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Effect of carbon content on the recrystallization of a single crystal nickel-based superalloy

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ABSTRACT

Carbon has recently been reintroduced to single crystal (SX) superalloys because of its beneficial effects, such as reducing the occurrence of casting defects and enhancing the tolerance of low angle grain boundaries. Meanwhile, the addition of carbon leads to changes in the carbide morphology and volume fraction and may subsequently affect the recrystallization (RX) behavior. The purpose of this paper was to identify the effect of the carbon content on RX in an SX nickel-based superalloy. The SX specimens were prepared with an identical crystal orientation but different carbon contents. It was found that with the increase of the carbon content from 0.012 wt% to 0.17 wt%, the volume fraction of carbides increased linearly, while the average size of the carbides was nearly unchanged. After shot peening and heat treatment, a layer of RX grains was generated on the surface. As the carbon content was increased, the RX depth increased at first and later decreased. These changes were interpreted as the combined effect of the carbides on the stored energy during deformation and the pinning force during RX grain growth.

1. Introduction

As plastic deformation is introduced into directionally solidified (DS) components during casting, grinding or shot peening, recrystallization (RX) will occur easily during high temperature heat treatment or service [1]. The mechanical properties of DS, especially single crystal (SX), components are dramatically affected by the transverse grain boundaries introduced by RX grains [2–6].

According to our previous studies, carbides play different roles on RX nucleation and grain growth in DS alloys depending on the deformation level and annealing temperature [7,8]. Carbides could initiate RX nucleation by a particle-stimulated nucleation (PSN) mechanism in areas with a low level of deformation or during low temperature annealing, while RX grain growth would be annihilated by carbides in areas that are less deformed [7]. Considering the popularity of added carbon currently, it is desirable to determine the effect of the carbon content on the RX in SX superalloys.

In this paper, different amounts of carbon were added to an experimental SX superalloy. All of the samples were carefully prepared with identical crystal orientation. The effect of the carbon addition on the carbide morphology, size, volume fraction and RX depth was investigated and analyzed in detail.

2. Materials and experimental procedure

The nominal composition of the experimental alloy is 9Cr, 10Co, 7 W, 2Mo, 4Al, 3Ti, 3Ta and the remainder Ni (wt%). A master alloy free of carbon was cast using a vacuum induction melting furnace, and then different amounts of carbon were added to the master alloy during DS casting using the liquid metal cooling (LMC) method. The resulting SX bars with 0.012 wt%, 0.045 wt%, 0.096 wt%, 0.12 wt% and 0.17 wt% carbon were named LS1, LS2, LS3, LS4 and LS5, respectively.

In the SX bars of different carbon contents, cross sections approximately 7 cm from the crystal selectors were grinded and fine polished. Five backscattered scanning electron microscope (SEM) micrographs with areas of $300 \times 400\ \mu m^2$ were taken from each sample at a magnification of $500\times$, and the size and volume fraction of the carbides in each alloy were analyzed.

Samples $10 \times 10 \times 15\ mm^3$ in size were cut along the DS direction with the $10 \times 15\ mm^2$ plane parallel to the (010) plane to avoid crystal orientation effects. All the samples were cut approximately 7 cm from the crystal selectors. The samples were shot peened (0.4 MPa, 100 s) on a surface of the (010) plane, then heat treated at 1240 °C for 2 h in sealed silicon tubes ($\varnothing 20 \times 100\ mm^2$) filled with argon. Subsequently, the samples were cut vertical to the DS direction, and the depths of the surface RX were measured every 100 μm along the surface to obtain the average RX depths. All the samples were observed by an optical microscope (OM) and an SEM equipped with EDX.

3. Results and discussion

The morphology of the carbides in the as-cast alloys with different carbon contents is shown in Fig. 1. Almost no carbides

