so the growing dendrites are easier to break by the magnetic vibration. Since the Lorentz force at the middle part of the melt along the longitudinal direction is much stronger than that at the both ends and the K4169 superalloy melt is an incompressible fluid, the edge part of the melt at the sample

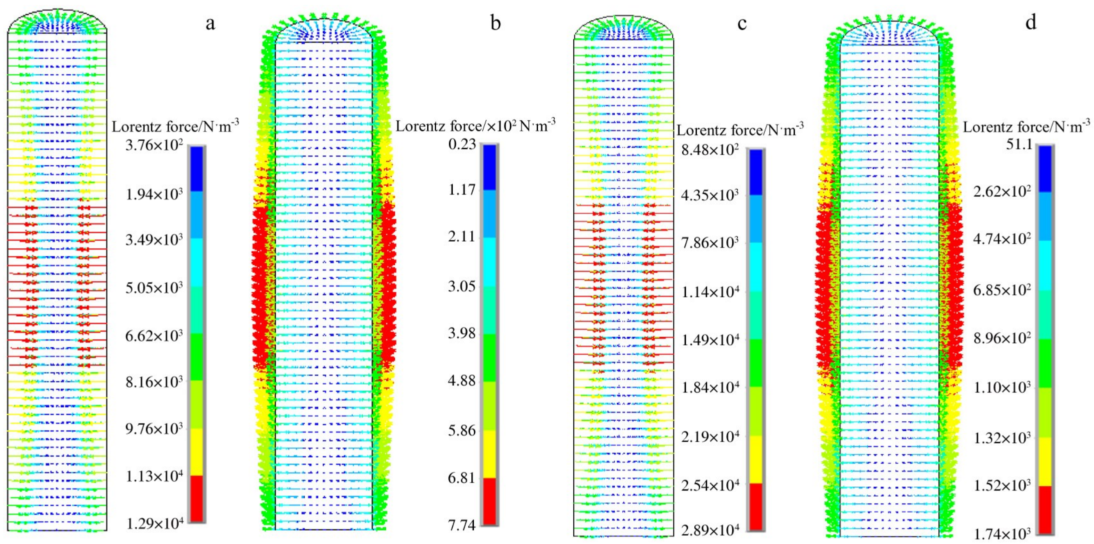


Fig.4 Lorentz force distributions in melt during pulse upward period (a, c) and pulse falling period (b, d) in LVPMF treatment at pulse voltage of 200 V (a–b) and 300 V (c–d)

middle along the longitudinal direction is driven to move inward firstly under the electromagnetic pressure force, and then it turns upwards or downwards, thus forming multi-circle flow on the longitudinal section, as shown in Fig. 5. On the one hand, the forced convection promotes the dendrite fragmentation and breaks the dendrite arm to disperse in the melt, thus acting as new nuclei[15]. On the other hand, the forced convection promotes a more uniform distribution of the melt temperature, reduces the temperature gradient ahead of the solidification front, and increases the undercooling zone, which is beneficial to the formation and remaining of equiaxed crystal nuclei. Therefore, under LVPMF application, the columnar front facilitates the formation and growth of equiaxed crystals, hindering the growth of columnar crystals and promoting the transition from columnar grain to equiaxed grain. Additionally, the structure transition of K4169 superalloy is attributed to the coupling effects of Lorentz force and forced convection.

When the pulse voltage of LVPMF treatment increases from 200 V to 300 V, the intensity of the magnetic field

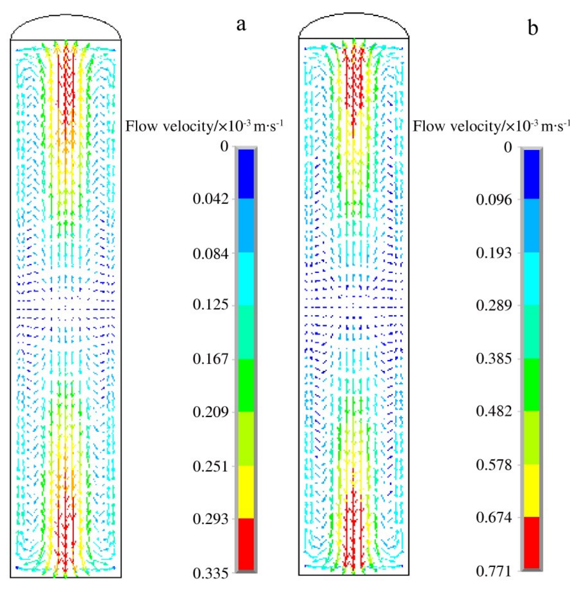


Fig.5 Flow distributions in melt during LVPMF treatment at pulse voltage of 200 V (a) and 300 V (b)

increases, so the Lorentz force and liquid velocity of forced convection induced by the alternating Lorentz force are raised. According to Fig. 4 and Fig. 5, the grain refinement effect is enhanced with the increase in pulse voltage. Furthermore, the increase in forced convection also leads to the more uniform temperature distribution at the solidification front. The homogenization of the temperature distribution is beneficial to the remaining of nuclei, which further contributes to the grain refinement.

## 3 Conclusions

1) Gradient structure of K4169 superalloy, including columnar grains, coarse grains, and fine grains, can be achieved by the combined method of LVPMF with directional solidification, which provides a new method for the gradient microstructure preparation of superalloys.

2) The structure transition of K4169 superalloy is attributed to the coupling effects of Lorentz force and forced convection. Increasing the pulse voltage of LVPMF treatment can enhance the effect of forced convection and refine the grain structures.

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# 低压脉冲磁场与定向凝固结合制备梯度组织K4169高温合金


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**摘　要：**研究了低压脉冲磁场对K4169高温合金组织转变的影响。将低压脉冲磁场与定向凝固相结合，制备了具有柱状晶、粗等轴晶和细等轴晶梯度组织特征的K4169高温合金，为高温合金梯度组织的制备提供了一种新的方法。揭示了合金微观组织的转变机制，模拟了低压脉冲磁场作用下洛伦兹力和流场的分布情况。结果表明：微观组织的转变归因于洛伦兹力和强迫对流的耦合效应。



**关键词：**脉冲磁场；梯度组织；高温合金；洛仑兹力；强制对流



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