# Mechatronics and Mechanical Engineering I

Edited by
He Rui, Puneet Tandon and Teresa T. Zhang

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# Mechatronics and Mechanical Engineering I

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September 6-8, 2014, Chengdu, China



*Edited by*

**He Rui,**
**Puneet Tandon and Teresa T. Zhang**

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# Preface

2014 International Conference on Mechatronics and Mechanical Engineering (ICMME 2014) was held in Chengdu, China during September 6-8, 2014. The conference provides a platform to discuss Mechatronics and Mechanical Engineering etc. with participants from all over the world, both from academia and from industry. Its success is reflected in the papers received, with participants coming from several countries, allowing a real multinational multicultural exchange of experiences and ideas.

The present volumes collect accepted papers and represent an interesting output of this conference. This book covers these topics: Acoustics and Noise Control, Aerodynamics, Applied Mechanics, Automation, Mechatronics and Robotics, Automobiles, Automotive Engineering, Ballistics, Biomechanics, Biomedical Engineering, CAD/CAM/CIM, CFD, Composite and Smart Materials, Compressible Flows, Computational Mechanics, Computational Techniques, Dynamics and Vibration, Energy Engineering and Management, Engineering Materials, Fatigue and Fracture, Fluid Dynamics, Fluid Mechanics and Machinery, Fracture, Fuels and Combustion, General mechanics, Geomechanics, Health and Safety, Heat and Mass Transfer, HVAC, Instrumentation and Control, Internal Combustion Engines, Machinery and Machine Design, Manufacturing and Production Processes, Marine System Design, Material Engineering, Material Science and Processing, Mechanical Design, Mechanical Power Engineering, Mechatronics, MEMS and Nano Technology, Multibody Dynamics, Nanomaterial Engineering, New and Renewable Energy, Noise and Vibration, Noise Control, Non-destructive Evaluation, Nonlinear Dynamics, Operations Management, PC guided design and manufacture, Plasticity Mechanics, Pollution and Environmental Engineering, Precision mechanics, Mechatronics, Production Technology, Quality assurance and environment protection, Resistance and Propulsion, Robotic Automation and Control, Solid Mechanics, Structural Dynamics, System Dynamics and Simulation, Textile and Leather Technology, Transport Phenomena, Tribology, Turbulence and Vibrations.

This conference can only succeed as a team effort, so the editors want to thank the international scientific committee and the reviewers for their excellent work in reviewing the papers as well as their invaluable input and advice.

Prof. He Rui, Southwest Jiaotong University, China
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# CHAPTER 1:

## Advanced Materials Engineering and Processing Technologies

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# Effects of Non-equilibrium Solidification and Aging Treatment on Microstructure Characteristic of a Ni-base Superalloy

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**Keywords:** Solidification; Precipitation; Microstructure; Ni-base superalloy

**Abstract.** Copper mould spray casting and aging treatment were performed to investigate the microstructure evolution of a Ni-base superalloy. With increasing the cooling rate during solidification, the morphology of primary $\gamma$ phase changes from coarse dendrite to fine dendritic structure with radial-like feature, accompanied by the inhibition of $\gamma'$ phase due to the shortened period during the subsequent solid state transformation process. After aging treatment, both the size and volume fraction of $\gamma'$ phase are increased with prolonging the isothermal time, which generate the morphology transition of precipitates from irregular and spherical to ellipse and rectangle due to the competition between the interface energy and strain energy.

## Introduction

Ni-base superalloys are widely used for high temperature application such as aircraft blade, discs, rocket engines and nuclear power components [1]. The excellent mechanical properties including better creep and oxidation resistance are controlled by the grain size and secondary dendritic arm spacing of primary phase, as well as the morphology and distribution of $\gamma'$ phase inside the $\gamma$ matrix [2-4]. From a theoretical interest and technological importance, it is essential to understand the microstructure characteristics and the underlying formation regularities to obtain the desired properties to the material [5-7].

Rapid solidification has become an important technique for producing novel alloys [8-10]. Due to being far from equilibrium, the microstructure formed in rapid solidification often deviates from its initial feature obtained by conventional near-equilibrium solidification [11-13]. In such a case, a finer dendrite spacing and weaker elemental segregation are generated, which are beneficial to eliminate the casting defects like porosity and hot tears [14]. Milenkovic et al. investigated the instability of solid/liquid interface with the cooling rate in the range of 0.25-10 K/s [15]. Zhang et al. established the relationship between the dendrite arm spacing and cooling rate by statistical method [16].

