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Strain-delocalizing effect of a metal substrate on nanocrystalline Ni film

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ABSTRACT

Uniaxial tensile test and scanning electron microscopy (SEM) are introduced to study the tensile properties of electrodeposited nanocrystalline nickel/coarse-grained copper (N/C) composite in this paper. Compared to the stress strain response of pure nanocrystalline (NC) nickel (Ni), the tensile ductility of N/C composite is enhanced significantly. Based on the experimental results, a multi-phase composite model is proposed to investigate the micromechanical behaviors of the NC Ni film and N/C composite plate. The constitutive models are implemented into ABAQUS/Explicit in the form of VUMAT subroutine. A series of numerical simulations are carried out and the predications were in good agreement with experimental results. It can be concluded that the coarse-grained (CG) substrate work well in suppressing the strain localization in the NC Ni film.

1. Introduction

Nanocrystalline (NC) metals, of which the grain size range less than 100 nm, have attracted a great number of researchers in the past few decades due to their remarkable physical and mechanical properties compared with conventional coarse-grained (CG) polycrystalline materials, especially the ultra-high yield and fracture strength [1–4]. However, most of the superior mechanical properties is accompanied with the decreased ductility, which performs as limited uniform elongation due to the high propensity of NC materials to the deformation localization [5,6]. It has been the most important barrier for the development and application of NC materials. Previous literatures [7] regard that the limited ductility is attributed to the pre-existing impurities and porosities in the materials, but recent examples with good quality still show limited ductilities [8]. Former researchers, such as Zhu et al. [9] and Wei et al. [10], have associated the low ductility with the plastic deformation localization, which is in the form of shear bands. As reported by those researchers, it is a significant mechanism during the plastic deformation of NC metals, and finally contributes to the early failure.

Thus, achieving a microstructure with both high strength and high ductility is still an important and constructive issue in the research and application of NC materials. A series of well-established strategies have been proposed to enhance the limited ductility. For example, metal with bimodal grain size distribution [11–13] was achieved through introducing a high ductility coarse-grained phase in the high strength nano-grained matrix. Also, laminated materials [14] and surface nanocrystallined materials were also introduced to achieve a relatively high ductility in NC metal. Fang et al. [15] developed a gradient structure, in which the CG copper will suppress the strain localization of the surface NC copper. Furthermore, previous researchers [16] have shown an effective confinement of ductile polymer substrate on the deformation localization of thin metal film in tensile test. However, no research paper has been reported to reveal the confinement of ductile substrate on the deformation localization of NC materials so far.

Finite element method (FEM) has been effectively used to simulate the micromechanical behavior and predict the overall mechanical response of NC materials in recent years. Several researchers have carried out a series of FEM simulations of the inelastic deformation behavior in NC materials [17–19]. Such FEM simulations provide valuable insights on the micromechanical behavior and damage mechanism in NC materials. Motivated by the aforementioned investigations, an experimental study will be performed to investigate the suppression effect of the CG Cu substrate on the evolution of shear band in NC Ni film and a multi-phase composite model will be developed. In addition, a dislocation density based theoretical model will be introduced to predict the mechanical properties of NC Ni and CG copper, and then

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implemented into the ABAQUS/Explicit code. Good agreement between the numerical results and the experimental results has been obtained. Finally, the effect of substrate thickness on the deformation localization in NG mental film will be revealed for the first time.

2. Experiments

2.1. Preparation of materials and samples

A series of methods preparing NC materials have been reported, such as inert gas condensation [20], high energy ball milling [21], severe plastic deformation [22,23], electrodeposition [24,25], crystallization of amorphous [26], and the materials produced by different method always exhibit diverse properties. By means of electrodeposition, it is capable of producing full dense metal with comparatively larger dimensions in a single batch. Haasz et al. [27] has electrodeposited full dense NC Ni plates with grain size ranging from 6 to 100 nm through varying the electrical and chemical parameters.

The material used in our study was purchased from Goodfellow Inc. and the dimensions are 24 mm × 24 mm × 0.5 mm, as shown in Fig.1a. The NC Ni film with a purity of 99.9% was deposited on CG Cu substrate and the nominal grain sizes are about 20 nm and 10 μm, respectively. The thickness of NC Ni film is about 20 μm. Before the test, the composite sheet (NC Ni and CG Cu) was polished on the Ni side with SiC paper. And then dog-bone shaped tensile samples were electro-discharge machined from previously polished composite sheet, as shown in Fig.1b.

