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Influence of high-temperature annealing on morphological and compositional changes of phases in Ni-base single crystal superalloy

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A B S T R A C T

Microstructure evolution during high temperature annealing of the CM186LC single crystal nickel-base superalloy in the temperature range of 900–1100 °C for up to 2500 h was investigated. Microstructural analyses were aimed at observing the changes in morphology of precipitates, in both two dimensions (2D) and three dimensions (3D). The changes in the chemical composition of constituting phases, caused by annealing, were also determined. Although no external stress was applied, after annealing at 1000 °C and 1100 °C the directional coalescence of the γ' phase in directions parallel to secondary dendrite arms occurred. In the temperature range of 900–1100 °C, decomposition of the primary MC carbides took place. The primary carbides were fragmented into small plate-shaped particles, and secondary carbides were also formed. Additionally, in the investigated temperature range, the precipitates of topologically close packed (TCP) phases were found. Those precipitates, plate-like in shape, grew up to a length of several micrometres. Coalescence of the γ′ phase and formation of TCP precipitates during high temperature exposure of CM186LC was accompanied by decreases in the concentrations of Co, Cr, W and Re in the γ phase.

1. Introduction

Single crystal Ni-base superalloys are modern high-temperature materials especially designed for gas turbine blade and vane application. Their invention was a result of both the development of directional solidification by application of the spiral grain selector and evolution of the chemical composition of superalloys strengthened by precipitates of the Ni_3Al-type γ′ intermetallic phase. Elimination of the grain boundaries allowed their creep resistance to be increased and thus the operating temperature of gas turbines to be increased. Due to the dendritic solidification, the microstructure of as-cast single crystal superalloys is not homogeneous and consists of dendrite arms, containing cuboidal γ′ phase precipitates surrounded by γ phase matrix channels, and interdendritic regions with $\gamma - \gamma'$ eutectic. To eliminate the eutectic and to homogenize the dendritic microstructure, multi-step solution annealing followed by ageing is applied. The chemical composition of single crystal superalloys is designed to maximize the volume fraction of γ′ phase precipitates and solid solution strengthening. Chemical elements which segregate to the grain boundaries, like carbon and boron, should be avoided. However, due to problems with casting defects, especially porosity and low angle grain boundaries arising in turbine vanes with thin-walled cooling channels, single crystal superalloys with improved castability were developed [1–4]. The modification of their chemical composition included the introduction of carbon and boron as well as increasing the amount of hafnium, strong carbide forming element. One representative of such alloys is the CM186LC superalloy, which is available in both columnar grained and single crystal form, called DS CM186LC and SC CM186LC, respectively. The addition of carbon and hafnium in CM186LC results in the precipitation of MC carbides.

The multiphase microstructure of the CM186LC superalloy should be stable at the high temperature working conditions of turbine blades and vanes. Microstructure evolution in DS CM186LC during annealing and creep in the temperature range of 850–1050 °C was investigated by Jo et al. [2]. They observed that the directional coalescence of γ′ precipitates, called rafting, occurs at temperatures above 950 °C. Moreover, with increases in the annealing temperature, the decomposition of primary MC carbides and precipitation of the secondary ones, which are rich in Hf, takes place. After creep at 1050 °C, topologically close packed phases (TCP) rich in W and Re were found. No TCP precipitates