Nevertheless, it should be noted that the fast cooling feature of rapid solidified specimens does not favor the precipitation of $\gamma'$ phase from the super-saturated $\gamma$ matrix because of shortened duration for this solid state transformation [17]. As is known, Ni-base superalloys are hardened by the $\gamma'$ precipitates. Thus, a subsequent aging treatment is required to optimize the mechanical properties of rapid solidified ingots. Due to the nucleation and growth factors controlling the whole precipitation process are changed significantly by the foregoing non-equilibrium transformation, the precipitation behavior of rapid-quenched sample is much different to the conventional fabrication routes [18-20].

Up to now, many fundamental studies are devoted to reveal the microstructure evolution of superalloys with different cooling rate. However, in-depth understanding of the transformation, especially the relationship between the non-equilibrium solidification and subsequent precipitation processes are still limited and a wider range of cooling rate is also needed. In present study, a comparison of microstructure evolution of a Ni-base superalloy was carried out by multi-step copper mould spray casting technique and then isothermal aging treatment was adopted to elucidate the temporal dependence of precipitation behavior of $\gamma'$ phase in the as-quenched ingot.

**Experimental procedures**

The superalloy studied had a nominal chemical composition (weight percent) of Co 12.0~15.0, Cr 8.5~9.0, Al 5.0~5.7, Ti 4.2~4.7, Mo 2.7~3.4, W 1.0~1.8, Nb 0.5~1.0, V 0.5~1.0, C 0.14~0.20 and Ni balance. The melting and spray-casting experiments were conducted in a high frequency induction unit with a vacuum degree of $6.67 \times 10^{-4}$ Pa. The temperature was measured by an infrared thermometer. After overheated by ~150 °C above its liquidus temperature and maintained for ~5 min, the melts with the weight of ~50 g was injected into a multi-step copper mould with varied diameter of $\Phi$12 mm, $\Phi$8 mm and $\Phi$6 mm. After spray casting experiment, the specimens with $\Phi$6 mm were conducted by aging treatment at 1000°C and the isothermal time was chosen as 30 min, 60 min, 120 min and 240 min, respectively. Detail information for the experimental procedure was described elsewhere [18, 19].

After experiment, the as-obtained samples were sectioned transversely and processed according to standard metallographic procedure. The microstructure was characterized using optical microscopy (OM, VHX-600, Keyence) and filed-emission scanning electron microscopy (FE-SEM, Nova Nano SEM450). The average grain size and volume fraction of $\gamma'$ phase were analyzed statistically by the software of Image-Pro Plus 6.0. According to Ref. [16], the size of spherical and irregular shape was determined by the equivalent circle method and that for the rectangle shape was calculated by the mean edge length method.

**Results and Discussion**

Fig. 1 shows the optical microstructures of superalloys fabricated by different cooling rates. As expected, coarse dendrite with well developed secondary arms appears in the as-cast condition, where the interdendritic eutectic phase distributes unevenly with polygonal shape (Fig. 1a). In contrast, fine dendritic structure with radial-like characteristic appears for spray-casted specimens, and this grain refinement phenomenon becomes more apparent as for larger cooling rate by decreasing the inner diameter of copper mould (Fig. 1b~d). The preferable distribution characteristic can be ascribed to the favorable growth of oriented grain in accordance with the fast heat withdrawn capacity, as well as the inhibition of copious nucleation because of narrow freezing range of superalloy. According to ripening theory [5], the development of side branches is associated with the length of mushy zone and local solidification time. These values are both reduced because of enhanced cooling rate. As a consequence, the secondary dendritic arm spacing is reduced accordingly. Moreover, the solute trapping arising from the accelerated interface migration rate and the refinement of primary phase contribute to the relief of solute segregation, which leads to the decline of the size of eutectic phase as well.

The precipitation behavior of $\gamma'$ phase in the dendritic core is also affected by the cooling rate, as verified by the FE-SEM pictures shown in Fig. 2. Clearly, a great amount of $\gamma'$ phases with the average size of 1.6 μm are well dispersed throughout the matrices for as-cast alloy (Fig. 2a). In contrast, no obvious precipitation could be observed in the condition of spray-casting (Fig. 2b). According to previous study [16], the formation of $\gamma'$ phase always experiences a successive stage including inoculation period, nucleation, growth and coarsening. Due to the existence of inoculation period and insufficient time for growth, the rapid cooing characteristic of spray casting is inclined to suppress the precipitation of $\gamma'$ phase from the primary dendrite phase.