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The effect of reheat treatment on microstructure and stress rupture property of a directionally solidified nickel-based superalloy after long-term thermal exposure

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ABSTRACT

The recovery of microstructure and creep properties of a directionally solidified superalloy after long-term thermal exposure was investigated. After reheat treatment, successful restoration of γ' microstructure is achieved including morphology, size and chemical composition. However, carbides degradations within interior grains and at grain boundaries are irreversible through the reheat treatment. Short and long-term creep rupture properties are effectively improved by the reheat treatment, but cannot be fully recovered compared to that of the original material. During prolonged thermal and creep exposure, grain boundary carbides degradation occurred rapidly in comparison with that in the original material, which is regarded as the main reason leading to the reduction of stress rupture lifetime.

1. Introduction

The materials applied in industrial gas turbine blades are subjected to a combination of elevated temperature, high stress and aggressive environments during long-term service, which inevitably cause various microstructural changes in the materials consisting of γ' precipitates coarsening and coalescence, primary MC carbide decomposition, formation of continuous secondary $M_{23}C_6$ carbide chains along the grain boundaries and undesirable TCP phases formation, almost all of which are detrimental to mechanical properties [1–5]. Some researchers have studied the effects of γ' size, morphology and distribution after long-term thermal exposure on creep properties in polycrystalline [6], directionally solidified [4] and single crystal superalloys [7]. The results of these studies show that long-term thermal exposure results in the increase of γ' size and particle spacing, morphology evolution from the cubic to spherical or irregular particle and misfit stress loss between the γ matrix and coherent γ' precipitates, all of which have some detrimental effects on the creep properties. Long-term thermal exposure causes irreversible microstructural deterioration consisting of MC decomposition and formation of heavy continuous coarsened $M_{23}C_6$ layer [1,4,8–11].

It is reported that the total service life of industrial gas turbine blades is beyond 50,000 equivalent operation hours (EOH) and the proper examining and repairing interval is 24,000 EOH [12]. Material deterioration and the very significant cost associated with replacement components necessitate the periodic rejuvenation of hot section components to extent their service lives.

Extensive studies have been conducted to evaluate the effect of rejuvenation procedures on microstructure and creep life recovery [8,13–19]. The success achieved in restoring creep properties by rejuvenation procedures varied widely. Some authors have reported significant creep life extension while others have found negligible improvement and some have even observed a reduction in creep life [19]. Successful rejuvenation has proven to be able to restore even severely overaged blade microstructure and mechanical properties to the level similar to new material. As reported [20,21], the most successful rejuvenation treatment consisted of a heat treatment and HIP, with creep properties being restored to 50–75% of the as-new levels. While, creep properties of polycrystalline blades cannot be restored completely by rejuvenation procedures in most studies due to some irreversible microstructural degradations [9].

After reheat treatment (RHT), including solution and aging steps, the size, morphology and distribution of multiple microstructures, consisting of γ' precipitates, carbides and grain boundary precipitates, have a significant effect on the creep properties and deformation mechanism of the gas turbine blades. Therefore, in order to effectively restore the mechanical properties of the gas turbine blades, it is necessary to study the influence of the reheat treatment on the evolution of the microstructure described above. Successful recovery by reheat treatment on γ' precipitates incorporates a complete solution

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and reprecipitation of γ′ in a size and distribution similar to that of the original microstructure. However, most related studies have focused on the recovery of γ′ appearance including size, morphology and distribution. The restoration of γ′ chemical composition, γ/γ′ coherency and stability during prolonged thermal exposure after reheat treatment are unknown. Evolution of carbides during reheat treatment is another important factor that may significantly influence the creep properties of polycrystalline and directionally solidified alloys. Although byproducts of MC decomposition such as $M_{23}C_6$ carbides and η phase can be dissolved through reheat treatment, the morphology, size and distribution of carbides vary significantly with the original materials, which may influence the microstructural deterioration and creep properties of the reheat treated alloys during prolonged thermal exposure cycle. It was reported that heavy secondary carbides such as $M_{23}C_6$ carbides reprecipitate by faster rate along grain boundaries in the rejuvenated polycrystalline alloy during prolonged thermal exposure, which sharply dropped the creep properties [1,8]. However, most studies on the reheat treatment of gas turbine blades are focused on the polycrystalline materials and related studies on directionally solidified superalloys have been seldom reported. Compared with polycrystalline materials, directionally solidified superalloys contain fewer carbides and less the number of grain boundary and grain boundary direction is parallel to the stress direction. Therefore, carbides and grain boundary microstructure evolution and deformation mechanism of directionally solidified superalloys after reheat treatment may present some differences from that of polycrystalline materials. Therefore, it is very necessary to study the influence of reheated treatment on microstructural evolution of carbides and mechanical properties of the long-term thermal exposed directionally solidified material.

It has been reported that short-term creep properties of polycrystalline blades such as GTD111 and IN738 alloy have been recovered effectively through reheated treatment [1,8,11,14]. Unfortunately, creep properties recovery of directionally solidified superalloys applied in gas turbine blades, especially for the long-term creep life recovery beyond some thousands of hours, is not clear. In the present study, reheat treatment of a directionally solidified superalloy exposed at 1173 K (900 °C) for 24,000 h has been carried on to explore the effect of reheat treatment on recovery of microstructure and long-term creep properties, taking into account the long service history of the experimental material mainly applied in industrial gas turbine blades.

