Scripta Materialia 149 (2018) 16–20

Contents lists available at ScienceDirect

Scripta Materialia

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

Regular article

Comparison of tensile properties between nanotwinned and nanograined CuAl alloys

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ARTICLE INFO

Article history:
Received 13 December 2017
Received in revised form 25 January 2018
Accepted 25 January 2018
Available online xxxx

Keywords:
Nanograin
Nanotwin
Tensile
Strength
Ductility

ABSTRACT

Both nanotwinned and nanograined samples were prepared in a CuAl alloy by means of plastic deformation. Tensile tests showed that the nanotwinned sample exhibits a high yield strength of ~357 MPa and a considerable uniform elongation of 18% while the nanograined sample has ultra-high strength of ~758 MPa with a very limited uniform elongation of 1.4%. The lower yield strength and higher ductility in the nanotwinned sample were discussed based on its deformation mechanism.

Nanostructured materials have attracted considerable attention in the past decades due to their unusual mechanical properties. Numerous experimental results showed nanograins usually have high strength and hardness but with a very limited ductility [1–4]. By contrast, the nanotwins induced by deposition and plastic deformation exhibit inconsistent mechanical properties. The deposited nanotwins have high strength and good ductility while strain-induced nanotwins exhibit relatively low strength and very limited ductility [5–9]. For example, the electrodeposited nanotwinned copper with the average twin/matrix (T/M) lamella thickness of 15 nm has a tensile yield strength of ~900 MPa and a uniform elongation of ~8.0%. Its yield strength is as high as that of nanograins with the same size and follows the Hall-Petch relation [6]. Nevertheless, the slope of Hall-Petch relation in the nanotwinned Fe-Mn steel prepared by dynamic plastic deformation (DPD) is lower than that of the nanograined one [8]. The uniform elongation of the DPD nanotwinned 316L stainless steel is <2%, similar to nanograins [9].

So far, the mechanical properties of strain-induced nanotwins is still unclear because the reported relevant investigations focus on the nanotwinned sample mixed with ~20–80 vol% nanograins and/or dislocation structure regions that could not present the intrinsic mechanical properties of deformation nanotwins [8–13]. Hence, the present challenge of the investigations on the mechanical properties of strain-induced nanotwins is to prepare the whole nanotwinned sample. In this work, surface mechanical grinding treatment (SMGT) was used to process a low stacking fault energy CuAl alloy, in which both nanograined and nanotwinned layers were obtained due to the gradient distribution of strain and strain rate along the depth. The nanograined and nanotwinned layers were removed from the SMGT sample, respectively, to investigate their mechanical properties.

The Cu-4.5 wt% Al alloy used in this work was annealed at 850 °C for 120 min to obtain homogeneous coarse grains (average size ~70 μm). The cylindrical samples with a diameter of 10 mm and a length of 20 mm were processed by using SMGT at ~173 K, the detailed principle of which was described in [14]. During the SMGT processing, the cylindrical sample rotates at a velocity of 360 rpm with respect to a hemispherical WC/Co tool tip with a radius of 3 mm. With a preset penetration depth of 40 μm into the sample, the tool tip slides at a velocity of 10 mm min^{-1} along the rod axis from one end to the other in one pass. In order to generate a thick and uniform deformation layer, SMGT was repeated for six times. The microstructural characterization of the sample was performed by FEI Nova NanoSEM 430 scanning electron microscope (SEM) and by JEOL-2010 high-resolution transmission electron microscope (TEM) operating at 200 kV.

The microstructure of the SMGT sample can be divided into three different regions from the treated surface to matrix, as shown in Fig. 1a: (i) nanograined (NG) region (0–50 μm in depth); (ii) nanograined and nanotwinned (NG&NT) region (50–160 μm in depth); (iii) nanotwinned (NT) region (160–270 μm in depth). The volume fraction and structure size of both nanograins and nanotwins in these regions are statistically measured using numerous SEM and TEM images, respectively. The typical microstructure of the NG region is shown in Fig. 1b. The nanograins are roughly equiaxed with random

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https://doi.org/10.1016/j.scriptamat.2018.01.031
1359-6462/

