Materials Science and Engineering A 532 (2012) 536–542

Contents lists available at SciVerse ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Effect of γ_2 phase evolution on mechanical properties of continuous columnar-grained Cu–Al–Ni alloy

Z. Wang, X.F. Liu, J.X. Xie*

Key Laboratory for Advanced Materials Processing (MOE), University of Science and Technology Beijing, Beijing 100083, China

ARTICLE INFO

Article history:
Received 21 July 2011
Received in revised form 2 November 2011
Accepted 3 November 2011
Available online 11 November 2011

Keywords:
Shape memory alloy
Continuous columnar grain
γ_2 phase
Heat treatment
Martensitic transformation

ABSTRACT

Effect of γ_2 phase evolution on mechanical properties of Cu–14%Al–3.8%Ni (mass fraction) alloy wires fabricated by continuous unidirectional solidification technology was investigated before and after heat treated at 700–780 °C. Mechanism for the improvement of mechanical properties of the alloy was analyzed. It was found that the alloy retained continuous columnar grains after heat treatment. With the heat treatment temperatures increasing from 700 °C to 770 °C, the coarse dendrite γ_2 phase evolved into the fine polygonal, ellipsoidal and spherical particles in the grains, while the long-banding, discontinuous block and ellipsoidal particles at the grain boundaries. The average size of the γ_2 phase decreased from 20 μm before heat treatment down to 2 μm, and its amount reduced from 50.0% down to 0.8%. The γ_2 phase was full dissolution at 780 °C. The tensile strength of the alloy treated at 700–780 °C ranged from 577 MPa to 710 MPa. The elongation of the alloy ranged from 7.5% to 23.8% and had a peak value at 760 °C. Excellent balance between strength and elongation could be obtained when the spherical γ_2 phase was distributed throughout the alloy with the size smaller than 5 μm and the amount in the range of 11.4–16.6%. The nano-hardness and elastic modulus of the γ_2 phase decreased gradually with the reduction of the amount, leading to the improvement of mechanical properties.

1. Introduction

In recent years, Cu–Al–Ni shape memory alloys (SMA) have attracted an increasing attention due to their low cost, excellent aging stability and thermal stability as well as higher operating temperature [1,2]. However, the engineering application of the alloy has been restricted seriously because equiaxed polycrystalline Cu–Al–Ni alloy is prone to intergranular fracture during plastic deformation due to the large grain size and the existence of brittle γ_2 phase [3]. Among the manufacturing methods available for improving mechanical properties of the alloy, the continuous unidirectional solidification technology is generally accepted as one of the most effective routes, which is based on the special competitive growth mechanism of crystal and can generate cast products with a beneficial texture [4]. Therefore, the highly oriented grains are deformed coherently under the axis load, which is helpful to avoid severe stress concentration at the grain boundaries. At present, columnar-grained Cu–Al–Ni alloy wires and pipes have been successfully fabricated by continuous unidirectional solidification technology [5–7].

In the study of grain refinement for Cu–Al–Ni alloy after high-temperature deformed, it was noted that the equiaxed grain growth during subsequent hot-working or heat treatment was retarded by the spherical γ_2 particles (about 5 μm), which is distributed throughout the microstructure. Meanwhile, the fine γ_2 phase would not be expected to have a harmful effect on the mechanical properties of the alloy [8]. Nevertheless, when the solidification rate of the alloy was slow, namely the alloy had a poor cooling ability, numerous coarsely block and dendritic γ_2 phase (about 10–15 μm) would be precipitated easily in the grains or at the grain boundaries of the alloy. This leads to the enlargement of the grain boundary embitterment and the degradation of mechanical properties [9]. It is demonstrated that the variation of the distribution, amount, size, and shape of the γ_2 phase obtained under different conditions plays distinct roles on mechanical properties of Cu–Al–Ni alloy. In order to accurately control the γ_2 phase and mechanical properties of the continuous columnar-grained Cu–Al–Ni alloy, it is necessary to study the evolution of the γ_2 phase and clarify the influence of this evolution on the mechanical properties of the alloy.

