

Influence of the Preheat Temperature and Withdrawal Rate on the Microstructure of Ceramic-Cored DS MAR-M247 Nickel-Based Superalloy

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Abstract. The research focuses on cored blades made from the MAR-M247® Ni-based superalloy, which were manufactured through directional solidification with varying withdrawal rates of either 3.4 mm/min or 5.0 mm/min, and shell mold temperatures of 1510 °C or 1566 °C after undergoing solution heat treatment. The characterization of four variants of the cored blades was conducted using several analytical techniques: X-ray diffraction (XRD), light microscopy (LM), scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX). The XRD analysis identified the presence of the γ matrix, the intermetallic γ' phase, MC carbides, and M_5B_3 phases. The dendritic regions of the cored blades consist of secondary γ' precipitates surrounded by a γ matrix, with a mean size ranging from 0.264 to 0.272 μm , depending on the fabrication parameters.

Introduction

Directionally solidified nickel-based superalloys are widely employed in aerospace applications, particularly in the fabrication of hollow turbine blades. Unlike alloys with equiaxed grains, the columnar grain structure of these castings eliminates grain boundaries perpendicular to the primary tensile stress axis. This microstructural feature significantly enhances creep resistance by limiting the initiation and propagation of cavitation and cracks along grain boundaries. A critical element in the production of these advanced turbine blades is the use of ceramic cores, which enable the formation of intricate internal cooling channels essential for effective thermal management under high-temperature operating conditions. Typically made from silica-based materials, these cores are precisely engineered to produce accurate cooling passage geometries during the investment casting process [1–3]. When the molten MAR-M247 nickel-based superalloy is poured around the ceramic core, the core maintains its structural integrity under extreme thermal conditions, ensuring faithful replication of the cooling channel design. Following solidification, the core is chemically etched, leaving behind a complex network of cooling channels that optimize heat dissipation and improve the blade's aerodynamic performance. The precision and quality of ceramic cores are of paramount importance, as they directly affect the turbine blade's durability, thermal efficiency, and overall performance in demanding aerospace environments. Advanced investment casting techniques, particularly those incorporating intricate ceramic cores, enable the production of hollow turbine blades with internal cooling systems. These cooling channels enhance engine efficiency by allowing higher operating temperatures while simultaneously reducing component weight and mechanical stress on the engine shaft. However, the increasing complexity of cooling channel designs presents

substantial manufacturing challenges, requiring ceramic cores with high dimensional stability, mechanical strength, and low thermal expansion. Additionally, the cores must exhibit sufficient porosity to permit chemical removal after casting. Traditional core fabrication methods, such as injection molding, are time-consuming and costly, spurring growing interest in alternative manufacturing approaches like 3D printing, which can significantly accelerate both prototyping and production [4,5]. The primary objective of this study was to perform a detailed investigation of the microstructure and selected properties of directionally solidified MAR-M247® nickel-based superalloy produced under two different withdrawal rates and two shell mold temperatures. Gaining deeper insight into the microstructure and mechanical properties of directionally solidified components immediately following solution heat treatment is crucial for understanding the influence of processing parameters and establishing the foundation for subsequent phase transformations during aging.

Materials and Methodology

Experimental castings used in this study, incorporating the gating system, were produced from the MAR-M247 nickel-based superalloy, whose chemical composition is presented in Table 1.

Table 1. Nominal chemical composition of DS MAR-M247 Ni-based superalloy, wt %.

Element	Co	W	Cr	Al	Ta	Hf	Ti	Mo	Zr	B	C	Ni
Concentration	10.0	10.0	8.40	5.50	3.0	1.4	1.1	0.65	0.05	0.015	0.15	Bal.

Directional solidification was performed in a vertical Bridgman vacuum furnace (ALD VIM-IC 2 E/DS/SC). Each ceramic mold was preheated to a specified temperature ($T_0 = 1510\text{ °C}$ or 1566 °C). The furnace was then heated to 1600 °C and held for 0.5 hours prior to initiating the withdrawal process at a predetermined rate. The pouring temperature was set at 1538 °C , resulting in T_0 being lower than the pouring temperature for variants LP3W and LP5W, and higher for variants HP3W and HP5W (Table 2).

Table 2. Directional solidification parameters of ceramic-cored MAR-M247® Ni-based superalloy.

