

## Grain refinement of as-cast superalloy IN718 under action of low voltage pulsed magnetic field

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**Abstract:** The grain refinement of superalloy IN718 under the action of low voltage pulsed magnetic field was investigated. The experimental results show that fine equiaxed grains are acquired under the action of low voltage pulsed magnetic field. The refinement effect of the pulsed magnetic field is affected by the melt cooling rate and superheating. The decrease of cooling rate and superheating enhance the refinement effect of the low voltage pulsed magnetic field. The magnetic force and the melt flow during solidification are modeled and simulated to reveal the grain refinement mechanism. It is considered that the melt convection caused by the pulsed magnetic field, as well as cooling rate and superheating contributes to the refinement of solidified grains.

**Key words:** superalloy; grain refinement; low voltage pulsed magnetic field; cooling rate; superheating

### 1 Introduction

Grain refinement is an effective method to improve the deformability and mechanical properties of superalloy. Fine grain casting of superalloy mainly includes the thermal control method [1], the chemical approach [2–3] and the dynamic method [4–5]. Up to now, new methods are still expected to be developed for refining as-cast microstructure of superalloy more efficiently. Recently, pulsed magnetic processing provides a new grain refinement approach.

The application of a pulsed magnetic field (PMF) in the solidification of alloy is considered an effective method to refine grains and improve the mechanical properties of the alloys, and it has been paid more attention in recent years. ZI et al [6–7] found that a strong PMF can significantly refine the solidification structures of aluminum alloy. BAN et al [8] found that a strong PMF can make the solidification structure of aluminum alloy change from big continuous dendrite network to thin discontinuous structure, and reduce the element segregation. LI et al [9–10] studied the effect of a strong PMF on the structural transformation of 1Cr18Ni9Ti austenitic stainless steel. The results show that the applications of pulsed magnetic field can significantly refine its microstructure, reduce the

solidification time, and also lead to the increase of the initiation and finishing solidification temperature. GAO et al [11] comparatively studied the structural transformation of low-melting pure Al and high-melting stainless steel under external pulsed magnetic field. The results showed that the refinement effect of PMF was more obvious for pure Al than for stainless steel.

Recently, the application of a low voltage pulsed magnetic field (LVPMF) on solidification, which is more secure and can be used in practice easily, has been introduced to the solidification processes of alloy. YANG et al [12–13] found that a LVPMF can refine the as-cast grains of magnesium alloy remarkably. MA et al [14–15] studied the refinement effect of a LVPMF under different thermal controls on superalloy and found that fine equiaxed grains can be acquired with proper thermal control under the action of LVPMF. However, the refinement effect of the pulsed magnetic field under different thermal controls is not clear. Furthermore, the refinement mechanism of the pulsed magnetic field also needs to be further investigated. The variation of magnetic force and the flow field distribution with the magnetic pulse in multiple periods is not clear because the PMF is transient, variable, interrelationship and complex. Because of the experimental restriction, it is hard to solve those questions through experiment observation. But numerical simulation provides an

effective analysis for experiment and industry production. The numerical analysis can contribute to understanding the mechanism why the LVPMF can refine microstructure [16]. In this work, the refinement effect of the pulsed magnetic field on as-cast microstructure of a nickel-based superalloy is studied. The refinement effect of the pulsed magnetic field under different thermal control (including cooling rate and melt superheating) on the as-cast microstructure is ascertained, and the magnetic force and flow distribution in the nickel-based superalloy melt are investigated under 5 Hz LVPMF in 20 pulse periods using the commercial Ansys finite element software.

## 2 Experimental

A nickel-based superalloy IN718 was used in the experiment, whose chemical compositions (mass fraction, %) are : C 0.015, Co 12, Cr 18, Ti 1.0, Al 0.5, Mo 3, Ta 3, B 0.018, Nb 4 and Ni balance. The experimental apparatus for solidification under a pulsed magnetic field consists of a generator of the pulsed magnetic field, a cooling water system, heat insulation refractory and an alumina mold with an inner diameter of 15 mm and height of 80 mm. In experiments, the superalloy IN718 was melted to 1 550 °C in an induction furnace, and then the melt was poured into the mold that was preheated in a resistance furnace together with the heat insulation refractory. The low voltage pulsed magnetic field was applied immediately after pouring and last for 5 min during solidification. The solidified microstructures on the longitudinal section of the solidified samples were observed with an optical microscope after the samples were ground, polished and etched by a  $\text{CuSO}_4\text{-HCl-H}_2\text{SO}_4\text{-H}_2\text{O}$  solution.