This paper focuses on the evolution of the γ_2 phase and corresponding mechanical properties of continuous columnar-grained Cu–14%Al–3.8%Ni (mass fraction) alloy wires before and after heat treatment (HT). The mechanism for the improvement of mechanical properties of the alloy was analyzed, thus to provide basis for accuracy control and reasonable utilization of the γ_2 phase in the Cu–Al–Ni alloy.

* Corresponding author. Tel.: +86 10 62332254; fax: +86 10 62332253.
E-mail address: jxxie@mater.ustb.edu.cn (J.X. Xie).

0921-5093/$ – see front matter
doi:10.1016/j.msea.2011.11.019

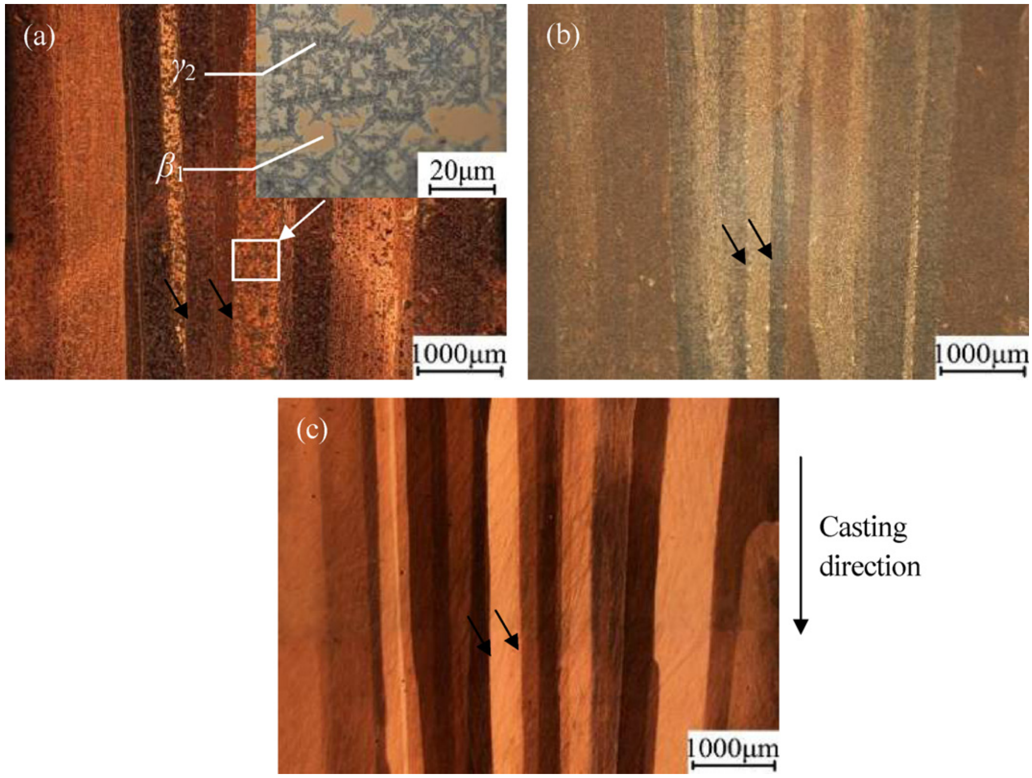

Fig. 1. Microstructures in longitudinal cross sections of the alloy wires, in which the black arrows show the columnar-grained boundaries: (a) as-cast, (b) 700 °C, and (c) 780 °C.