Casting	Shell mold temperature, °C	Pouring temperature, °C	Withdrawal rate, mm/min.
LP3W	1510	1538	3.4
LP5W			5.0
HP3W	1566		3.4
HP5W			5.0

X-ray diffraction (XRD) was conducted to determine the phase composition of the castings, using a Bruker D8 Advance diffractometer ($\lambda_{\text{Co}} = 1.789\text{ Å}$). Microstructural observations were performed using a Leica DM1000 light microscope and a Phenom XL scanning electron microscope (Thermo Fisher) operating at an accelerating voltage of 20 kV. Quantitative analysis of the backscattered electron (BSE) images was carried out using ImageJ software. Given that γ' precipitates in superalloys typically exhibit a cubic morphology, their mean size in this study was expressed as the side length of a square equivalent to the precipitate area (i.e., the square root of the precipitate area).

Results and Discussion

Based on the XRD spectra, the γ matrix, intermetallic γ' phase, MC carbides, and M_5B_3 borides were identified (Fig. 1). Chemical etching revealed a typical dendritic structure (Fig. 2). Despite the heat treatment, features of the primary solidification structure remain visible. The dendritic regions (primary dendrite cores and secondary arms) exhibit a relatively homogeneous microstructure, whereas the interdendritic areas contain numerous γ - γ' eutectic islands and carbides. The solution heat treatment (SHT) ensured the dissolution of minor phases such as Ni_7Hf_2 and M_3C_2 (present in as-cast state) without causing local incipient melting.

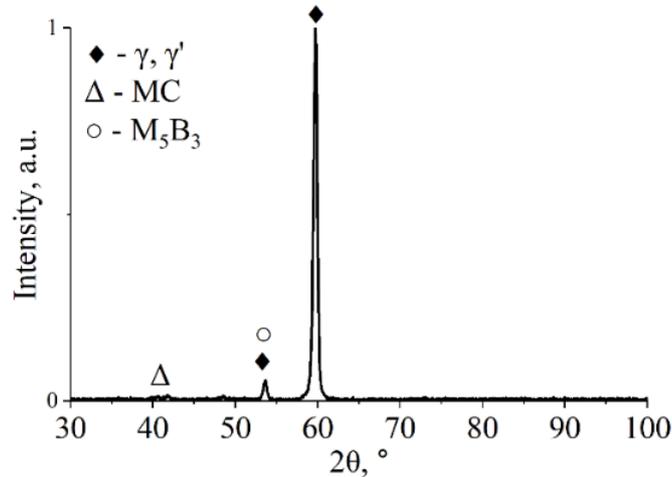


Fig. 1. X-ray diffraction pattern of the DS MAR-M247 after SHT.

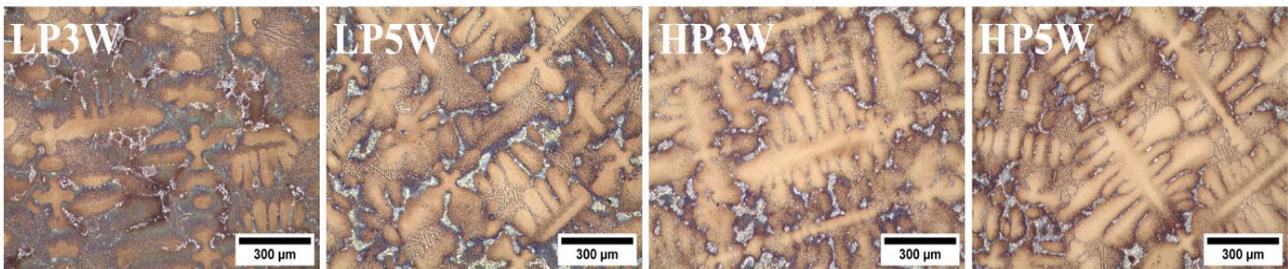


Fig. 2. Dendritic microstructure of the ceramic-cored DS MAR-M247 castings after SHT.

Primary γ' precipitates formed during directional solidification as a result of the $L \rightarrow \gamma + \gamma'$ eutectic phase transformation (Fig. 3). The presence of these precipitates remains significant even after solution heat treatment, indicating considerable aluminum enrichment in the residual liquid during solidification. Although the γ - γ' eutectic phase is undesirable, it cannot be completely dissolved in MAR-M247 during heat treatment without risking incipient melting.