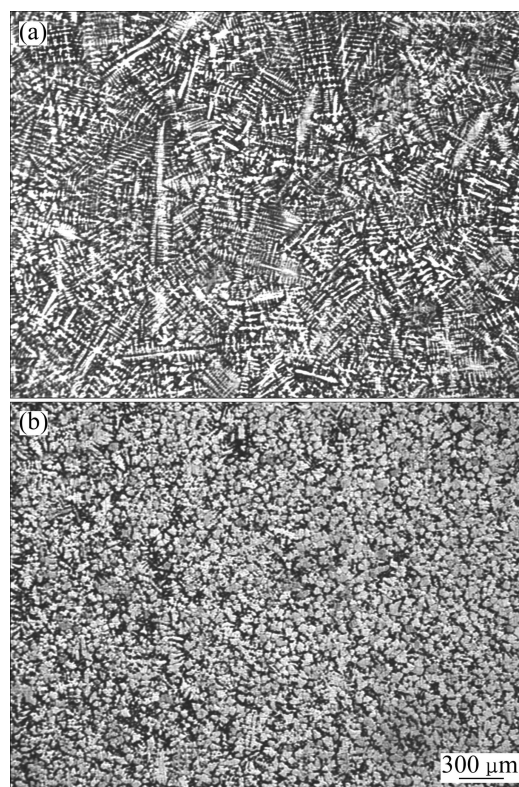
## 3 Results and discussion

### 3.1 Effect of LVPMF on grain refinement

The as-cast microstructures of the superalloy IN718 with and without LVPMF are shown in Fig. 1. Without LVPMF, columnar dendrites along the cooling direction are yielded on the surface of the sample and coarse equiaxed grains are produced in the center of the sample, as shown in Fig. 1(a), while complete fine equiaxed grains with the average grains size of about 60  $\mu\text{m}$  are produced in the whole sample solidified with low voltage pulsed magnetic field, as shown in Fig. 1(b).

### 3.2 Effect of cooling rate on grain refinement with LVPMF

When the melt superheating is fixed to a certain temperature, the cooling rate of the melt depends on the heat transfer ability of the mold. Higher cooling rate



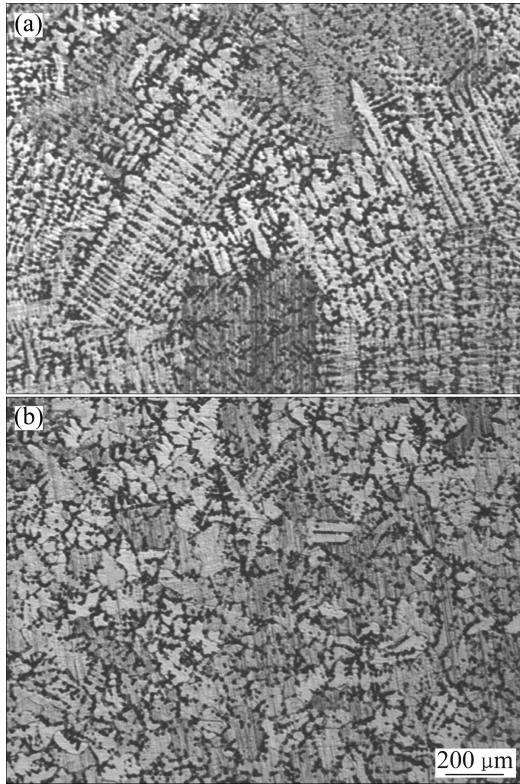
**Fig. 1** As-cast microstructures of superalloy IN718 without (a) and with (b) LVPMF

corresponds to lower temperature of the mold. So, the cooling rate can be controlled by adjusting the mold temperature.

