Effect of Rectangular Cross-Section Aspect Ratio on Grain Refinement of K4169 Superalloy under Pulsed Magnetic Field (Postprint)

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Abstract

This study investigated the solidification structure of K4169 superalloy rectangular cross-section specimens under pulsed magnetic field, as well as the grain refinement effect on rectangular cross-section specimens with different width-to-thickness ratios. Computational simulations were conducted to determine the distribution of electromagnetic field and flow field in the specimen melt under pulsed magnetic field, and the refinement mechanism was analyzed. Experimental results demonstrate that after applying pulsed magnetic field, the solidification structure of K4169 superalloy rectangular specimens was refined to varying degrees; when the specimen width-to-thickness ratio was 1, applying pulsed magnetic field could significantly refine the solidification structure grains; as the specimen width-to-thickness ratio increased, the grain refinement effect of pulsed magnetic field weakened. Computational simulation results indicate that pulsed magnetic field generates periodic compressive-tensile electromagnetic forces in the melt, causing periodic oscillations and convection in a circulating pattern. Under pulsed magnetic field with the same magnetic flux density, the closer the specimen width-to-thickness ratio is to 1, the greater the electromagnetic force and flow velocity within the specimen, which facilitates the detachment of mold wall nuclei and dendrite arm fragmentation, thereby achieving grain refinement.

Full Text

Preamble

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Effect of Rectangle Aspect Ratio on Grain Refinement of Superalloy K4169 Under Pulsed Magnetic Field

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Abstract

The researches on the grain refinement by applied pulsed magnetic field (PMF) during solidification have received much attention in recent years and lots of positive experimental results indicate that it is a potential method for controlling solidification process. Various grain refinement mechanisms under PMF are proposed and most of them are considered to be relevant to the convection of melt driven by the electromagnetic force. An obvious fact is that the forced convection caused by PMF is strongly limited by the shape of the melt. However, most of previous studies were focused on cylindrical samples rather than rectangular ones, and actually the later one was widely used in industry. The aim of this work is to investigate the influence of PMF on the grain refinement of K4169 superalloy rectangular samples with various aspect ratios. Grain refinement of K4169 superalloy under PMF was experimentally investigated in the rectangular samples with the aspect ratios of 1.0, 2.0, 4.5 and 5.5 on the transverse section. In order to study the influence of aspect ratio on the forced convection, the distributions of the electromagnetic field, electromagnetic force and melt flow caused by PMF were numerically simulated by finite element software ANSYS. The experimental results show that the grains of the K4169 rectangular samples are coarse equiaxed grains without PMF and the grain size slightly decreases with the increase of aspect ratio. Under the PMF with same excitation voltage and frequency, the grains are refined remarkably in the sample with the aspect ratio of 1.0. As the aspect ratio is increased, the grain refinement effect can still be observed but not such obvious. The numerical simulation results indicate that the periodic pushing-pulling electromagnetic force is induced by the PMF, which drives the melt to vibrate and flow circularly. Under the same PMF, the electromagnetic force and fluid rate decreases with the increase of aspect ratio. When the aspect ratio increases from 1.0 to 5.5, the average electromagnetic force and fluid rate in the melt is reduced to 40% and 60%, respectively. The strongest fluid flow and vibration occur in the sample with section aspect ratio 1.0 in the present experiment, which is beneficial for grain refinement due to detachment of the solidified nuclei from mould wall and the break of dendrite arms from dendrite trunks.

KEY WORDS superalloy, grain refinement, pulsed magnetic field, aspect ratio, numerical simulation

Introduction

Investment casting of superalloy components can significantly reduce manufacturing costs while improving reliability and service life. However, castings produced by investment casting often exhibit coarse internal grain structures, which degrade comprehensive mechanical properties, particularly low-cycle fatigue performance [1]. Currently, industrial production commonly employs methods of lowering pouring temperature and adding surface refiners to refine solidification structures [2,3]. However, lowering the pouring temperature reduces melt fluidity, which is unfavorable for mold filling. While adding surface refiners can significantly refine surface grains, the effect on internal solidification structure refinement in thick-walled castings is generally limited, and inclusions may be introduced.

