Abstract

The effect of cooling rate ($10\text{-}10^4$ K/s) on the microstructure evolution in terms of volume fraction of the phases, lamellar spacing, secondary dendritic arm spacing, as well as the mechanical properties of ingots and rods of 2-5 mm diameter (Ø) of $(Ni_{0.92}Zr_{0.08})_{100-x}Al_x$ ($0 \leq x \leq 4$ *at.*%) nano-/ultrafine eutectic composites (NECs), have been investigated. The microstructure of the NECs is comprised of micrometer size 20-31 vol.% of γ-Ni dendrites embedded in a lamellar fcc γ-Ni and Ni_5Zr matrix with varying average lamellae thickness (λ_w) of 39 nm – 275 nm. All these NECs exhibit high hardness up to 4.6 GPa, and yield strength up to 1.6 GPa with large compressive plasticity up to 22% at room temperature. Furthermore, the strain rate sensitivity (m) lies between 0.0080 and 0.0102, whereas the activation volume (V^*) has been estimated to be between $29.7b^3$ and $49.8b^3$ in the strain rate range of 8×10^{-5} /s and 8×10^{-3} /s at room temperature. High-resolution transmission electron microscopy studies confirm the dislocation mediated plastic flow including dislocation-lamellae interaction, and their pile-up at the interface. A mathematical model has been developed to correlate the m with λ_w for the experimented NECs with wide microstructure length scale and solute content. High-temperature in-situ x-ray diffraction analysis suggests that the coefficient of thermal expansion (α) of these eutectic phases are similar and the lamellar morphology is stable even up to 1000 °C. Transmission electron microscopic studies revealed the evolution of 2-15 nm size $L1_2$–type precipitates in annealed $x = 4$, which exhibited improved yield strength and bulk hardness. The strain hardening behavior of the precipitation hardened NECs has been analyzed using extended Kocks–Mecking-Estrin model to explore the underlying mechanism of dislocation-precipitate interaction. In addition the oxidation behavior of the NECs have been investigated at 500-900 °C up to 120 h of exposure. The specific mass gain (Δw) is low and varies between 0.91 mg/cm^2 ($x = 1$) and 1.67 mg/cm^2 ($x = 4$) at 500 °C, and between 10.36 mg/cm^2 ($x = 0$) and 11.20 mg/cm^2 ($x = 2$) at 900 °C. The mass gain has increased with temperature ue to the enhanced diffusivity of the ions in presence of large fraction of the lamellae interface and lamellae refinement upon Al addition. The oxide scale is comprised of mainly NiO, which forms at the scale/air interface due to the oxidation of Ni_5Zr and the reaction between outwardly diffused Ni-ions with oxygen. The oxidation kinetics follow nearly parabolic at 500 °C exhibiting the rate exponent $n = 0.45\text{-}0.56$ and sub-parabolic ($n = 0.21\text{-}0.37$) in the temperature range 600-900 °C, causing decrease of Δw with exposure time, which is lower than that of eutectic superalloys. The mechanism of oxidation of the NECs, and the mass gain are explained considering the phase fraction and Δw of individual eutectic phases using an analytical model.

Keywords: Ni-alloys; Nanoeutectic; Cooling rate; Casting; Lamellar microstructure. Transmission electron microscopy (TEM); Dislocations; Precipitation hardening; Mechanical properties; Strength; Strain hardening; Oxidation, Diffusion.