Size and geometrical effects of single- and poly-crystal metals in micro-indentation test

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ABSTRACT Micro-indentation tests at scales on the order of sub-micron have shown that measured hardness increases strongly with decreasing indent depth or indent size, which is frequently referred to as the size effect. In this paper, the micro-indentation experiments for single crystal copper(Cu) and aluminum(Al) are carried out. The experimental results of loading-displacement curves and hardness-depth relations are obtained, which displays the strong size effect. Meanwhile, in order to investigate the micro geometrical size effects, the indentation experiment for material of polycrystal Al is carried out. Finally, the strain gradient plasticity theory is used to model the size effect and geometrical effect for the materials undergoing the micro-indent. The material length parameter is predicted.

KEY WORDS: Micro-indentation test, size effect, geometrical effect, length parameter

1. INTRODUCTION

Indentation test is an important and effective experimental method, and has been used extensively to estimate the plastic properties of solids undergoing the plastic deformation. Through indentation test, the loading-unloading relation between hardness and indent depth is measured. Thereby, the material parameters, such as the yielding stress, strain hardening exponent, Young's modulus, etc. are estimated. Recently, with the advancement of experimental technique and measuring precision, it is possible to carry out the indentation tests at the scale levels of one micron or sub-micron for obtaining more detailed material information. Such small-scale indentation experiments are frequently referred to as micro-indentation tests (or nano-indentation tests). In the micro-indentation test, a new result, which is different from the conventional one, size-dependent result has been revealed extensively [1-4]. For metal materials, the measured hardness may double or even triple the conventional hardness as indent size (or depth) decreases to a fifth micron. The effect is often referred to as the size effect. In addition, at the micron scale if material is constructed by some micro-geometrical structures and if the geometrical structure size is comparable to the indent depth, the size-dependent hardness results mentioned above must be influenced additionally by the geometrical size. We call this effect as the geometrical effect in. However, the trends of both size effect and geometrical effect are at odds with the size-independence implied by conventional elastic-plastic theory.

In this paper, the micro-indentation experiments for single crystal copper(Cu) and aluminum(Al) are carried out. The experimental results of loading-displacement curves and hardness-depth relations are obtained, which displays the strong size effect. Meanwhile, in order to investigate the micro geometrical size effects, the indentation experiment for material of polycrystal Al is carried out. Finally, the strain gradient plasticity theory is used to model the size effect and geometrical effect for the materials undergoing the micro-indent. The material length parameter is predicted.

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2. EXPERIMENTAL METHOD AND RESULTS

The detailed experimental researches are carried out for the single crystal tungsten, copper and aluminum at the National Key Laboratory of Friction and Lubrication, Tsinghua University; and the National Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences.

Conventional experimental results of the indentation hardness are measured based on a unique loading point on the material surface (it is referred to as *the continuous stiffness method*). The experimental curve of hardness with depth is relatively smooth. However, such a hardness curve should be dependent of the status at the loading point (defects or reinforced particles, etc.). In view of the reasons, in the present experimental research, select many loading points and indent depths on the surface, and one loading point corresponds to the only one measured value for the hardness/depth relation, so that a data strip about the hardness/depth relation is obtained. Furthermore, based on the data strip, a region of the micro-scale parameter taken can be determined.