Since the 21st century, electromagnetic stirring and oscillation technologies [4,5] have gained increasing attention as methods for grain refinement. Numerous studies have demonstrated that applying electromagnetic fields during solidification of aluminum alloys [6,7], magnesium alloys [8], and steel [9] can significantly refine their solidification structures. If electromagnetic fields can be used to refine superalloy solidification structures, it would be highly significant for improving superalloy casting performance. Jin et al. [10] showed that applying electromagnetic fields during vacuum melting and casting of K417 superalloy could significantly refine and increase the equiaxed grain structure, substantially improve central shrinkage and porosity, greatly reduce dendritic segregation, and substantially improve ingot quality. Jin et al. [11] compared the effects of electromagnetic fields and refiners during casting of IN100 alloy, finding that applying electromagnetic fields with appropriate parameters could significantly refine solidification structures, and adding refiners on the investment surface could further enhance refinement. Jia et al. [12] systematically studied the influence of electromagnetic field frequency and intensity on grain refinement of Inconel 625 alloy, demonstrating that at 100 A current and 5-8 Hz frequency, superalloy solidification structures could be significantly refined. Our previous research [13-15] applied low-voltage pulsed magnetic fields during solidification of K417 and IN718 superalloys, showing that low-voltage pulsed magnetic fields have significant grain refinement effects, and that optimal refinement can be achieved by comprehensively considering pulsed magnetic field parameters and thermal parameters.

Studies have shown that electromagnetic forces and convection effects generated by electromagnetic fields in castings are important causes of grain refinement [16,17]. However, the distribution of electromagnetic forces and flow patterns in non-axisymmetric castings (such as square billets) differ greatly from those in axisymmetric cylindrical castings. For example, numerical simulations of coupled electromagnetic field, fluid flow, and heat transfer in cylindrical melts by Zhang et al. [18,19] indicated that circulating melt flow exists on the axisymmetric longitudinal section but not on the transverse section. Research on electromagnetic fields and flow fields in square billets during continuous casting by Ren et al. [20] showed that electromagnetic fields generate vortex-shaped flow fields on the horizontal plane of the billet, with tangential velocity proportional to distance from the center, and four vortices present in the longitudinal section. Yu et al. [21] studied the electromagnetic pressure on rectangular components with different aspect ratios under alternating electromagnetic fields; both simulation and experimental results showed that the inductor generated greater electromagnetic pressure at corners, and the electromagnetic force on narrow sides increased with aspect ratio. For pulsed magnetic fields, researchers have studied electromagnetic force distribution and casting flow in cylindrical castings [22,23], but relevant studies and grain refinement effects for other casting shapes have not been reported. Therefore, investigating the refinement effects and oscillation/convection effects of pulsed magnetic fields in non-axisymmetric castings is important for understanding the refinement mechanism and expanding the application range of pulsed magnetic fields.

This work investigates the grain refinement effects of low-voltage pulsed magnetic fields on K4169 superalloy rectangular cross-section samples with different aspect ratios. Through finite element simulation, the distribution patterns of electromagnetic forces and flow fields in rectangular cross-section samples are presented, and the influence of sample cross-section aspect ratio on electromagnetic forces and flow, as well as on pulsed magnetic field grain refinement effects, is analyzed based on experimental and simulation results.

Experimental

The experiments employed K4169 superalloy with main chemical composition (mass fraction, %) of: C 0.05, Co 0.01, Ni 52, Mo 3.05, Nb 5.3, Cr 8.4, Al 0.55, Ti 1.05, Fe balance. First, the master alloy with oxide skin removed by grinding was remelted under vacuum induction. After remelting, the master alloy was heated and refined for 5 minutes. When the melt temperature dropped to a certain value, pouring was performed and the samples were solidified under pulsed magnetic field with frequency and excitation voltage of 5 Hz and 200 V, respectively. The pulsed excitation coil was a multi-turn annular coil with inner diameter 260 mm, outer diameter 280 mm, and height 120 mm.

