Scripta Materialia 124 (2016) 103–107

Contents lists available at ScienceDirect

Scripta Materialia

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

Regular Article

High strength and high ductility copper obtained by topologically controlled planar heterogeneous structures

Xiaowei Liu [a], Kai Wu [b], Ge Wu [a], Yuan Gao [a], Linli Zhu [a,b], Yang Lu [a,c,*], Jian Lu [a,c,*]

[a] Centre for Advanced Structural Materials (CASM), Department of Mechanical and Biomedical Engineering, City University of Hong Kong, Kowloon, Hong Kong, China
[b] Department of Engineering Mechanics and Key Laboratory of Soft Machines and Smart Devices of Zhejiang Province, Zhejiang University, Hangzhou 310027, Zhejiang Province, China
[c] Shenzhen Research Institute, City University of Hong Kong, Shenzhen 518057, China

ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form 2 July 2016
Accepted 5 July 2016
Available online xxxx

Keywords:
Strength
Ductility
Copper
Surface mechanical attrition treatment (SMAT)
Planar heterogeneous structure

ABSTRACT

By using topologically controlled surface mechanical attrition treatment (SMAT), we processed annealed copper (Cu) and obtained an improved strength without sacrifice of ductility. The partially SMAT process demonstrated its ability to introduce a planar heterogeneous structure in the Cu, while the hardness measurements and microstructure characterization showed that the "hard phase" SMATed areas were embedded in the "soft matrix" of coarse grained Cu, forming a unique bimodal structure combined with both coarse grains and nano-twinning grains, contributing to the overall strengthening. Finite element simulation and theoretical modeling were performed to explain the underlying mechanism for the material property enhancement.

The attainment of both strong and tough is vital for the applications of most structural materials, but the properties of strength and toughness are mutually exclusive in most of the materials [1]. The traditional techniques can easily improve the strength of materials but usually comprise the ductility, which is in the form of uniform elongation during the process of uniaxial tensile test [2,3]. Many advanced techniques have been developed to improve the strength of materials, but only a few works have been reported to improve the strength of materials while keep the ductility of materials within a certain regime [4–10]. For example, Ma et al. prepared a bimodal grain size distributed Cu with micrometer sized grains embedded in the nanocrystalline/ultrafine grain matrix [7], in which the distributed inhomogeneous coarse grains kept the strain hardening during tensile deformation, resulting in the achievement of high strength and good ductility in such nanostructured Cu [7]. Besides, Lu et al. have revealed the surface mechanical grinding treatment (SMGT) Cu with gradient nano-grained (GNG) structure above the coarse grain (CG), called as the GNG/CG architecture Cu [8], which possessed both high strength and good ductility due to the mechanically driven grain boundary migration process with the concomitant grain growth of the nano-grained material [8]. Recently, Wei et al. reported the gradient nanotwinned structure of cylindrical twinning-induced plasticity (TWIP) steel with doubled strength but no significant reduction in ductility [9]. These works applied the severe plastic deformation (SPD) with high strain rate and strain gradient to effectively refine the material structures to change their mechanical properties. Some experimental and theoretical works have also been reported to give an insight into the underlying relationship between properties and structures of materials [11–16].

Recently, surface mechanical attrition treatment (SMAT) has been applied to metals and alloys to effectively improve the mechanical properties of materials [17–21]. Most previous SMAT related works usually generated the uniform layered structures, however, here by processing the materials (in this work, pure copper) via SMAT in a different way—to partially SMAT process the Cu sheets, we demonstrated that we can topologically control the planar structure of Cu for both high strength and high ductility. Hardness of the partially SMAT Cu and the structure characterization by TEM have been applied to reveal the details of the microstructure. Finite element method (FEM) will be used to simulate the surface impact during SMAT and provide the residual stress distribution. By applying the mechanism-based plastic model for the partially SMAT Cu, we will also theoretically analyze the relationship between the mechanical properties and the heterogeneous structures. This work could provide a new strategy to design the structures of materials to achieve the good combination of high yield strength and good ductility.