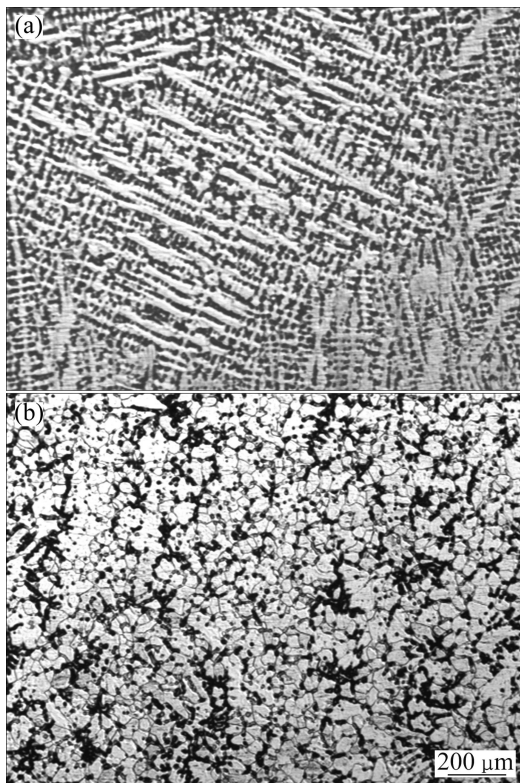
The solidification microstructures with LVPMF under different cooling rates are shown in Fig. 2. Under high cooling rate (with the mold temperature of 800 °C), the solidification microstructure is coarse equiaxed grains and the well-developed dendrites are formed in the equiaxed grains, as shown in Fig. 2(a). Under low cooling rate (with the mold temperature of 850 °C), the solidification microstructure consists of fine equiaxed grains, and the grain size is refined, as shown in Fig. 2(b). The results show that the refinement effect of LVPMF becomes weak when the cooling rate increases.

### 3.3 Effect of superheating on grain refinement with LVPMF

The microstructures solidified with low voltage pulsed magnetic field with different melt superheating are shown in Fig. 3. Coarse equiaxed dendrites are produced in the solidified microstructure when the melt superheating is 90 °C. While fine equiaxed grains are produced when the melt superheating is 60 °C, as shown in Fig. 3(b). The results show that the refinement effect of LVPMF becomes weak when the melt superheating increases.



**Fig. 2** As-cast microstructures in center of samples with LVPMF at different mold temperatures: (a) 800 °C; (b) 850 °C

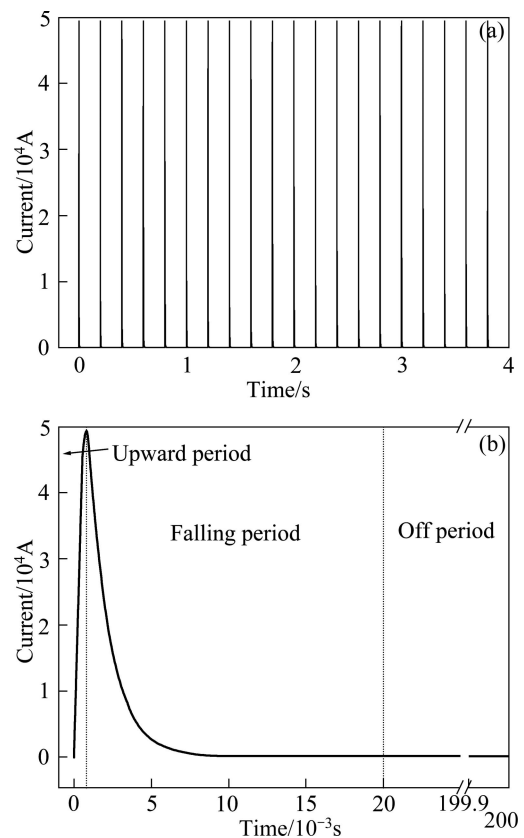


**Fig. 3** As-cast microstructures in center of samples with LVPMF at different melt superheating: (a) 90 °C; (b) 60 °C

### 3.4 Refinement mechanism of LVPMF

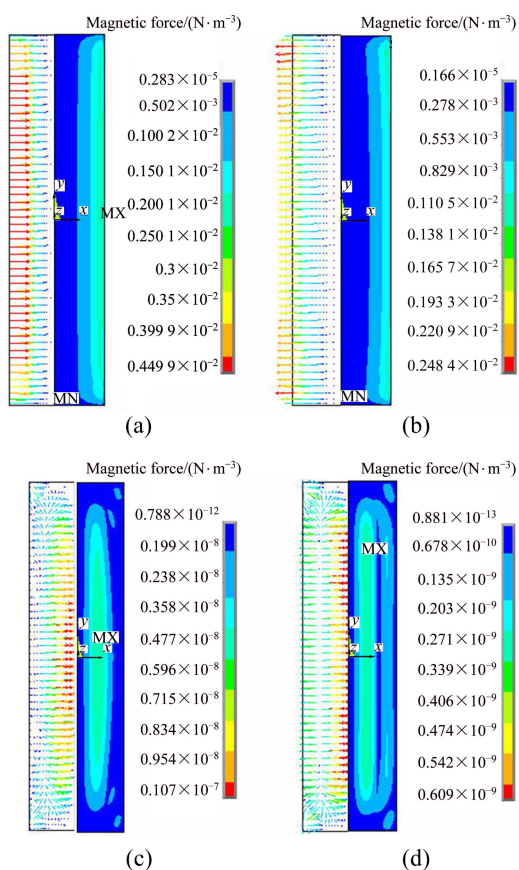
In order to investigate the refinement mechanism of LVPMF, the variation of magnetic force and flow field distribution produced by the pulsed magnetic was investigated by the finite element numerical simulation.