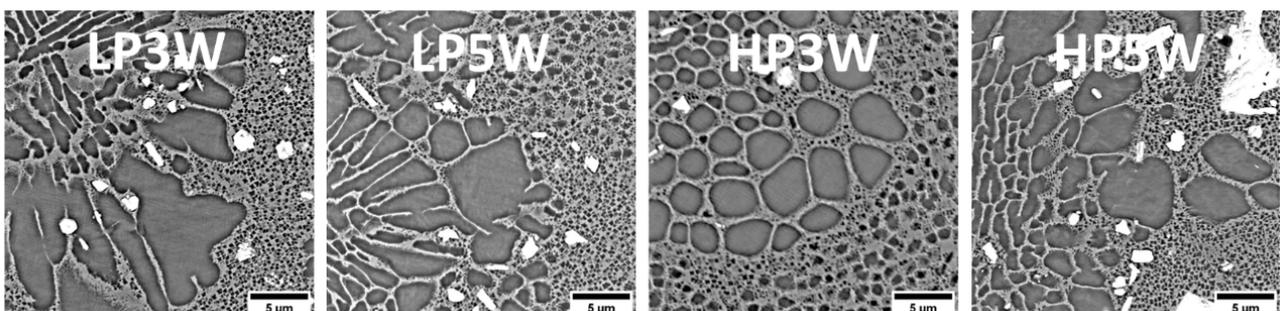


Fig. 3. Morphology of the primary γ' precipitates in the DS MAR-M247 castings after SHT.

Secondary γ' precipitates exhibit a cubic morphology, and their volume fraction in the microstructure exceeds 35% (Fig. 4). Image analysis was used to determine the size distribution of the γ' precipitates, with average sizes ranging from 0.264 to 0.272 μm . The exceptional high-temperature strength of cast nickel-based superalloys is primarily attributed to the ordered L1₂ structure of the γ' precipitates, which remain coherent with the disordered γ matrix. However, as-cast alloys are unsuitable for direct use because they often contain coarse, irregularly shaped secondary γ' precipitates, significant amounts of the γ - γ' eutectic phase, and pronounced dendritic segregation. Therefore, optimizing the morphology and distribution of γ' precipitates is essential. To enhance creep resistance, strengthening the matrix with uniformly distributed cubic γ' particles approximately 0.35–0.50 μm in size has proven particularly effective. Precise control of precipitate size and morphology can be achieved through tailored solution heat treatment and ageing.

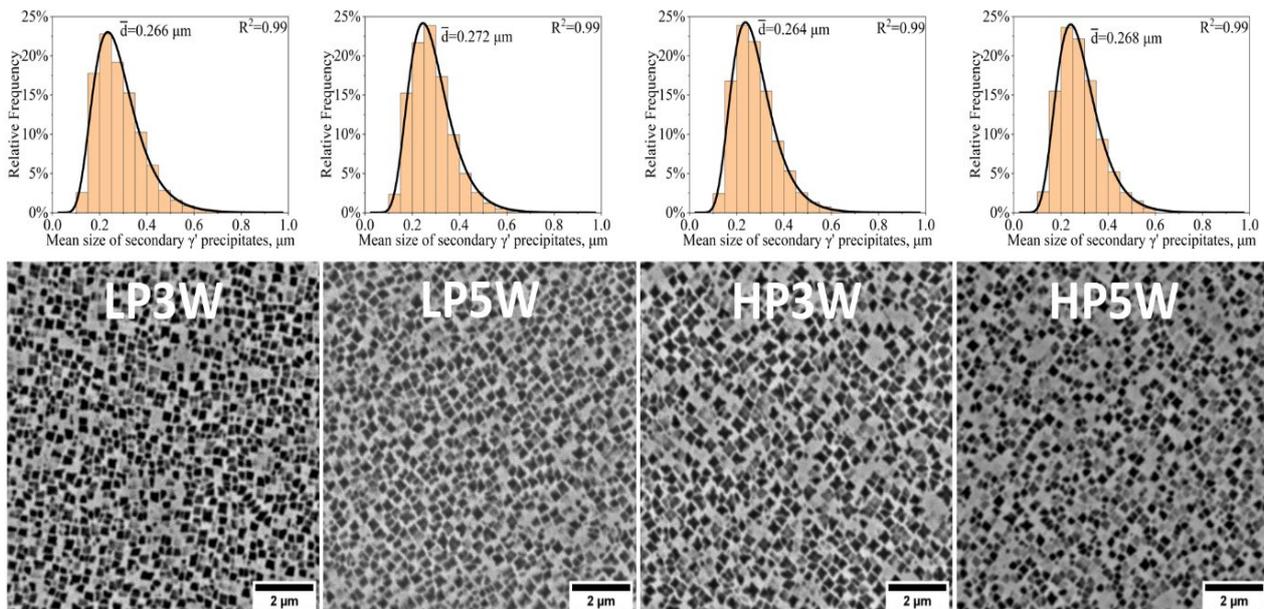


Fig. 4. Morphology of the secondary γ' precipitates in dendritic regions of the ceramic-cored DS MAR-M247 with corresponding size distribution.