Rectangular cross-section samples were obtained using preheated investment molds with cross-section dimensions of 42 mm × 42 mm, 60 mm × 30 mm, 90 mm × 20 mm, and 100 mm × 18 mm, corresponding to aspect ratios of 1.0, 2.0, 4.5, and 5.5, respectively, and all with height 120 mm. The sample central axis coincided with the symmetry axis of the annular coil, with the sample bottom at the same horizontal plane as the coil bottom. After solidification, samples were sectioned 15 mm from the bottom along the transverse section and prepared as metallographic specimens. The solidification structure was etched using a corrosive agent of 15 g $CuSO_4$ + 3.5 mL H_2SO_4 + 50 mL HCl.

Solidification structures were obtained and observed using a Microtek i800plus optical scanner, and average grain size was measured using the intercept method. Eight intercept lines were taken on each transverse section, and average grain size was obtained by calculating the ratio of intercept length to number of intersected grain boundaries.

2 Simulation Model

The governing equations for electromagnetic field simulation are Maxwell's equations (1)-(4), Lorentz force is calculated by equations (5) and (6), and the governing equations for flow field are the mass conservation equation (7) and momentum conservation equation (8):

[Maxwell's equations would appear here as (1)-(4)]
[Lorentz force equations (5)-(6)]
[Mass conservation (7) and momentum conservation (8)]

where H is magnetic field intensity vector (A/m); s is melt electrical conductivity (1.18×10^{6} S/m); E is electric field intensity vector (V/m); B is magnetic flux density vector (T); J is induced current density (A/m^2); F is electromagnetic force density (N/m^3); r is melt density (7900 kg/m^3); t is time (s); v is velocity vector (m/s); p is pressure (Pa); m is effective viscosity coefficient (0.005 kg/(m·s)); Fb is total volume force including electromagnetic force. Material physical parameters reference those of pure Ni [24].

Based on solidification experiments under pulsed magnetic field, corresponding three-dimensional finite element models were established in ANSYS finite element software with the following assumptions and simplifications: (1) The melt is an incompressible Newtonian fluid with laminar flow; (2) Melt electrical conductivity and relative magnetic permeability do not vary with temperature, and melt flow does not affect electromagnetic field distribution; (3) Solute and solidification effects are not considered, melt physical parameters are isotropic and do not vary with time; (4) Pouring process effects on flow are not considered. Based on these assumptions, this work employs a one-way magnetic field-flow field coupling approach. As shown in [Figure 1: see original paper], the excitation pulse current waveform generated by the pulse generator is simplified as an asymmetric triangular wave pulse current in each period consisting of a 0.005 s rising stage ta, 0.055 s falling stage td, and 0.014 s pause stage tp. The excitation current density linearly increases from 0 to a peak value of 2×10^{7} A/m^2 during the rising stage, linearly decreases from the peak to 0 during the falling stage, and remains constant at 0 during the pause stage. Each stage is divided into 10 substeps for calculation. The excitation current is piecewise loaded onto coil elements in the magnetic field analysis, and magnetic flux line parallel boundary conditions are applied on the entire model outer surface to calculate the electromagnetic field and electromagnetic force at different times. Then, the electromagnetic forces at corresponding nodes and elements are loaded into the flow field model at corresponding times, and no-slip wall boundary conditions are applied on the flow field model outer surface to calculate the melt flow field distribution and the variation 规律 of melt velocity over multiple pulse cycles.

To investigate the refinement effects of pulsed magnetic fields on rectangular cross-section samples with different aspect ratios, corresponding finite element models were established for each aspect ratio. The finite element model and mesh for the rectangular cross-section sample with aspect ratio 5.5 are shown in [Figure 2: see original paper]. The electromagnetic field model consists of the sample in the central region, excitation coil (partially shown), and an air sphere surrounding the entire space (not shown). The flow field model only includes the sample region shown in [Figure 2: see original paper]. The height direction is defined as Z-axis, width direction as X-axis, and thickness direction as Y-axis. To balance computational efficiency and accuracy, the mesh size in the melt region is set to 1-2 mm with 10,000-20,000 elements.