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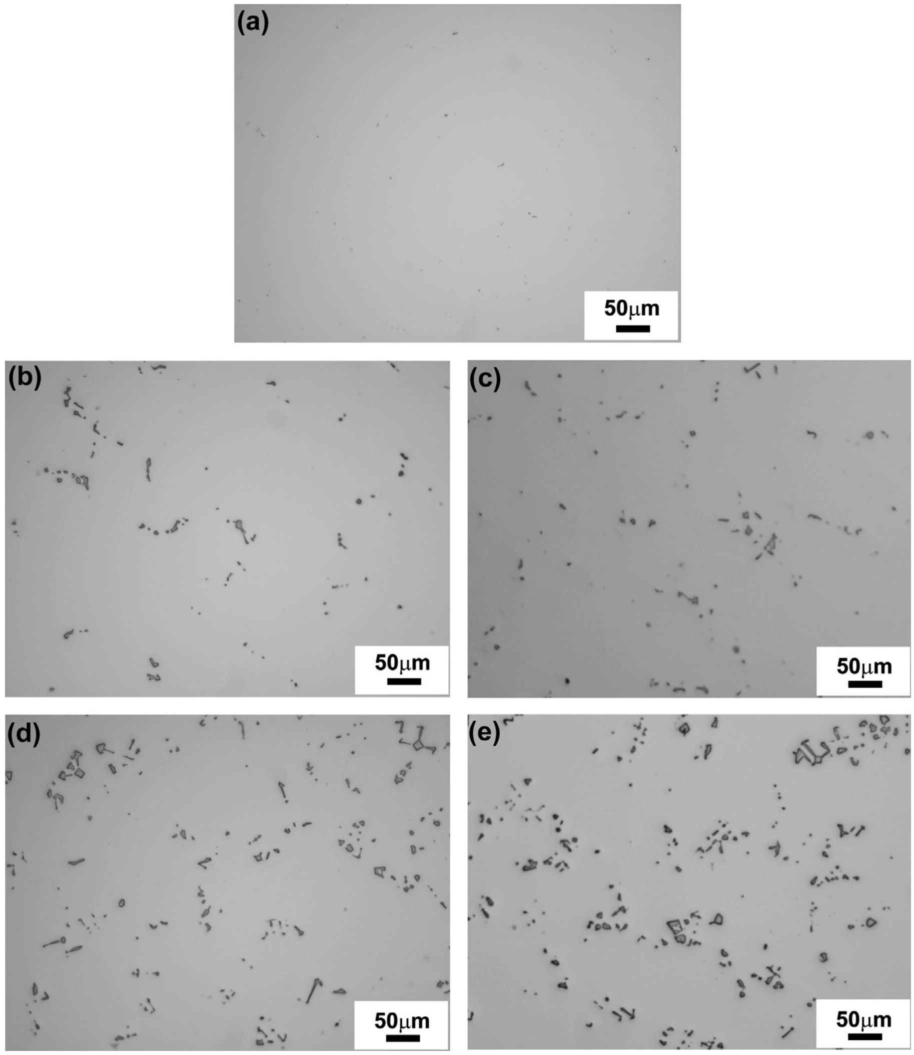

Fig. 1. Carbide morphology in as-cast alloys with different carbon contents: (a) LS1: 0.012 wt%, (b) LS2: 0.045 wt%, (c) LS3: 0.096 wt%, (d) LS4: 0.12 wt%, and (e) LS5: 0.17 wt%.

Table 1
Size and volume fraction of the carbides in the different alloys.

Alloy	LS1	LS2	LS3	LS4	LS5
Average diameter (μm)	–	1.98 ± 1.35	1.96 ± 1.19	2.19 ± 1.45	2.68 ± 1.59
Volume fraction (%)	–	0.39 ± 0.21	0.70 ± 0.08	1.20 ± 0.21	2.03 ± 0.22

were observed in alloy LS1 (Fig. 1a). A small amount of blocky carbides was observed in alloy LS2 (Fig. 1b). More carbides precipitated as more carbon was added. As seen in Fig. 1b–e, most of the carbides remain blocky. According to the EDX results, all the carbides were confirmed to be MC-type carbides containing Ti and Ta.

The size and volume fraction of the carbides in the different alloys are listed in Table 1. The average diameter of the carbides was approximately 2 μm in alloys LS2, LS3 and LS4, and it increased to 2.68 μm in the LS5 alloy. The volume fraction of the carbides increased linearly from 0 to 2.03% with increasing carbon content.

As shown in Fig. 2, after 2 h annealing at 1240 °C, no residual eutectics were observed in all the experimental alloys. A layer of RX grains was generated on the surface of each sample. Pinning of the RX grain boundaries by the carbides was observed in alloys with high carbon content (Fig. 2f).

The RX depths from the sample surface were measured and are summarized in Fig. 3. The RX depths increased from approximately 20 μm to 30 μm with the increase of carbon from 0.012 wt% to 0.096 wt%. Further increases of the carbon content led to a decrease of the RX depth (approximately 24 μm in the alloy containing 0.17 wt% carbon).

With the change of carbon content, different amounts and sizes of carbides were generated in the as-cast samples (Fig. 1). After deformation and 1240 °C annealing, as mentioned in [7], carbides were the sole remaining second phase particles. Therefore, the different RX depths mainly resulted from the different carbon contents. The effect of the second phase particles on the RX behavior was summarized by Humphreys [9]: (a) large particles may act as nucleation sites for RX; (b) closely spaced particles have a significant pinning effect on the grain boundaries and (c) the stored energy and hence the driving force for RX may be increased.

First of all, according to the previous study on the DS version of the experimental alloy, RX occurred rapidly in dendritic core regions at 1240 °C, though the carbides are large enough to stimulate RX by a PSN mechanism [7].