Journal of Iron and Steel Research, International 24 (2017) 390—396

Contents lists available at ScienceDirect

Journal of Iron and Steel Research, International

journal homepage: www.chinamet.cn

Plasticity performance of $Al_{0.5}$CoCrCuFeNi high-entropy alloys under nanoindentation

Li-ping Yu[1], Shu-ying Chen[2], Jing-li Ren[1,3,*], Yang Ren[4], Fu-qian Yang[5], Karin A. Dahmen[6], Peter K. Liaw[2,**]

[1] School of Mathematics and Statistics, Zhengzhou University, Zhengzhou 450001, Henan, China
[2] Department of Materials Science and Engineering, The University of Tennessee, Tennessee 37996, USA
[3] State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, CAS, Beijing 100190, China
[4] X-ray Science Division, Argonne National Laboratory, Illinois 60439, USA
[5] Department of Chemical and Materials Engineering, University of Kentucky, Kentucky 40506, USA
[6] Department of Physics, University of Illinois at Urbana-Champaign, Illinois 61801, USA

ARTICLE INFO

Key words:
High-entropy alloys
Nanoindentation
Critical behavior
Chaotic behavior

ABSTRACT

The statistical and dynamic behaviors of the displacement-load curves of a high-entropy alloy, $Al_{0.5}$CoCrCuFeNi, were analyzed for the nanoindentation performed at two temperatures. Critical behavior of serrations at room temperature and chaotic flows at 200 ℃ were detected. These results are attributed to the interaction among a large number of slip bands. For the nanoindentation at room temperature, recurrent partial events between slip bands introduce a hierarchy of length scales, leading to a critical state. For the nanoindentation at 200 ℃, there is no spatial interference between two slip bands, which is corresponding to the evolution of separated trajectory of chaotic behavior.

1. Introduction

Serrated flow, associated with cyclic softening and hardening of materials, during plastic deformation, has been studied extensively since the discovery of the Portevin-Le Chatelier (PLC) effect[1]. It is one of the few prominent examples of the complexity of the spatiotemporal dynamics arising from the collective behavior of defect populations[2]. The discontinuous serrated flow indicates that the material responds in a jerky way with stress drops, reflecting sudden-local softening in the material. Understanding the intriguing spatio-temporal instability and its influence on the mechanical properties of various materials has drawn great attentions, the results on nanometer-sized single crystals[3,4], microcrystals[5-7] and bulk metallic glasses[8-12] can be found.

As a new class of materials, high-entropy alloys (HEAs) found in 1990′s have been continuously studied[13-32]. For slow compression or tension at certain temperatures and (small) strain rates, HEAs deform via sudden slips that are associated with the stress drops in stress-strain curves[17-22]. Zhang et al. [17] pointed out that the serrations of HEAs during the compression tests at the strain rate of 10^{-3} s^{-1} seem to be greater than those at the strain rate of 10 s^{-1}. Carroll et al. [22] found that at a strain rate of 10^{-4} s^{-1}, the serrated stress-strain curves of the CoCrFeMnNi HEA move from type-A to B to C PLC-band with increasing temperature from 200 to 620 ℃. Recently, Chen et al. [23] first investigated the serration behavior of a high-entropy alloy $Al_{0.5}$CoCrCuFeNi in nanoindentation test at holding time of 5, 10, and 20 s (when the load reaches the maximum value of 100 mN, then maintained at 100 mN for different time of 5, 10, and 20 s). They divided serrated flow into three stages: loading stage, holding stage and unloading stage; then they found the displacement sequence at holding stage manifests a chaotic behavior. Naturally, a new question arises: whether the dynamic behavior at loading stage is also chaotic or not and what is the underlying mechanism of the serrated flow at

L.P. Yu and S.Y. Chen are joint first authors.
* Corresponding author. Prof., Ph.D.
E-mail address: *renjl@zzu.edu.cn* (*J.L. Ren*).
** Corresponding author. Prof., Ph.D.
E-mail address: *pliaw@utk.edu* (*P.K. Liaw*).

Received 8 December 2016; Received in revised form 20 February 2017; Accepted 21 February 2017
Available online 15 April 2017
1006-706X/

loading stage. Motivated by these, here nanoindentation was used to study the displacement burst at loading stage of the $Al_{0.5}CoCrCuFeNi$ HEA at room temperatures and 200 ℃. The dynamical analysis and statistical analysis are conducted for plastic dynamics at two temperatures.

2. Experimental

The $Al_{0.5}CoCrCuFeNi$ (molar ratio) HEA in the shape of cylindrical rod was fabricated by arc-melting the mixed principal elements with high purity (purity exceeding 99.9 wt. %) in a water-cooled copper mold. Repeated melting for at least five times was carried out to improve the homogeneity of the material. The molten alloy was drop-cast into copper molds with 2 mm in diameter. Disks cut from the as-cast $Al_{0.5}CoCrCuFeNi$ HEA rods were mechanically ground and polished to obtain two parallel surfaces of a mirror quality to avoid surface effects.