The presence of alloying elements with a strong chemical affinity for carbon in MAR-M247, combined with their segregation during directional solidification, creates favorable conditions for the precipitation of minor phases within the interdendritic regions. The precipitates composed of high atomic number elements, appearing as bright-contrasted precipitates, were identified as MC carbides. These carbides exhibit diverse morphologies, including simple block-like shapes, sharp-edged parallelograms, and characteristic herringbone (Chinese-script) patterns (Fig. 5).

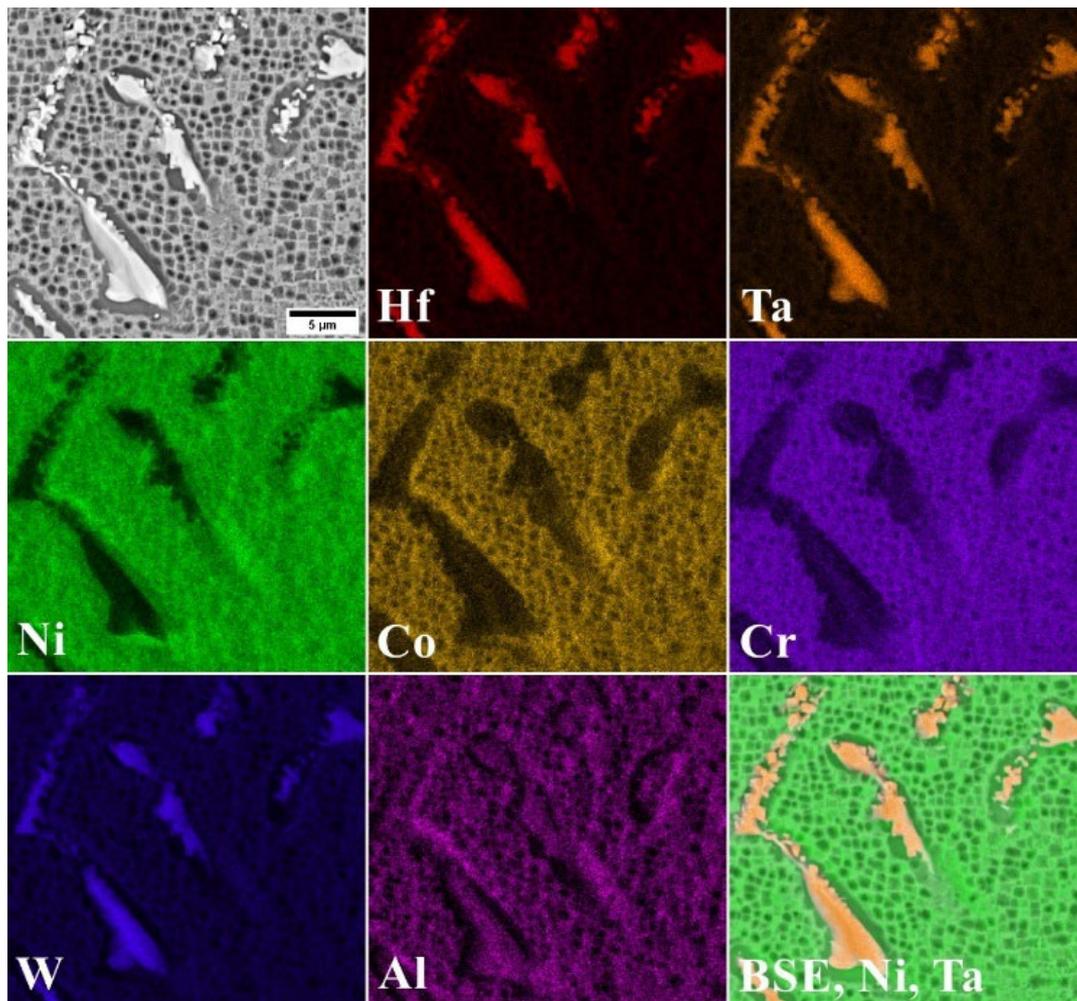


Fig. 5. Distribution of selected alloying elements in the "Chinese script" MC carbides.

Summary

In this study, the microstructure and properties of the ceramic-cored DS MAR-M247 nickel-based superalloy, produced under varying withdrawal rates and shell mold temperatures, were characterized. The following conclusions can be drawn:

- The solution heat treatment promoted partial homogenization of the dendritic structure and resulted in the complete dissolution of minor phases, with no evidence of incipient melting.
- The DS MAR-M247 nickel-based superalloy castings were free from typical casting defects such as misruns, excessive porosity, or non-metallic inclusions arising from reactions between the ceramic cores and the molten alloy.
- The applied casting parameters facilitated the formation of γ' precipitates within the dendritic regions, yielding a volume fraction exceeding 35% and an average size range of 0.264–0.272 μm .

Acknowledgments

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