3 Results and Discussion

3.1 Grain Refinement of Rectangular Cross-Section Samples with Different Aspect Ratios Under Pulsed Magnetic Field

The solidification structures of K4169 superalloy rectangular cross-section samples with different aspect ratios with and without pulsed magnetic field are shown in [Figure 3: see original paper], and the corresponding average grain sizes are given in [Figure 4: see original paper]. Combined analysis of [Figure 3: see original paper] and [Figure 4: see original paper] shows that without pulsed magnetic field, the samples exhibit coarse grains with average grain size of 3-4 mm, and grain size gradually decreases with increasing aspect ratio. This occurs because, for a constant cross-sectional area, increasing aspect ratio increases the cross-section perimeter, i.e., the heat dissipation area in contact with the mold, leading to higher cooling rates and consequently smaller average grain size with increasing aspect ratio. After applying pulsed magnetic field, grain size in samples of all aspect ratios is refined to varying degrees. For the sample with aspect ratio 1.0, the pulsed magnetic field produces the most significant refinement effect on solidification structure, reducing average grain size to 1.68 mm. For samples with aspect ratios of 2.0, 4.5, and 5.5, the average grain size decreases slightly under pulsed magnetic field. Thus, under the same pulsed magnetic field, rectangular samples with larger aspect ratios show weaker refinement effects.

3.2 Electromagnetic Force in Melt Under Pulsed Magnetic Field

Using the sample with aspect ratio 1.0 as an example to illustrate the distribution 规律 of magnetic flux density, induced current, and electromagnetic force in the melt. The magnetic flux density distributions in the melt when excitation current reaches the peak of rising stage and the midpoint of falling stage are shown in [Figure 5: see original paper]a and b, respectively (the central box indicates melt region, side boxes indicate coil region). The results show that magnetic flux density vectors in the melt have the same direction, basically parallel to the Z-direction, with larger magnetic flux density on both sides of the melt. The induced current distributions in the melt are shown in [Figure 6: see original paper]a and b, where the small figures in the upper right corner show the induced current distribution on the central transverse section. Pulsed magnetic field generates circumferential induced current in the melt, with opposite circulation directions during rising and falling stages of excitation current. The electromagnetic force distributions in the melt are shown in [Figure 6: see original paper]c and d, with small figures in the upper right corner showing electromagnetic force on the central transverse section. During the rising stage of excitation current, the melt experiences pressure toward the central axis; during the falling stage, the melt experiences tension toward the side surfaces. Under pulsed magnetic field, the melt is subjected to periodic pushing-pulling electromagnetic forces, which gradually increase from the melt center to side surfaces. To verify electromagnetic field calculation results, a standard Tesla meter was used to measure the Z-component of peak magnetic flux density at positions I, II, and III in [Figure 5: see original paper]a. The calculated and measured results are listed in , showing good agreement between finite element calculations and experimental measurements.

To investigate electromagnetic forces generated by pulsed magnetic field in rectangular samples with different aspect ratios, the maximum and average values of electromagnetic force density for all elements in different aspect ratio models were 统计 at the peak excitation current moment, as shown in [Figure 7: see original paper]. Both average and maximum electromagnetic force densities in samples show decreasing trends with increasing aspect ratio. For the rectangular sample with aspect ratio 5.5, its maximum and average electromagnetic force densities are 0.7 times and 0.6 times those of the sample with aspect ratio 1.0, respectively. This occurs because although the cross-sectional area and magnetic flux through the section remain constant with similar rates of change, resulting in similar induced electromotive forces, changes in aspect ratio alter the shape of the closed loop where induced current circulates. For samples with larger aspect ratios, each loop of induced current corresponds to a longer closed loop with higher total resistance, resulting in smaller induced current. Since electromagnetic force density is the product of magnetic flux density and current density, samples with larger aspect ratios experience smaller electromagnetic forces.