2. Experimental procedure

Cu–14 wt.%Al–3.8 wt.%Ni alloy wires with a diameter of 6 mm and smooth surface were prepared from pure Cu, Al and Ni of 99.99% purity by using the vacuum melting and argon-shield vertical continuous unidirectional solidification equipment [7]. The investigated alloy was heated to a given temperature in a box-type resistance furnace and then quenched into room temperature water. Since phase in the alloy is difficult to be adjusted at a low temperature and the alloy oxidizes easily at a high temperature, the HT temperatures were set at 700, 730, 750, 760, 770 and 780 °C, respectively. In order to improve the efficiency of heat treatment and realize the on-line heat treatment in the future, the holding time was kept for 1 min.

Phase composition of the alloy was determined by an X-ray diffractometer (XRD) with an operated voltage of 40 kV, a current of 150 mA and a scanning speed of 10°/min. The spatial group, the lattice parameters and the atom positions of the γ_2 phase (Cu_9Al_4, $P\bar{4}3m$, $a = 0.8720$ nm, $\alpha = \beta = \gamma = 90°$), β_1 phase (DO_3, $Fm\bar{3}m$, $a = 0.5822$, $\alpha = \beta = \gamma = 90°$), β_1 martensite phase ($18R_1$, $C2/m$, $a = 3.8190$ nm, $b = 0.5190$ nm, $c = 0.4490$ nm, $\alpha = \gamma = 90°$, and $\beta = 89.7°$), γ_1' martensite (2H, $Pmmn$, $a = 0.5342$ nm, $b = 0.4224$ nm, and $c = 0.4390$ nm) and α_1' martensite (DO_{22}, $I4/mmm$, $a = 0.3590$ nm, and $c = 0.7550$ nm) were determined referring to Refs. [10–12]. The martenstic transformation (MT) temperatures (M_f, M_s, A_s, A_f) of the alloy treated at different HT temperatures were measured using a differential scanning calorimeter (DSC) with a cooling rate and heating rate of 10 °C/min. Optical microscopy (OM), transmission electron microscopy (TEM) and scanning electron microscopy (SEM) equipped with an energy dispersive spectrometer (EDS) were employed to characterize the microstructures, the fracture morphologies and the composition in the remaining β_1 phase of the alloy. Uniaxial tensile tests at room temperature were performed along the axial direction of the alloy wire at a rate of 0.02 mm/s, using a MTS810 testing machine. The hardness and elastic modulus of the γ_2 phase under different conditions were determined by a Nano Indenter II micro-mechanical probe.

3. Results

3.1. Effect of heat treatment temperature on evolution of the γ_2 phase of Cu–Al–Ni alloy

Fig. 1 shows the microstructures of the continuous columnar-grained Cu–Al–Ni alloy wires before and after heat treatment. It can be seen that the alloys treated at 700 °C and 780 °C retain columnar grains, and the grain boundaries (marked by the black arrows in Fig. 1) are clear and straight. The average grain size of the heat-treated alloy is about 440 μm, which is identical with that of the as-cast alloy. This implies that the grain size has no effect on the mechanical properties of the alloy in this study. From Fig. 2, the as-cast alloy consists of mainly β_1 phase and γ_2 phase. The γ_2 dendrite phase is in a dense distribution with the amount of 55.7%, and the average dendrite-arm span is about 20 μm (Fig. 1a).

Fig. 3 shows the morphologies of γ_2 phase in Cu–Al–Ni alloy wires at different HT temperatures. When the HT temperature is 700 °C, one can see that most of the coarse γ_2 dendrite phase in the grains evolves into the fine ellipsoidal particles, usually in the size of 2–5 μm, while a small amount of it is transformed into the polygonal structure with a size range of 5–9 μm. At the grain boundaries, the dendritic γ_2 phase are accumulated to the long-banded structure and their longitudinal axis is in accordance with casting direction, which may cause significant anisotropic properties. With the HT temperature increasing from 730 °C to 770 °C, the polygonal γ_2 phase in the grains is further changed into the ellipsoidal and spherical particles, and the long-banded ones at the grain boundaries evolve into the discontinuous block and