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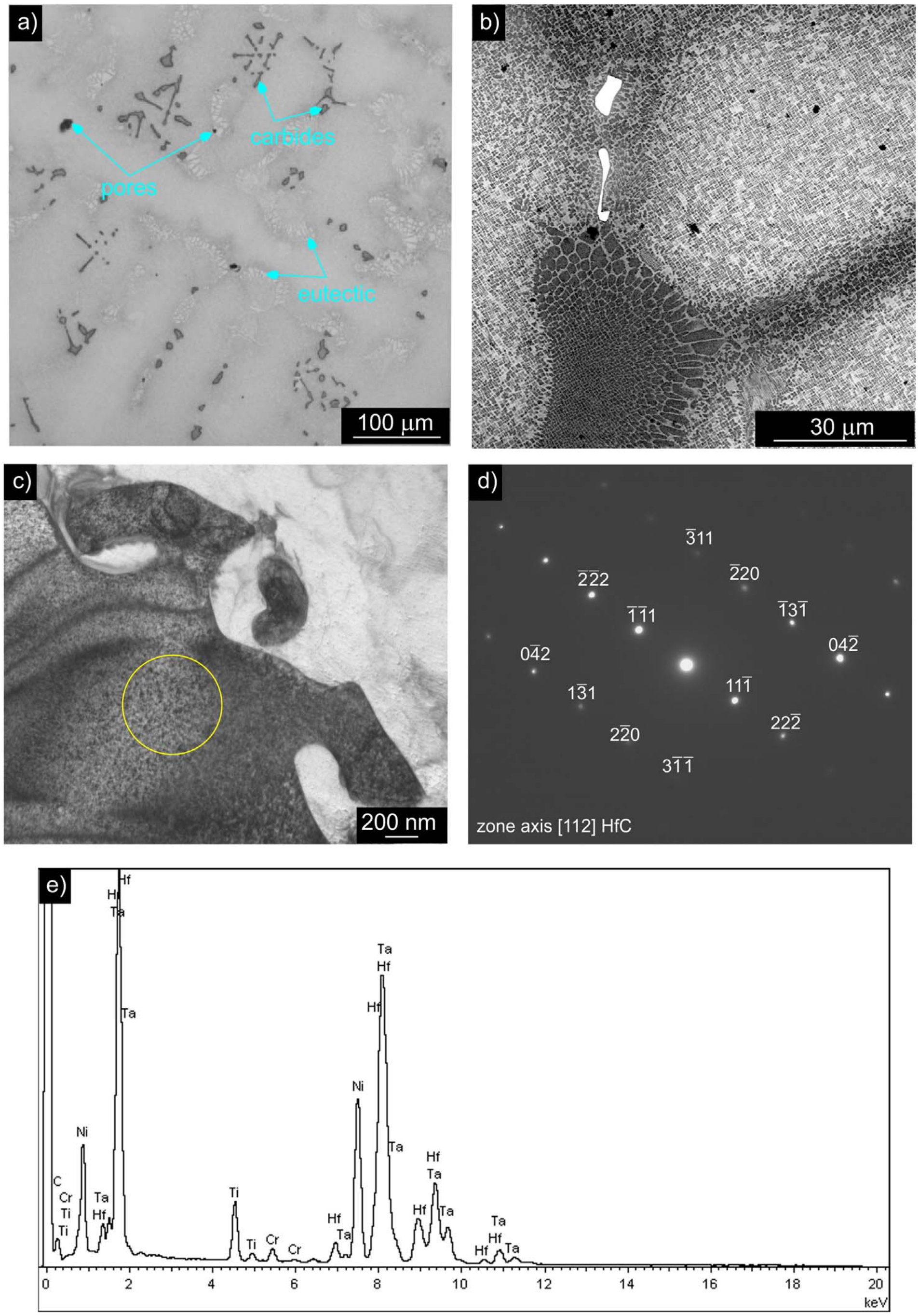

Fig. 1. Microstructure of the CM186 LC single crystal superalloy in the as-received condition after standard heat treatment: a) LM image, b) SEM image, c) TEM image of the carbide particle, d) SAED pattern from the area marked by a circle, e) EDS spectrum.

were observed in specimens creep deformed at lower temperatures and in DS CM186LC annealed in the temperature range of 950–1050 °C.

Kaciulis et al. [5] investigated the relation between the microstructure and chemical composition of the γ and γ′ phases in the CM186LC superalloy after creep at a temperature of 900 °C and stress of 220 MPa by SEM, X-ray photoelectron spectroscopy (SPEM) and scanning photoemission microscopy (SPEM). They determined that the distribution of Ni, Co, Re and Ta in the γ and γ′ phases did not substantially change after creep. The most pronounced effect was the diffusion of W from the γ to γ′ phase.

The literature reports that the microstructure of SC CM186LC was investigated after standard heat treatment and high temperature creep [2–10]. However, it is important to thoroughly examine the microstructure evolution in SC CM186LC during high temperature annealing without external stress up to a temperature of 1100 °C, and to determine the associated changes in the chemical composition of constituting phases. Therefore, the aim of the present work was to investigate the microstructure and chemical composition changes in micro-areas of the single crystal CM186LC annealed in the temperature range of 900–1100 °C, up to 2500 h, by combination of analytical electron microscopy, electron tomography and X-ray diffraction.