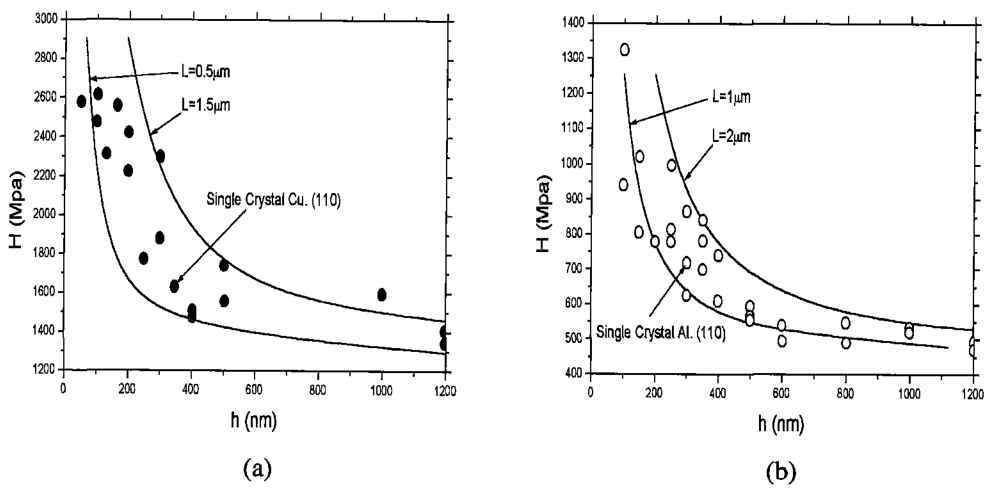


Figure 1. The hardness-indent depth relations for single-crystal Cu(a) and Al(b); indentation experimental results(dots) and numerical simulations(curves).

Figure 1(a) and (b) show the experimental results of hardness-depth relation, respectively for single crystal copper and single crystal aluminum. The strip results are obtained from selecting the loading point on the specimen surface randomly. For the same depth, higher hardness value data is corresponding to the strong region indented, while the lower hardness value data is corresponding to the weak area being indented. From figure 1 (a) and (b), clearly, size effects are obtained, which are characterized by hardness data trends elevation. From figure 1 for both material cases, conventional weakly hardening metal, the hardness increases from 400nm sharply with decreasing the indent depth. Alternatively, with indent depth increasing, the hardness value tends to a stable value, conventional material hardness, i.e., triple the yielding stress of the material.

Figure 2 shows the experimental results of the hardness-depth relations for polycrystal aluminum for different grain size cases. A series of grain sizes, t=600nm, 1000nm and 2000nm, are considered.