2. Experimental

The composition of the nickel base superalloy DZ411 used in our present study is a typical hot corrosion resistant alloy with 14.2 Cr, 9.5 Co, 3.1 Al, 5.0 Ti, 3.0 Ta, 3.6 W, 1.5 Mo, with 0.1 C and 0.01 B, and balance Ni, in weight percent. The cylindrical specimens with the size of Φ16 mm × 220 mm were directionally solidified by the conventional Bridgman process.

The specimens received the solution and aging heat treatment, 1493 K (1220 °C)/2 h/air cooling (AC), 1393 K (1120 °C)/2 h/AC, and 1123 K (850 °C)/24 h/AC (AC: air cooling). Then the as heat-treated specimens were subjected to a long-term thermal exposure at 1173 K (900 °C) up to 24,000 h. The reheat treatment using the same parameters applied to the new alloy was conducted on the long-term thermally exposed samples. The reheat treated specimens were machined into creep specimens with gauge length of 25 mm and a gauge diameter of 5 mm to perform the creep rupture tests at 1253 K (980 °C)/220 MPa and 1123 K (850 °C)/280 MPa. In addition, a prolonged long-term thermal exposure at 1173 K (900 °C) for another 5000 h was conducted on the as new heat-treated and reheat treated alloy for the comparative investigation on the microstructural stability

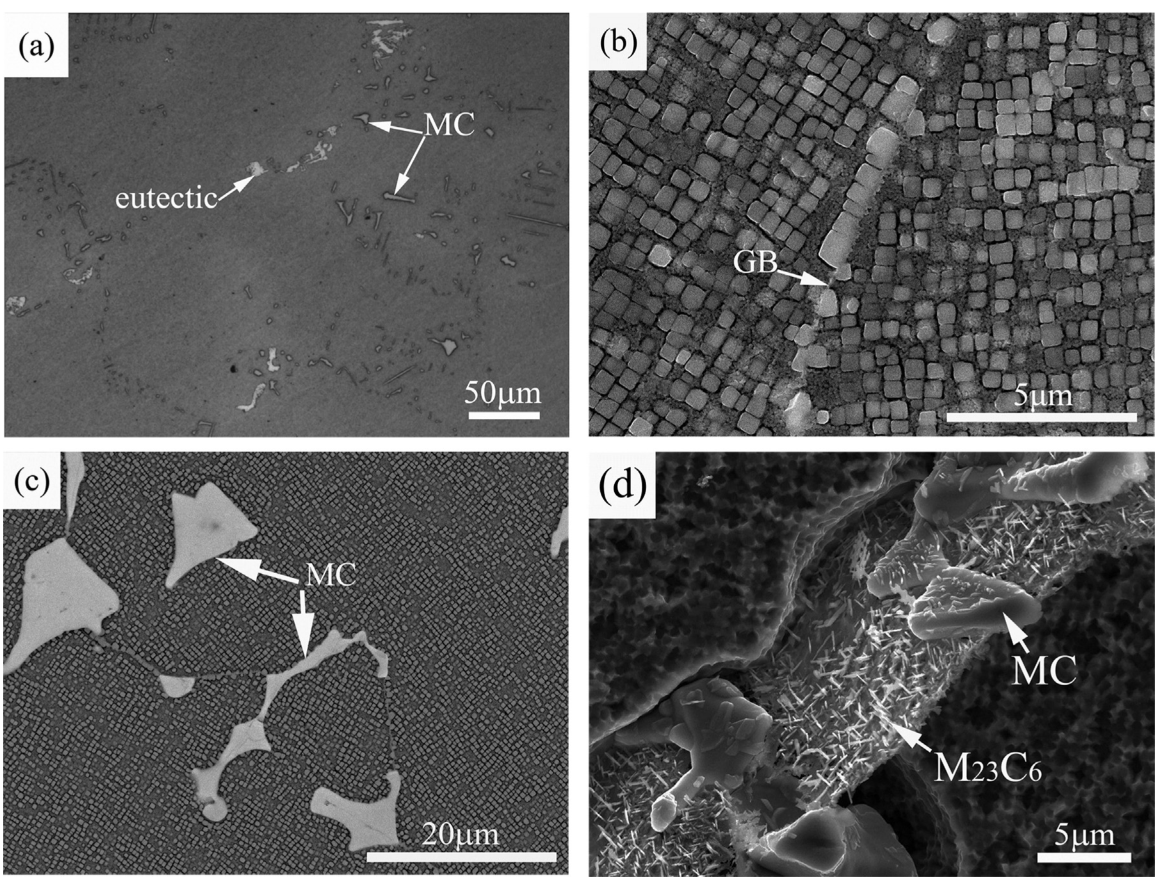

Fig. 1. Microstructure of the as heat treated alloy: (a) residual γ/γ′ eutectics and MC carbides, (b) γ′ precipitates, (c) primary MC carbides within GIs and along GBs, and (d) $M_{23}C_6$ grains near grain boundary region.