The nanoindentation tests were carried out using a Nano Test Vantage (Micro Materials). A diamond Berkevich indenter with a nominal tip radius of about 50 nm was used. The machine compliance was calibrated to be 0.30 nm/mN. The nanoindentation test was performed under the mode of load control with the peak load of 100 mN. Both the loading rate and unloading rate were 10.00 mN/s. Indentation tests were performed at two temperatures (room temperature and 200 ℃). For each indentation condition, at least 3 indents were performed. The indentation depth and indentation load were used to analyze the near-surface mechanical behavior of the $Al_{0.5}CoCrCuFeNi$ HEA.

3. Results and Discussion

Fig. 1(a) shows typical indentation load-displacement (σ-h) curves at different temperatures. The load-displacement curves seem to be regular in the loading stage, and there are no obvious shear steps. The amplification of the curves in the loading stages reveals the presence of the displacement-drop events, as shown in Fig. 1(b). It needs to eliminate the influence from the indentation depth increase in order to analyze these events[33]. A polynomial function ($y=A+B_1x+B_2x^2$) was used to establish a baseline by fitting the indentation displacement-load curves in the loading stage. Using the baseline, the variation of the normalized serration with the indentation load is inserted in Fig. 1(b).

The serrated flow presented in the indentations at room temperature and 200 ℃ can then be determined, as shown in Fig. 2(a). Introducing a variable

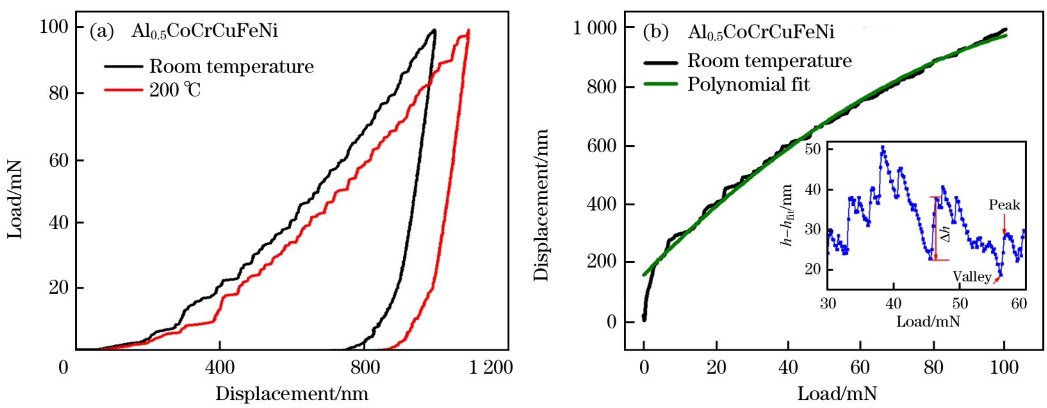

Fig. 1. Load-displacement curves during nanoindentation at room temperature and 200 ℃ of high-entropy alloy $Al_{0.5}CoCrCuFeNi$ (a) and polynomial function fitting curve of displacement-load (the inset shows the serration events) (b).

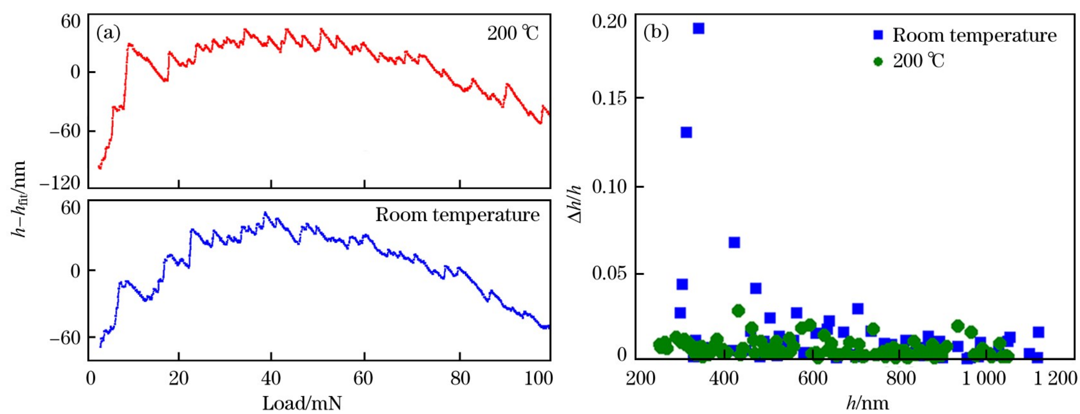

Fig. 2. Serration events on high-entropy alloy $Al_{0.5}CoCrCuFeNi$ at room temperature and 200 ℃ (a) and displacement burst size distribution as a function of depth at two temperatures (b).