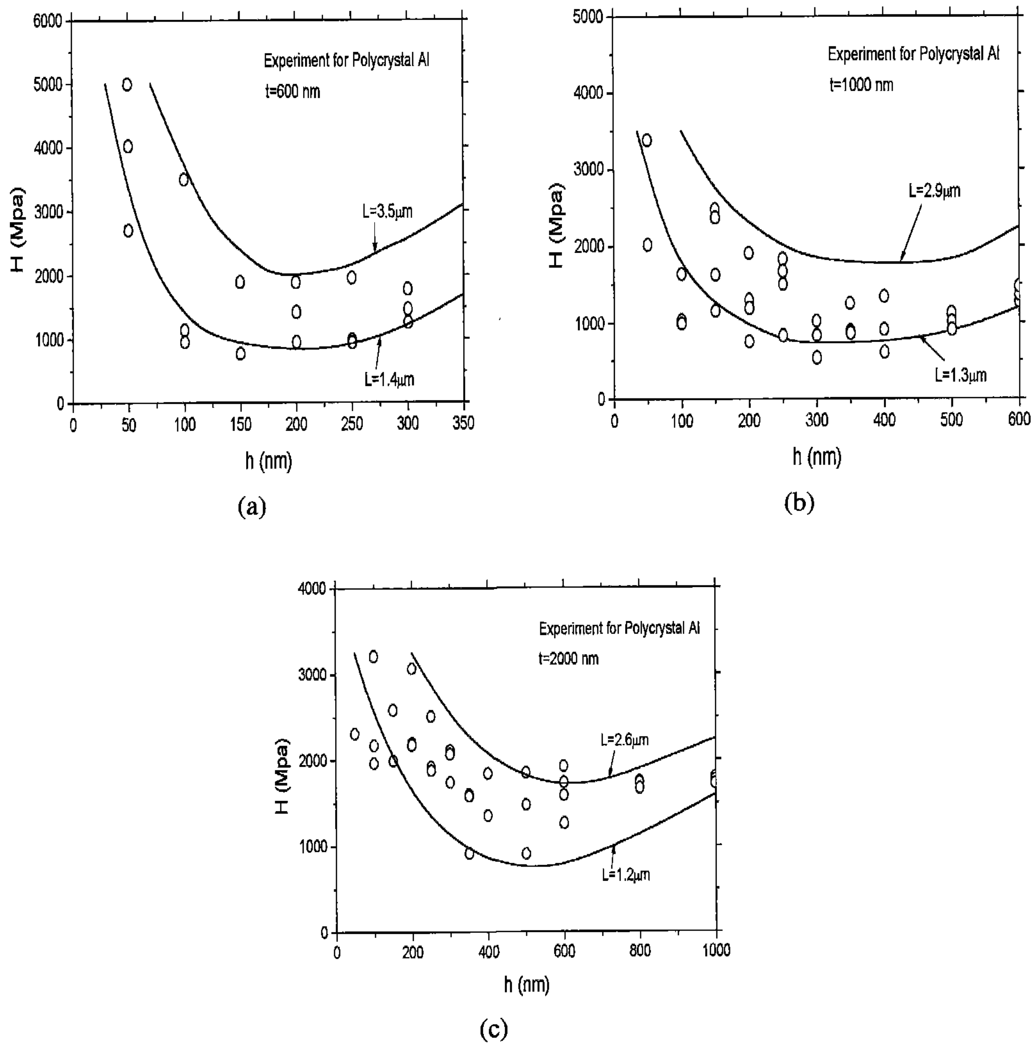


Figure 2. The hardness-indent depth relations for poly-crystal Al for different grain size cases; Indentation experimental results(dots) and numerical simulations(curves).

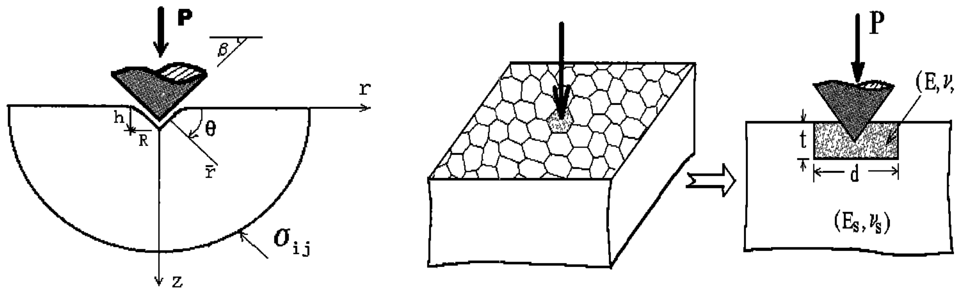
From figure 2, in the indentation test, when indent depth is small and as indent depth increases, the hardness decreases. To the some depth, the hardness tends to increase. The hardness-depth curve is like a "U type" curve. The former phenomenon is the size effect, and the latter one is the grain size effect, i.e., geometrical effect.

3. NUMERICAL SIMULATION OF SIZE AND GEOMETRICAL EFFECTS

On the simulation of the micro-scale size effect and geometrical effect, one can't use conventional elastic-plastic theory, because inside it no any length parameter is included to differ from the macro-scale with micro-scale cases. Strain gradient plasticity theory[5,6] can be used to do this. In strain gradient theory, some length parameters are included:

$$\varepsilon^e = \{\tfrac{2}{3}\varepsilon'_{ij}\varepsilon'_{ij} + L_1\eta^{(1)}_{ijk}\eta^{(1)}_{ijk} + L_2\eta^{(2)}_{ijk}\eta^{(2)}_{ijk} + L_3\eta^{(3)}_{ijk}\eta^{(3)}_{ijk}\}^{1/2},\ L_1 = L, L_2 = \tfrac{1}{2}L, L_3 = (\tfrac{5}{24})^{\frac{1}{2}}L\,. \quad (1)$$

For single crystal metal and for polycrystal metal, analysis models are shown in figure 3(a) and (b), respectively. The simulation results have been shown in figure 1 and figure 2.



(a) (b)

Figure 3. Simplification models for single crystal (a) and polycrystal (b).

4. CONCLUSIONS

Size and geometrical effects are studied experimentally and numerically and both phenomena have been displayed clearly. The numerical result is consistent with the experimental result. Through comparison of both results, the length parameters are predicted.

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