The change of the pulse current for LVPMF is shown in Fig. 4 based on the result of resistance-inductance-capacitance (RLC) circuit analysis. There are three periods including upward period, falling period and off period in one whole pulse period lasted for 0.2 s. Figure 4(b) shows the detailed result of the change of the pulse current in one period of pulse. The current reaches peak (50 kA) in the whole coil after being pulse applied 0.000 8 s, and then decreased to zero at 0.02 s. The melt density is 8 240 kg/m<sup>3</sup>, and the viscosity is 0.006 6 Pa·s. Twenty pulse periods are solved, and the results in the 16th period are obtained because the magnetic force and flow field distribution become stabilization during this period.



**Fig. 4** Variation of pulsed electricity in coil: (a) 20 whole periods of current; (b) Result of change of pulse current in one period of pulse

The magnetic force distribution in the 16th period is shown in Fig. 5. The magnetic pressure force appears inside the melt during the upward period of pulse. The magnetic pull force appears in the melt at the initial time of falling period, and a magnetic force oscillation appears at the final time of the falling period. During the

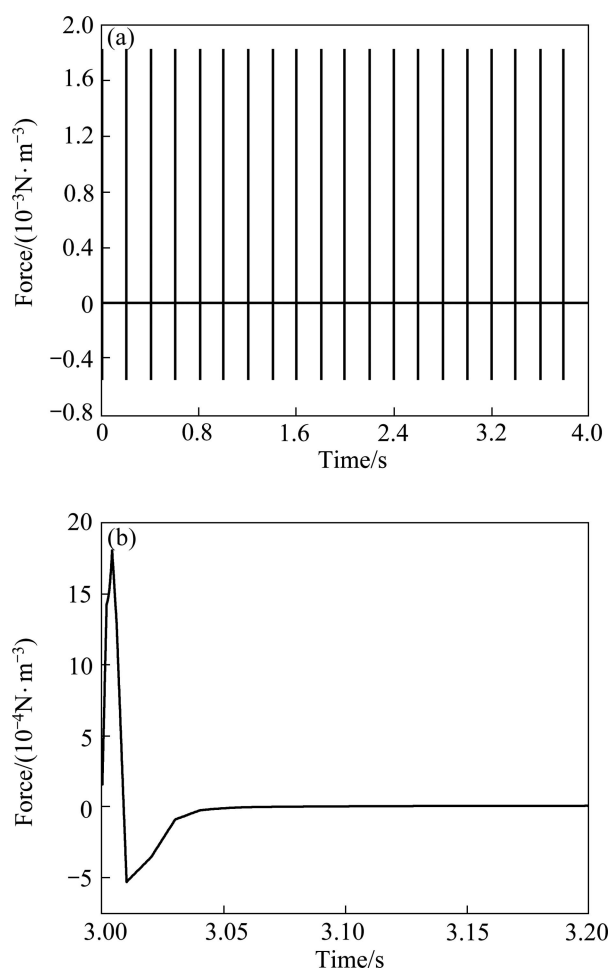


**Fig. 5** Magnetic force distributions in melt: (a) Pulse peak (3.000 8 s); (b) Start of falling period (3.000 9 s); (c) End of falling period (3.02 s); (d) End of off period (3.2 s)

off period of pulse, the magnetic pressure force appears at the center of the melt and the magnetic pull force appears on the surface of the melt. Figure 6 shows the curves of component of magnetic force of the node at external center of the melt. It is obvious that the magnetic force has a strenuous change of the value during the upward period and falling period of pulse, which can lead to melt flow.

The flow field distribution in the 16th period is shown in Fig. 7. It is obvious that the flow pattern remains identical during the whole period. The velocity of melt is larger at the center of the melt than that on the surface of the melt. The flow velocity increases during the upward period of pulse, and decreases during the falling period and off period of pulse. The convection is formed at the bottom of the melt during the falling period, and exists in the whole melt during the off period.

