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The influence of Al elements on the structure and the creep behavior of $Al_xCoCrFeNi$ high entropy alloys

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ABSTRACT

The microstructure, crystal structure, creep behavior and mechanism of $Al_xCoCrFeNi$ (x is in molar ratio) high entropy alloys were examined. The low Al content of $Al_{0.15}CoCrFeNi$ alloy had single FCC structure with columnar cell microstructure, while the high Al content of $Al_{0.60}CoCrFeNi$ alloy contained FCC+BCC duplex crystal structure with columnar dendrite microstructure. The creep property, evaluated by stress relaxation test, showed that the $Al_{0.15}CoCrFeNi$ alloy had a higher creep resistant property than that of the $Al_{0.60}CoCrFeNi$ alloy. The creep constitutive equation for the $Al_{0.15}CoCrFeNi$ alloy was established with an average stress exponent of 5.56 and an average activation energy of 385 kJ mol^{-1}, while it was with a larger average stress exponent of 8.82 and a smaller average activation energy of 334 kJ mol^{-1} for the $Al_{0.60}CoCrFeNi$ alloy. The analysis of apparent activation volume reveals that both alloys were in a rate limiting mechanism of cross-slip. Then, the higher stacking fault energy of the $Al_{0.60}CoCrFeNi$ alloy was considered to result in its higher creep rate. Therefore, it was concluded that the increased Al element tended to reduce the creep resistant property of the $Al_xCoCrFeNi$ alloys by increasing the stacking fault energy.

1. Introduction

High entropy alloy (HEA) is a new concept alloy, which is considered as a potential high-temperature material [1,2]. Several HEAs have been demonstrated excellent property at elevated temperature, such as good thermal stability [3], remarkable compressive strength [4], etc. The $Al_xCoCrFeNi$ (x is in molar ratio) alloys are typical HEA which have been widely studied [5–7] on microstructure, mechanical performance, electrical property, etc., but its creep resistant property was rarely reported. In the current paper, the creep properties of the $Al_xCoCrFeNi$ alloys are explored by using stress relaxation test (SRT) proposed by Woodford et al. [8] with the consideration of Al element. The stress exponent (n) and the activation energy (Q) were calculated to establish the creep constitutive equation, and the apparent activation volume (V^*) and stacking fault energy (SFE) were used for deformation mechanism analysis.

2. Materials and methods

The studied $Al_xCoCrFeNi$ alloys with different Al content were designed by referring article [5]. It was prepared in vacuum induction smelting furnace with 99.9% pure raw materials. The well mixed ingots with dimension of $110 \times 110 \times 20\ mm^3$ were finally obtained after 5 more times re-melting process. The whole procedure was executed under pure the argon atmosphere. The final compositions of these ingots are $Al_{0.15}CoCrFeNi$ (denoted as $Al_{0.15}$) and $Al_{0.60}CoCrFeNi$ (denoted as $Al_{0.60}$).

The microstructure was observed by Zeiss supra 55 scanning electron microscope after etching in Aqua-regia. The crystal structure was analyzed by X-ray diffractometer (XRD, Cu target) under voltage of 30 kV and current of 40 mA, the diffraction angle (2θ) ranged from 20° to 100° at a rate of 4 deg.min^{-1}.

To ensure the uniformity of microstructure, the samples for SRT were cut from the center of the ingots with a diameter of 5 mm and a gauge length of 25 mm. SRT was executed at 0.20% strain for 4 h on electromechanical universal testing machine. The loading strain rate was $8 \times 10^{-5}\ s^{-1}$. Generally, the common materials, such as SUPER304H and HR3C heat resistant steels, are often tested at temperature above 0.5 melting temperature (0.5Tm, ~600 °C) in their creep strength design test. Based on this, the test temperature was set at 580–700 ± 1 °C around 0.5Tm and above 0.3Tm.

3. Results and discussion

Fig. 1 shows the microstructure and the XRD patterns of the $Al_{0.15}$ and the $Al_{0.60}$ alloys. The $Al_{0.15}$ alloy in Fig. 1a shows the

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columnar cell microstructure, whereas the $Al_{0.60}$ alloy in Fig. 1b displays a columnar dendrite microstructure. The XRD patterns in Fig. 1c reveal that the $Al_{0.15}$ alloy has single FCC structure and the $Al_{0.60}$ alloy has FCC+BCC mixed structure. It indicates that the increase of Al element inclines to form BCC structure and dendrite microstructure.

The SRT's results of the $Al_{0.15}$ and the $Al_{0.60}$ alloys are shown in Fig. 2a and b, respectively. It is seen that the $Al_{0.15}$ alloy has a lower relax rate than that of the $Al_{0.60}$ alloy. At high temperature, the total strain (ϵ_t) during SRT is divided into elastic deformation (ϵ_e) and creep deformation (ϵ_c) as $\epsilon_t=\epsilon_e+\epsilon_c=0.20\%$. Therefore, the creep rate ($\dot{\epsilon}_c$) can be deduced as follows:

$$\dot{\epsilon}_c = -\dot{\epsilon}_e = -\frac{1}{E}\frac{d\sigma}{dt} \quad (1)$$

where, $\dot{\epsilon}_e$ is the elastic deformation rate, σ is stress, t is test time, and E represents elastic modulus

By Eq. (1), the response of $\sigma - t$ was converted into relationship of $\dot{\epsilon}_c - \sigma$ shown in Fig. 2c. The $Al_{0.60}$ alloy displays a higher creep rate than that of $Al_{0.15}$ alloy under the same stress. Normally, the

