A NEW ELASTIC-PLASTIC MODEL FOR DESCRIBING THE NANOINDENTATION SIZE EFFECTS OF SURFACE-NANOCRYSTALLINE MATERIALS

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Summary Size effects of mechanical properties are found in experiments for nanostructured materials obviously. For a micro/nano-scale sample, surface and interface effects play an important role, and they will cause the obvious size effects of materials properties. In order to explain the influence of surface and interface effects, some researchers come up with a parameter of specific surface area. From author early work, for samples with different scales an approximate linear relationship between yield strength and specific surface area (or surface energy density) was obtained by order and dimensional analysis. This relationship explains the size dependence of single crystal nicke/gold in the experiments of uniform compression effectively. In the present research, authors extend the yield strength relationship to the case of surface-nanocrystalline (SNC) materials. Through finite element simulations based on the new model, the nanoindentation size effect of the surface-nanocrystalline materials is displayed clearly. The interface effect is also displayed, and result shows that the interface effect is an important contribution to the size effect of the mechanical properties of the nanocrystalline materials. Through comparison, finite element results agree well with the experimental results.

INTRODUCTION

Compressive experiments for single crystal gold [1] displayed that yield strength increases with decreasing the sample sizes when sample sizes are at submicron scale. The compressive yield strength obtained for a sample with size of 200nm diameters reaches 30 times of that when the sample size is at macroscopic scale. Above experimental results display the obvious size effect of yield strength of single crystal samples with size at several hundred nanometers or submicron. We think that the obvious size effect of yield strength for single crystal gold at hundred nanometers of sample size under compression is come from surface effect [2]. When sample size is smaller than one micron, the surface effect increases quickly due to the increase of the specific surface area (SSA, ratio of surface area to volume) of sample. In the present research, we intend to build a relationship of yield strength with surface energy density and size of specimen firstly, then use the relationship to describe the nano-indentation size effect of surface-nanocrystalline Al-alloy duo to the interface effect [3].

MODEL AND DESCRIPTIONS

Considering the surface effect, yield strength for pillar with submicron size scale under uniform loading can be expressed as follows,

$$\frac{\sigma_s}{\sigma_Y} = \pi_f \left(\frac{\gamma}{\sigma_Y L}, \frac{L_1}{L}, \frac{L_2}{L}, \ldots\right) \tag{1}$$

Where γ is the surface energy density, σ_Y is yield strength for bulk case, L is a representative size of the sample, L_1 and L_2 are other sizes. Expanding Eq. (1) a Taylor series for $\gamma / \sigma_Y L$ and keeping the first order term, we have,

$$\frac{\sigma_s}{\sigma_Y} = 1 + \left(\frac{\gamma}{\sigma_Y L}\right) f_1 \tag{2}$$

Where f_1 is the function of aspect ratios of sample.

In the following studies, Eq. (2) will be adopted to describe the flow stress for surface-nanocrystalline Al-alloy. In that case, γ is corresponding to the interface energy density. f_1 is only a simulation parameter, is related with aspect ratios of grain size. L describes the grain size at the present location, is a function of location, and can be expressed approximately as follows.

$$L = D_0 + \frac{0.001(D_\infty - D_0)}{1 - x / x_L} \tag{3}$$

Where x is the coordinate away from the nanocrystalline surface, D_0 is grain diameter at surface ($x=0$), D_∞ is grain diameter at remote site $x = x_L$ without nanocrystalline effect, see Fig.2.