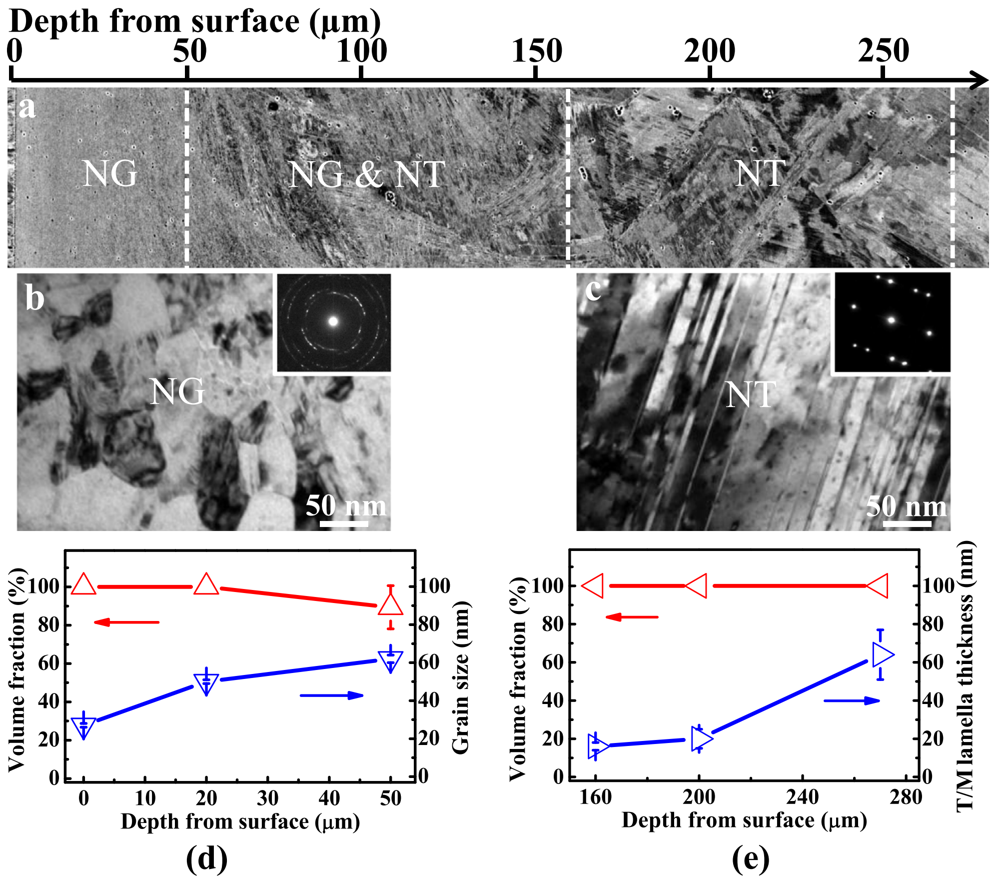

Fig. 1. (a) Typical longitudinal section SEM image of the SMGT Cu-4.5 wt% Al sample; bright-field TEM images of (b) nanograins and (c) nanotwins; variations in volume fraction and structure size of (d) nanograins and (e) nanotwins as a function of depth from the treated surface. The nanograins and nanotwins are labeled with "NG" and "NT", respectively.

crystallographic orientations, as indicated in the inserted selected-area electron diffraction (SAED) pattern. The average grain size increases from ~27 nm at the top surface layer of ~5 μm thick to ~50 nm at the depth of ~20 μm (Fig. 1d). With increasing the depth (>20 μm deep), a few volume fraction of nanotwins can be found in the NG region. At the depth of 50 μm, the volume fraction of nanograins slightly deceases to ~90% and the average grain size increases to ~62 nm. In the span of 50–160 μm deep, more nanotwins are induced with increasing depth and the microstructure consists of nanograins and nanotwins. The microstructure of the span from 160 μm to 270 μm is characterized by nanotwins. There is high density of dislocations inside nanotwins, typical of deformation twins. The thickness of the twin lamella is nearly unchanged while the thickness of the matrix lamella obviously increases with the depth. The average T/M lamella thickness increases from ~16 nm at the depth of 160 μm to ~64 nm at the depth of 270 μm (Fig. 1e). The twin boundaries have an approximate 30° incline angle with respect to the treated surface.

The induction of nanograins and nanotwins may be attributed to the gradient distribution of strain and strain rate along the depth during the SMGT processing. In the topmost layer with the highest shear strain and strain rate (as high as 10^4 s^{-1} [14]), deformation twinning can be activated and dominate plastic deformation in the CuAl alloy under cryogenic temperature [12]. Nano-sized grains could be formed through shear banding of the nanotwins with subsequent straining, analogous to the mechanism for formation of the nanograins in the DPD CuAl alloy [12]. The average grain size of the topmost surface layer in this work (~27 nm) is in good agreement with that of the DPD CuAl alloy (~25 nm) [12]. With the depth increasing, more and more nanotwins are retained due to the decreasing strain and strain rate so that the volume fraction of nanotwins increases from ~10% at the depth of 50 μm to 100% at the depth of 160 μm.

The NG layer (0–50 μm in depth) and NT layer (160–270 μm in depth) were removed from the SMGT sample and cut into dog-bone shaped tensile specimens with a gauge section of 3 × 1 × 0.05 mm^3 (NG sample) and 3 × 1 × 0.11 mm^3 (NT sample), respectively. For comparison, the same tensile tests were performed on the original annealed coarse-grained sample (CG sample), with a gauge section of 3 × 1 × 0.11 mm^3. Uniaxial tensile tests were performed for more than three times on each sample on an Instron 5848 microtester machine at a strain rate of 1×10^{-3} s^{-1} at room temperature. The tensile results (Table 1) showed that the 0.2% offset engineering strength increases from ~132 MPa in the CG sample to ~758 MPa in the NG sample. However, a significant reduction in ductility from ~32% in the CG sample to ~1.4% in the NG sample is noted. The yield strength of the NT sample is ~357 MPa, which is half that of the NG sample, while the uniform elongation is ~18%, ten times higher than that of the NG sample, as shown in Fig. 2a. The NT sample showed a high strength and a considerable ductility in comparison with the super-high strength and very limited ductility of the NG sample. The residual stress can be introduced in the materials processed by SMGT, but the value of residual stress is usually low. Moreover, in this work, most of the residual stress has been released during the cutting of both NG and NT samples from the whole

Table 1
Tensile properties of the nanotwinned (NT), nanograined (NG) and coarse grained (CG) Cu-4.5 wt% Al alloys. σ_{YS}: 0.2% offset yield strength; ε_u: uniform elongation; σ_{UTS}: ultimate tensile strength; ε_f: elongation to failure.

Samples	σ_{YS} (MPa)	ε_u (%)	σ_{UTS} (MPa)	ε_f (%)
NG	758 ± 132	1.4 ± 0.4	822 ± 162	3 ± 1
NT	357 ± 28	18 ± 1	406 ± 26	26 ± 2
CG	132 ± 8	32 ± 2	334 ± 13	43 ± 3