2.2. Sample tensile testing

To investigate stress–strain response of the N/C composite previously described, the mechanical tests were conducted on the tensile testing machine (Instron Inc. 3367, as shown in Fig. 1c) at room temperature with a quasi-static strain rate of $3 \times 10^{-4}\ s^{-1}$. At the end of the test, a stress–strain curve was obtained. In order to get a further documentation of the morphology of N/C composite during strain softening stage, SEM method was introduced to investigate the macro morphology and fracture mechanism of N/C composite.

3. Computational model of NC Ni and CG Cu

3.1. Voronoi tessellation with grain boundary of a constant thickness

To investigate the micromechanical properties of NC Ni, a composite model, in which the materials are treated as multiphase

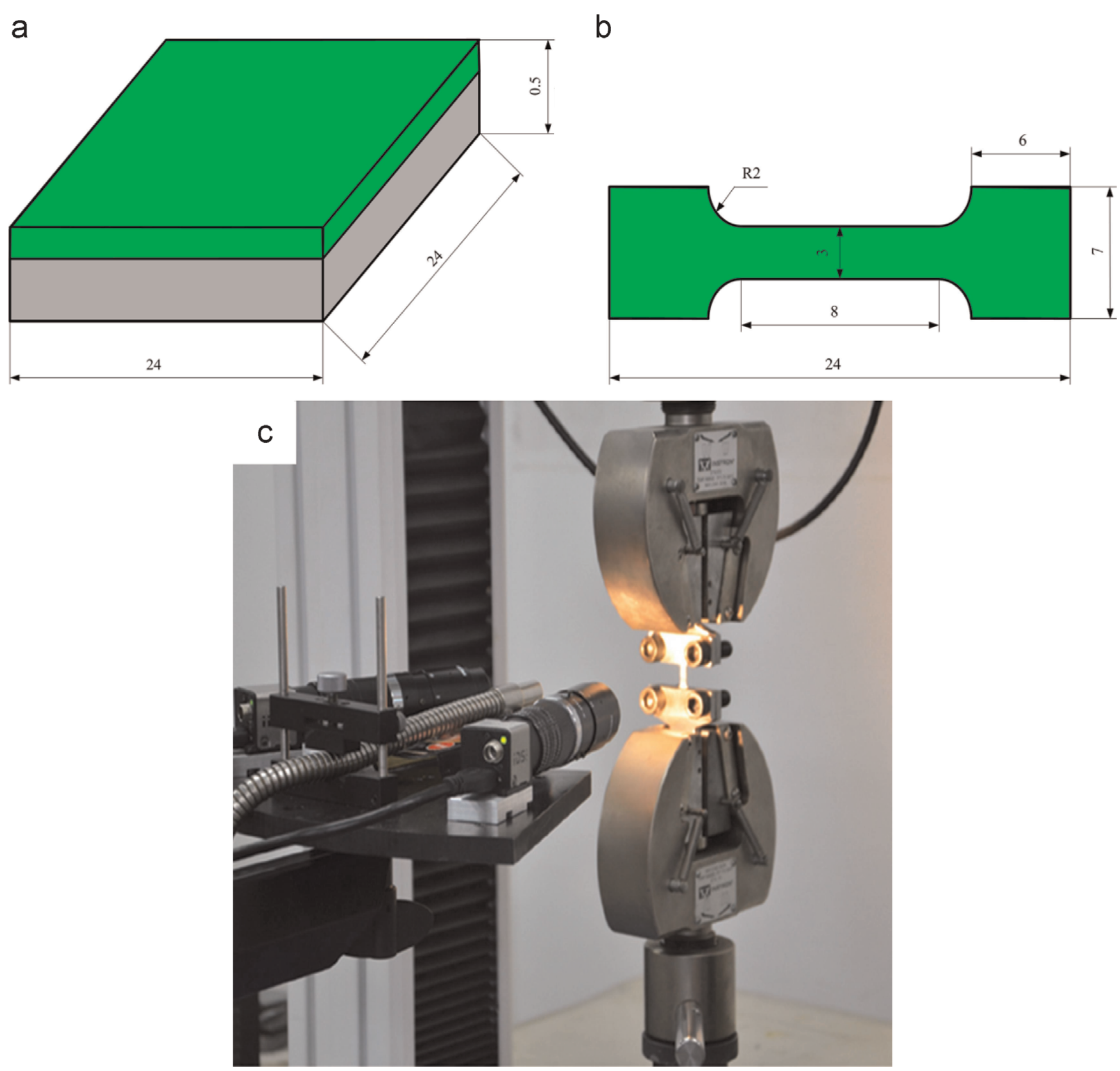

Fig. 1. a Shows the dimensions of the original composite sheet; b shows the dimensions of the dog-bone shape sample; c is the tensile testing machine.