3.3 Melt Flow Under Pulsed Magnetic Field

Due to the periodic oscillation characteristics of electromagnetic force, both magnitude and direction of melt flow velocity vary with time. The variation 规律 of velocity at a node 75 mm high on the central axis of the rectangular cross-section sample with aspect ratio 1.0 over 40 s is shown in [Figure 8: see original paper], with the inset showing velocity during 5 pulse cycles between 25-26 s. The melt velocity exhibits two characteristics. First, velocity shows pulsed characteristics because the pulsed magnetic field consists of rising, falling, and pause stages: velocity gradually increases during the rising stage; during the falling stage, electromagnetic force direction is opposite to that in the rising stage, causing velocity to gradually decrease; during the pause stage, electromagnetic force is minimal and velocity slightly decreases due to viscous forces. Second, melt velocity is a gradually developing process. Since electromagnetic force during the rising stage is much greater than during the falling stage, velocity initially increases with time. After some time, increased velocity leads to increased viscous forces, and the velocity decrease during falling and pause stages equals the increase during rising stage, resulting in stable melt flow where velocity magnitude and direction at the same position are identical at the beginning of each cycle. [Figure 8: see original paper] shows that after 125 pulse cycles at 25 s, melt flow has become relatively stable.

[Figure 9: see original paper] shows the velocity vector diagrams in melts of samples with different cross-section aspect ratios at 25 s. All melt flow patterns exhibit circulating flow forms. As shown in [Figure 8: see original paper], melt flow is primarily driven by electromagnetic force during the rising stage. In samples with smaller aspect ratios ([Figure 9: see original paper]a), melt on the central horizontal plane experiences electromagnetic force toward the melt center (as shown in [Figure 6: see original paper]c) and moves inward, while melt around the periphery flows toward the center and then toward the top and bottom surfaces. After contacting the bottom surface, melt flows outward along the bottom, forms 回流 when reaching the four side surfaces, and the upper and lower 回流 converge on the central horizontal plane to form circulating flow. The flow velocities at the four side surfaces are similar. With increasing aspect ratio, the 回流 velocity formed on the wide surface becomes significantly smaller than that on the narrow side. In the sample with aspect ratio 5.5 ([Figure 9: see original paper]d), the 回流 on the wide surface is influenced by melt flow from the center toward the top and bottom surfaces and merges into the 回流 on the narrow side. Consequently, the wide surface flow velocity is significantly smaller than the narrow side velocity.

[Figure 10: see original paper] shows the maximum and average velocities of all nodes in different aspect ratio models at 25 s. Both maximum and average melt flow velocities gradually decrease with increasing cross-section aspect ratio. In the rectangular sample with aspect ratio 5.5, the maximum and average flow velocities are 0.4 times those in the sample with aspect ratio 1.0. This is because increasing aspect ratio reduces electromagnetic force, thereby reducing the driving force for forced convection. Additionally, since melt flow is in a circulating pattern, larger aspect ratio shapes impose greater constraints on the circulation, resulting in slower melt flow in samples with larger aspect ratios.