Based on the finite element numerical simulation results, periodic variable magnetic force and flow field in the nickel-based superalloy are produced under the action of LVPMF. The refinement effect of the pulsed magnetic field is mainly attributed to the nuclei dissociation from the mold wall by the melt vibration and



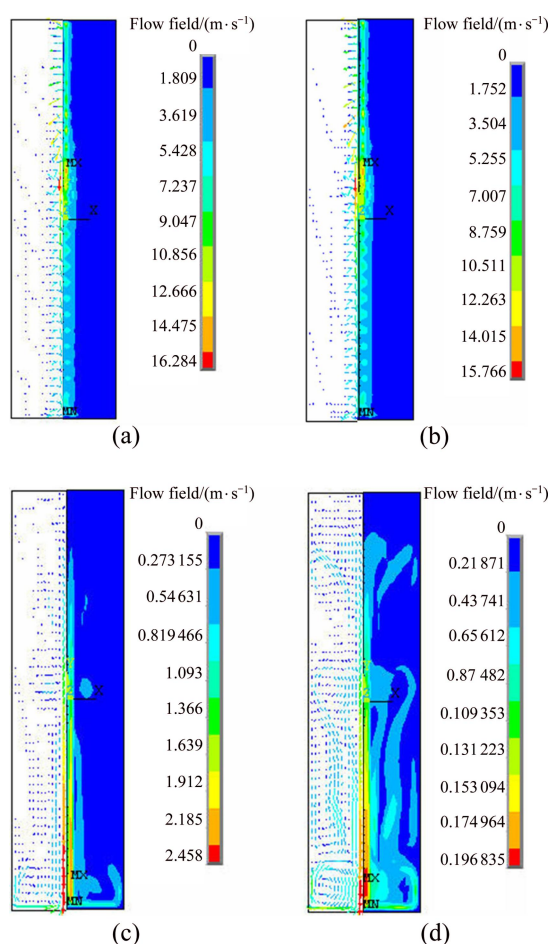
**Fig. 6** Curves of magnetic force of node at external center of melt: (a) 20 whole periods; (b) Change of magnetic force in upward period and falling period of pulse

the subsequent separation of nuclei by the melt convection. Further, the LVPMF forced convection may lead to dendrite fragmentation, and promote the broken dendrite arm to disperse in the whole melt as new nuclei. Thus, a mass of nuclei are produced in the bulk melt. Finally, fine equiaxed grains are formed. Therefore, the refinement mechanism of pulsed magnetic field may attribute to the heterogeneous nucleation enhancement.

The experimental results with different mold temperature and superheating are also consistent with the heterogeneous nucleation enhancement of pulsed magnetic field.

The increase of mold temperature prolongs the solidification time of the alloy, which means that the heterogeneous nucleation enhancement process of pulsed magnetic field gains more time. Therefore, the solidified grains are refined with the increase of mold temperature.

The melt superheating influences the survival probability of nuclei in the melt. With the increase of melt superheating, the dispersed nuclei in the melt tend to remelt, which cannot increase the effective nuclei in



**Fig. 7** Flow field distributions in melt: (a) Pulse peak (3.000 8 s); (b) Start of falling period (3.000 9 s); (c) End of falling period (3.02 s); (d) End of off period (3.2 s)

the melt. Therefore, the cooperation of thermal control is necessary for pulsed magnetic field to refine solidified structures.

## 4 Conclusions

1) The refinement effect of LVPMF on superalloy IN718 was investigated. Fine equiaxed grains are acquired. The refinement effect of LVPMF is improved with the decrease of the cooling rate and the melt superheating.

2) The magnetic force and flow distribution in the nickel-based superalloy melt under 5 Hz LVPMF in 20 pulse periods are obtained by the finite element numerical simulation. The pulsed magnetic field will produce a magnetic force oscillation, and produce melt convection in the melt.

3) It is considered that the melt convection caused by the pulsed magnetic field, as well as cooling rate and superheating contributes to the refinement of solidified grains.

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# 低压脉冲磁场对铸态 IN718 高温合金凝固组织细化的影响

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**摘 要:** 研究低压脉冲磁场对 IN718 高温合金凝固组织细化的影响。结果表明: 在低压脉冲磁场作用下可以获得完全细小的等轴晶组织。熔体冷却速度和过热度显著影响低压脉冲磁场的细化效果, 降低冷却速度和过热度有利于提高脉冲磁场的细化效果。利用商业有限元软件模拟计算高温合金凝固过程中熔体中的电磁力和流场分布情况以揭示脉冲磁场的细化机制。认为脉冲磁场引起的熔体对流, 以及同熔体冷却速度和过热度的合理配合是合金凝固组织细化的主要原因。

**关键词:** 高温合金; 晶粒细化; 低压脉冲磁场; 冷却速度; 过热度

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