In this work, pure copper sheet with the purity of 99.99% was used. Before SMAT, the specimens were annealed at 900 °C for 1 h and then the annealed Cu samples were gently polished to mirror like surface before the process of SMAT. Two sides of the Cu sheet

* Corresponding authors at: Centre for Advanced Structural Materials (CASM), Department of Mechanical and Biomedical Engineering, City University of Hong Kong, Kowloon, Hong Kong, China.
E-mail addresses: yanglu@cityu.edu.hk (Y. Lu), jianlu@cityu.edu.hk (J. Lu).

http://dx.doi.org/10.1016/j.scriptamat.2016.07.003
1359-6462/

(70 mm × 70 mm × 1 mm) were processed with standard working parameters [17] and the treatment time ranged from 15 s to 60 s, which is much shorter than former reported SMAT works [19–21]. Samples for the uniaxial quasi-static tensile test were cut into dog-bone shape with the gauge dimension of $25 \times 6 \times 1$ mm^3 and were tested on MTS RT/30 Electro-Mechanical Material Testing System (MTS) with the strain rate of 1×10^{-3} s^{-1} at room temperature. Nano-indentation test was carried out on Hysitron TI 750 with the loading force of 2000 μN to test the hardness of the SMAT Cu matrix and cross-sectional areas of SMAT area. Morphology observation of samples was done with Keyence digital microscope. Transmission electron microscope (TEM) observation was carried out on the JEM 2010 with the operating voltage of 200 kV to study the structures of annealed and partially SMAT Cu samples. All the samples were processed in exactly the same way for TEM observation. Firstly, the samples were polished with sandpapers from one side to about 70 μm and then the solution (V (phosphoric acid):V (alcohol):V (water) = 1:1:4) was used for double jet at 0 °C to get the thin area for TEM observations.

Previous works demonstrated that the SMAT process can significantly improve the strength of materials through the generation of gradient uniform layered nanostructures [19–23]. In this work, different from the previous processes, the SMAT process was conducted with very short time and we got the partially SMAT samples. The yield strength, uniform elongation and the ultimate strength for different process time SMAT Cu samples were summarized in Table 1 based on the tensile testing results. The engineering stress-strain curves of different process time Cu were plotted in Fig. 1(a), and the strength-tensile uniform elongation synergy curve were plotted in Fig. 1(b), comparing with the results of GNG/CG Cu extracted from Refs. [8,18]. As a comparison, the annealed Cu has the 0.2% yield strength of about 48 MPa with the uniform elongation of about 40% and the ultimate tensile strength of about 218 MPa, but here the yield strength of the partially SMAT Cu was more than twice of the annealed Cu with little decrease of uniform elongation for different treatment times processed samples. As the SMAT time increased from 15 s to 45 s, the yield strength of the material increased linearly from 102 MPa to 152 MPa, and there was slight drop of uniform elongation. As indicated in Fig. 1(b), the overall mechanical properties of the partially SMAT Cu were up-right lifted in the strength-tensile uniform elongation synergy curve, better than the properties of the GNG/CG Cu. For relatively long time SMAT Cu samples, such as 60 s SMAT Cu, the strength increased further but with much more sacrifice of ductility.

Due to the random collision of the flying stainless steel (SS) balls for SMAT processing, the velocities of these flying balls impacting on the surface of materials were different between each other, leading to the formation of different sized SMAT areas as shown in the morphology observation (see Fig. 2(a) and (b)). For short time SMAT Cu (see the morphologies in Fig. 2(a) for 15 s SMATed Cu and Fig. 2(b) for 30 s SMATed Cu), the surfaces were partially covered with SMAT areas to get the planar heterogeneous structures. As the treatment time increased, the fraction of SMAT areas increased and occupied more area of the surface of materials. When the SMAT time increased to 60 s, the surface of the material was fully covered with SMAT area and the uniform layered structured sample was obtained as previous works demonstrated [19–25]. As the mechanical property results shown in Fig. 1, the yield strength of SMAT Cu increased as the SMAT time increased,