3.4 Mechanism Analysis

The current understanding of pulsed magnetic field grain refinement mechanisms primarily involves two mechanisms: detachment of chill nuclei from mold walls and dendrite arm fragmentation [6,13,14,25]. Under pulsed magnetic field, periodically varying electromagnetic forces generate oscillation and convection in the melt, which can promote detachment of chill nuclei from mold walls or fragmentation of dendrite arms. These fragments are then dispersed throughout the melt by flow to form new nucleation cores, resulting in overall ingot structure refinement. Ma et al. [26] applied pulsed magnetic fields at different solidification stages in IN718 alloy and found that refinement primarily occurs during the nucleation stage at the beginning of solidification, consistent with Li et al.'s [27] experimental results in Al-Cu alloy. Ma et al. [26] further conducted sieve experiments and found that the solidification structure between the sieve and mold wall was significantly refined under pulsed magnetic field, while refinement inside the sieve was poor, suggesting that promoting mold wall nuclei detachment and 游离 is the main cause of grain refinement. Our simulation results show that under pulsed magnetic field, the melt edge experiences large electromagnetic forces and melt flow exists, which can cause oscillation or 冲刷 of mold wall nuclei leading to their detachment and 游离. Meanwhile, convection generated by pulsed magnetic field can promote uniform distribution of 游离 nuclei throughout the melt. Under their combined effects, the number of effective nuclei in the melt increases. Consequently, solidification structures of samples with different cross-section aspect ratios are all refined to varying degrees under pulsed magnetic field.

The weakening of pulsed magnetic field refinement effects on rectangular samples with increasing aspect ratio is mainly due to changes in melt force and flow. According to simulation results, on one hand, under the same pulsed magnetic field intensity, when sample cross-section aspect ratio is 1.0, the melt experiences maximum average electromagnetic force and flow velocity ([Figure 7: see original paper] and [Figure 10: see original paper]), producing the strongest electromagnetic oscillation and convection, and thus the best refinement effect. As sample cross-section aspect ratio increases, average electromagnetic force and flow velocity gradually weaken, reducing electromagnetic oscillation and convection, which is unfavorable for detachment of chill nuclei from mold walls, dendrite arm fragmentation, and dispersion of these heterogeneous nuclei. This is fundamentally consistent with the principle that reduced external magnetic field intensity leads to weaker refinement effects in cylindrical samples [13]. On the other hand, forced flow patterns differ among rectangular samples with different aspect ratios. In samples with smaller aspect ratios ([Figure 9: see original paper]a), melt side surface velocity distribution is relatively uniform, and nuclei formed on mold walls all experience strong 冲刷作用. In samples with larger cross-section aspect ratios ([Figure 9: see original paper]d), wide surface velocity is small while narrow side velocity is large, but the wide surface has a large area that can provide numerous chill nuclei. This flow pattern is unfavorable for detachment and dispersion of mold wall chill nuclei. These two factors together result in weaker grain refinement effects on samples with larger aspect ratios under pulsed magnetic field ([Figure 3: see original paper]). Therefore, for samples with larger aspect ratios, the refinement effect using annular coils is relatively limited. If excitation coil design is optimized and pulsed magnetic field parameters and application methods are modified to obtain larger electromagnetic forces, stronger melt flow, and flow patterns favorable for mold wall 冲刷, the refinement effect of pulsed magnetic field on samples with larger aspect ratios could be improved.

Conclusions

1. Under pulsed magnetic field, grains in solidified K4169 superalloy rectangular samples are refined to varying degrees. Under the same pulsed magnetic field, rectangular samples with smaller aspect ratios show stronger refinement effects. When sample cross-section aspect ratio is 1.0, pulsed magnetic field produces the most significant grain refinement effect. When aspect ratios are 2.0, 4.5, and 5.5, pulsed magnetic field produces weaker grain refinement effects.
2. Simulation results show that under pulsed magnetic field, K4169 superalloy melt experiences periodic pushing-pulling electromagnetic forces that generate circulating flow. Melt flow velocity gradually increases during the rising stage of pulsed magnetic field and gradually decreases during falling and pause stages, exhibiting pulsed characteristics. In samples with smaller aspect ratios, flow velocities at the four side surfaces are similar. In samples with larger aspect ratios, wide surface flow velocity is significantly smaller than narrow side velocity.
3. Under the same pulsed magnetic field, electromagnetic forces and flow intensities differ significantly among rectangular samples with different cross-section aspect ratios. As cross-section aspect ratio increases from 1.0 to 5.5, the maximum electromagnetic force decreases by about 30% and average electromagnetic force decreases by about 40%; maximum flow velocity and average flow velocity decrease by about 60%.

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