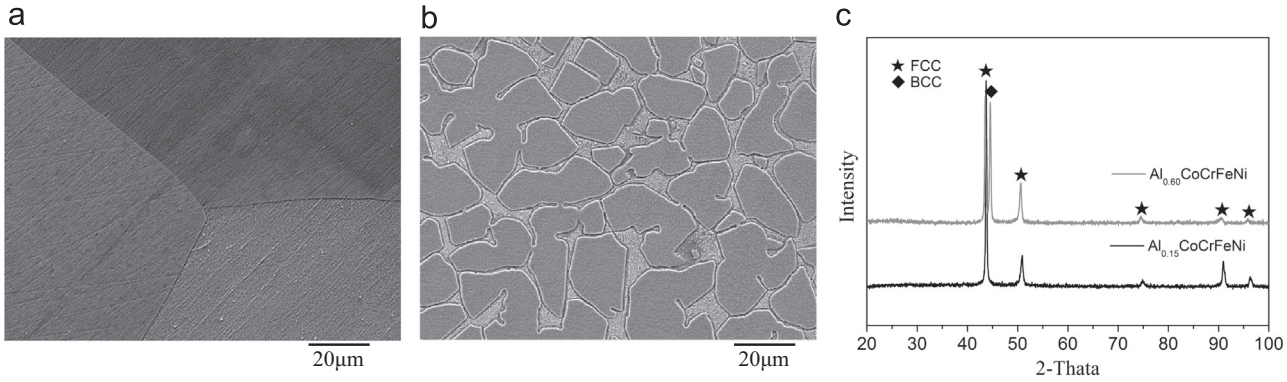

Fig. 1. SEM micrographs of (a) $Al_{0.15}$ and (b) $Al_{0.60}$ alloys. (c) XRD patterns.

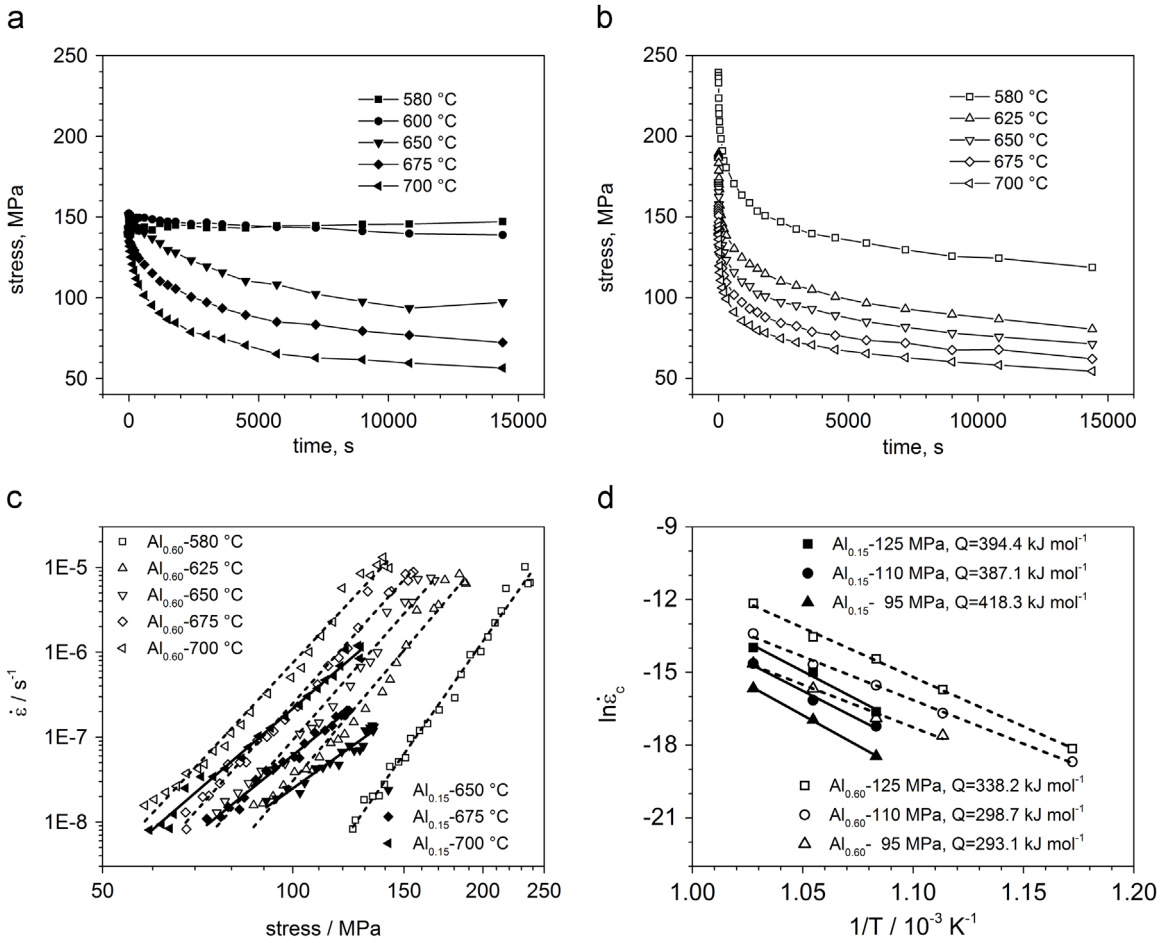

Fig. 2. Stress relaxation curves of (a) $Al_{0.15}$ and (b) $Al_{0.60}$ alloys. (c) Stress versus creep rate curves. (d) Relationship between $\ln \dot{\epsilon}_c$ and $1/T$.