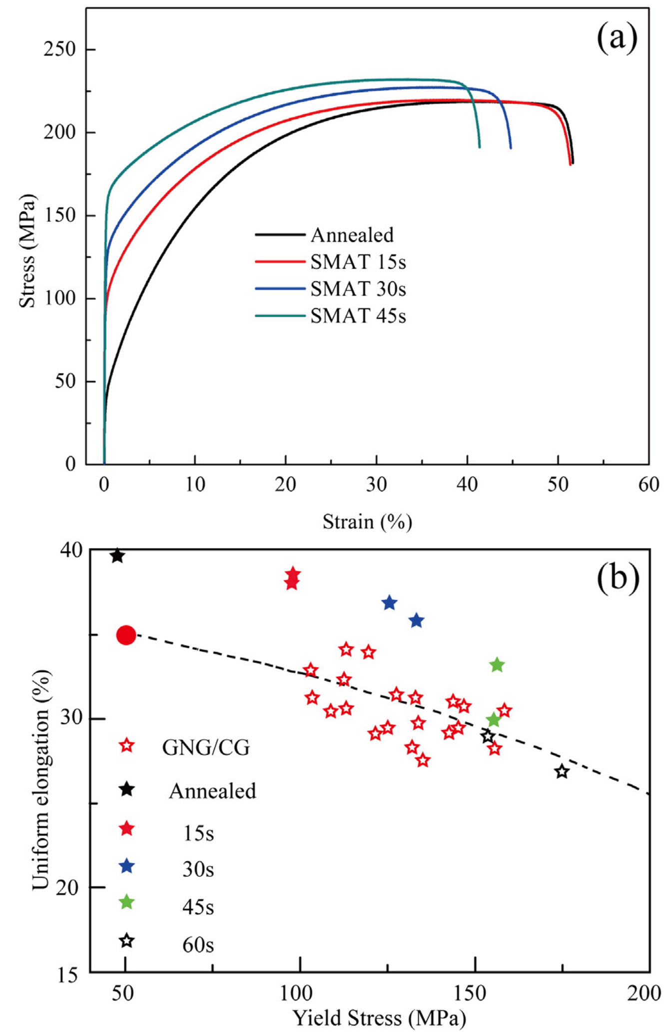

Fig. 1. (a) Engineering stress-strain curves of different SMAT time processed Cu. (b) Strength-tensile uniform elongation synergy curve of partially SMAT Cu together with the result of GNG/CG Cu as reference.

which was equivalent to the covered area of surfaces over SMAT while with some decrease of ductility. And this was shown in the strength-tensile uniform elongation synergy curve that the values slipped from upper-left to lower-right in Fig. 1(b). For relatively long time SMAT Cu samples, the strength also increased but with sacrifice of ductility as the SMAT 60 s Cu data indicated in the synergy curve, which crossed over with the GNG/CG Cu. By tuning the SMAT time to topologically control the planar heterogeneous structures, high strength and high ductility properties can be obtained.

Fig. 2(c) and (d) further shows the hardness testing results from the polished cross-sectional area of the SMAT samples. For the single isolated SMAT area, it can be found from the nano-indentation results in Fig. 2(c) that the hardness decreased from topmost surface to the matrix. Along the depth of the SMAT area, the hardness of the first 40 μm was about 2.3 GPa, which was much higher than the remaining parts. It decreased sharply to the level of matrix within a very small depth of about 30 μm. This is a typical heterogeneous structure with the isolated hard phase inserted in soft matrix. And in the partially SMAT Cu samples, the hard phase of SMAT area was randomly distributed in the matrix. Finite element method was applied to simulate the ball-impacting process of flying balls hitting the surface of materials during SMAT [26, 27]. The analysis was conducted with ABAQUS and the model as meshed with C3D8R elements (eight-node linear brick, reduced integration, hourglass control). The size and thickness of the Cu plate model were

Table 1
Tensile test results of annealed Cu and partially SMATed Cu samples.

SMAT time (s)	Yield stress (MPa)	Uniform elongation (%)	Ultimate tensile stress (MPa)
0	48 ± 1	40 ± 0.7	218 ± 1.53
15	102 ± 4	37 ± 2	222.4 ± 2.3
30	130 ± 4	35 ± 2	228.2 ± 3.1
45	152 ± 2	32 ± 2	232.6 ± 2.15
60	162 ± 25	28 ± 1	238.8 ± 7.35