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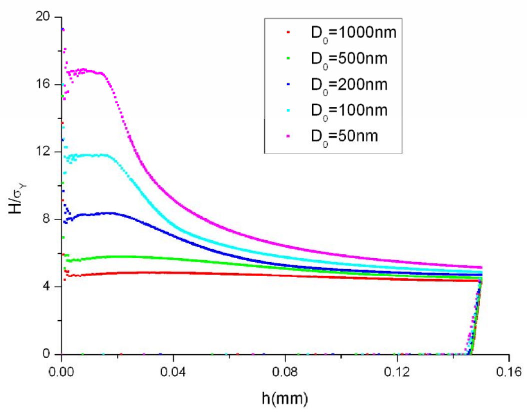
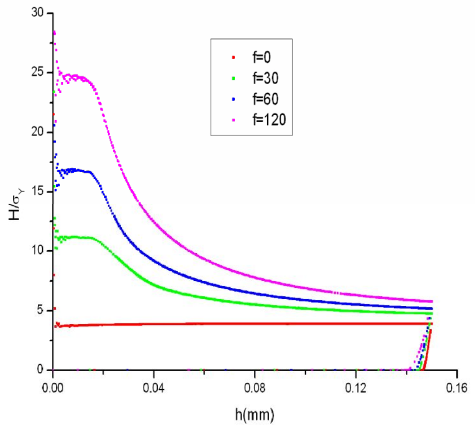
RESULTS AND BRIEF DISCUSSIONS

Fig.1 shows the hardness-depth relations of elastic-plastic finite element simulations obtained on the new method. Nanoindentation size effect can be seen clearly. Fig.1(a) corresponds the hardness-depth relations for different grain sizes at the nanocrystalline surface. Fig.1(b) describes the hardness-depth relations for different simulation parameters which is the function of sample aspect ratio. Fig.2 show one case for measuring the grain size distribution of surface-nanocrystalline Al-alloy. Fig.3 shows the comparison of the finite element simulation results based on the new model with experimental measurement results for surface-nanocrystalline Al-alloy [3]. From Fig.2 and Fig.3, both finite element results based on the present new elastic-plastic model considering interface effect and the experimental results are consistent. Therefore, the new elastic-plastic model is effective.



(a)



(b)

Fig.1. Hardness-depth relations based on elastic-plastic FE simulations based on new method.

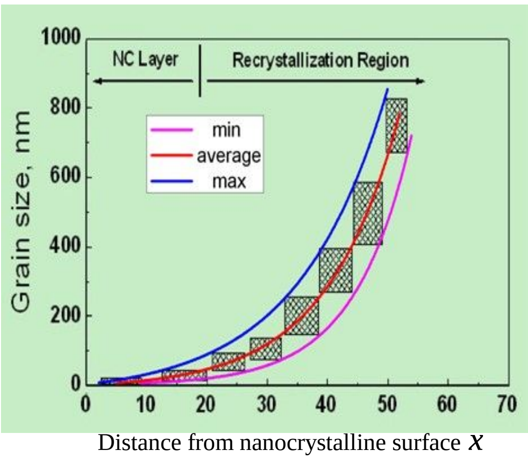


Fig.2. Relation of grain size with distance from nanocrystalline surface.

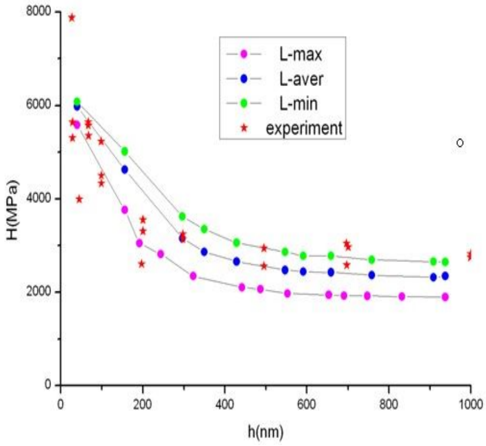


Fig. 3. Comparison of FE simulation with experiments for SNC Al-alloy[3].

References

[1] Greer JR, Oliver WC, Nix WD. Acta Meteriallia, 2005, 53: 1821-1830
[2] Chen XL, Ma HS, Liang LH, Wei YG. Comput. Mater. Sci., 2009, 46: 723-727
[3] Wei YG, Shu S, Du Y, Zhu C, Int. J. Plasticity 2005, 21: 2089-2106