Effects of Power-Law Plasticity on Deformation Fields underneath Vickers Indenter*

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Abstract

The effects of power-law plasticity (yield strength σ_y and strain hardening exponent n) on the plastic strain distribution underneath a Vickers indenter was explicitly investigated by recourse to macro- and micro-indentation experiments on heat-treated Al-Zn-Mg alloy. With carefully designed aging profile, Al alloy can achieve similar σ_y with different n , and vice versa. Using the Vickers tip, the samples were macro-indented, sectioned and micro-indented to construct the sub-surface strain distribution. Thus, the effects of σ_y and n on strain distribution underneath Vickers indenter were revealed.

Key words: Power-Law, Vickers Indentation, Deformation Field

1. Introduction

Instrumented sharp indentation, where load P and depth of penetration h being measured continuously, has been used widely as a non-destructive tool to probe and extract mechanical properties of the indented sample, due to its ease of sample preparation, requirement of small volume and simple test procedure. It is not surprising to see instrumented indentation being used to measure properties of materials at nano-, micro- and macro-scale or in various disciplines ranging from biology, food science and pharmaceutical industry. Nonetheless, complex elastic-plastic contact mechanics during the indentation has called for direct experimental observation to support limited theoretical framework. In the present study, cross-section deformation behavior underneath Vickers indenter was experimentally investigated, following the method of Chaudhri⁽¹⁾. The plastic strain distribution was then correlated to yield strength (σ_y) and strain hardening exponent (n).

2. Experimental Procedure

A commercial 7075 Al alloy (Al-7.6Zn-4.6Mg-1.0Si, wt%) was machined for tensile specimens with 35 mm gage length and 3×1.6 mm² cross section, with a thickness of 2 cm. All specimens were solutionized at a temperature of 480°C for 2 hours and aged at a temperature of 150°C in an oil bath, in order to achieve the most symmetrical hardness H vs. aging time t_a curve⁽²⁾. At each t_a , the hardness value of each sample was determined by measuring the average of the two imprinted diagonal lengths (of the roughly square shape) after the indentation load of 30N at the grip section. The hardness value in kgf/mm² was then converted to MPa by multiplying a conversion factor of 9.807, see Table 1. Then, each sample was subjected to a uniaxial tensile testing at a strain rate of 10^{-3} 1/s to obtain σ_y

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and n . Figure 1 shows the plots of H , σ_y and n vs. t_a so the aging profiles were selected at $t_a = 6, 36$ and 94 hrs so that (σ_y, n) can be of value $(348 \text{ MPa}, 0.07)$, $(445 \text{ MPa}, 0.066)$ and $(344 \text{ MPa}, 0.11)$, respectively (see Table 1). To analyze the effect of yield strength, the aging times of 6 and 36 hrs can be compared. On the other hand, the effect of strain hardening exponent can be analyzed by comparing the aging time of 6 and 94 hrs. Figure 2 shows the true stress-true strain curves of the three aging profiles prescribed, quantifying detailed mechanical properties of these three conditions. For each t_a value, cylindrical samples of 15mm in height and 10mm in diameter were given various levels of compressive plastic strain ε_p at a strain rate of 10^{-3} 1/s , prior to micro-hardness measurement. Then, the conversion graph from micro-hardness to plastic strain for each aging time was created.

(a)

(b)

Figure1. Aging profiles for (a) hardness and yield strength, and (b) strain hardening exponent

Table 1. Mechanical properties resulting from different aging profiles

Aging time, t_a (h)	Hardness, H (MPa)	Yield Stress, σ_y (MPa)	Strain-hardening exponent, n	Diagonal Length, D (μm)
6	1452	348	0.070	805
36	1667	445	0.066	790
94	1432	344	0.110	808

Figure 2. True stress-true strain curve for various aging profiles

For each t_a profile, a block of 3cm in length and $1 \times 1 \text{ cm}^2$ in cross-section was polished down to $1 \mu\text{m}$ diamond paste prior to Vickers indentation with a load of 700N to create a large indent. Then, the indented block was sectioned perpendicular to the indented surface, along its median plane using a $25 \mu\text{m}$ thick copper wire in the electro discharge machining to minimize any mechanical deformation from the sectioning process. The sectioned planes were gently polished down to $0.25 \mu\text{m}$ diamond paste, and the arrays of micro-hardness indentations were conducted on the deformed region with a load of 0.5N (the diagonal length of the micro-indent is about $22 \mu\text{m}$) in order to probe for hardness map underneath the large indent, as schematically depicted in Fig. 3. For generalization, the x and z distances were normalized with large indent diagonal on the xy plane.

Figure 3. A typical microhardness map on the cross-section of the large indent (xy is the plane for indentation along the z direction)

In order to convert the microhardness map shown in Fig. 3 to a contour plot of equivalent plastic strain ϵ_p map, the cylindrical samples of 15mm in height and 10mm in diameter (polished to $0.25 \mu\text{m}$ finish) from each aging profile were compressed to various levels of compressive plastic strain ϵ_p (with quasi-static strain rate of 10^{-3} 1/s), and indented with a load of 0.5N. Thus, the correlation between compressive plastic strain ϵ_p and hardness value was established, see example in Fig. 4 for the 6 hr aging case.

Figure 4. A correlation between hardness number and compressive plastic strain used to convert microhardness map to contour plot of plastic strain underneath the indenter

3. RESULTS & DISCUSSION

The plastic strain distribution maps (normalized by indent diagonal, D) underneath the Vickers indenter are illustrated by iso-strain contours shown in Fig. 5, for both the case of similar σ_y but different n (6 and 94 hr aging in Fig. 5a) and the case of similar n but different σ_y (6 and 36 hr aging in Fig. 5b). The x/z distances are normalized by indentation diagonal on the xy plane with the contour line for visual guiding only. Note that the unevenly-spaced contour interval is selected for easier contour line drawing only since the typical deformation field underneath the indenter shows large strain gradient near the tip with gradually less gradient further away. Figure 5a suggests that the strain field is relatively shallower for a higher n material with similar σ_y . This is consistent with general observation of indentation sink-in effect for high n material (e.g. annealed sample) because material has large resistance to plastic deformation with limited spread of plasticity⁽³⁻⁵⁾. On the other hand, Fig. 5b suggests that the strain field is relative smaller in both x and z directions for a higher σ_y material with similar n . The range of plastic strain value shown in Fig. 5 is consistent with the range of 0-0.36 in well annealed copper sample⁽¹⁾.

Figure 5. The contour plot of plastic strain distribution underneath Vickers indenter for (a) 6 vs. 94 hr aged sample (similar σ_y but different n) and (b) 6 vs. 36 hr aged sample (similar n but different σ_y). The x/z coordinates are normalized by large indenter diagonal reported in Table 1. Note that the contour line is drawn for visual help only.

4. CONCLUSION

Deformation behavior underneath Vickers indenter was experimentally correlated with the power-law plasticity parameter, yield strength and strain hardening exponent, via a cross-sectional micro-indentations of the macro-indentation using Vickers tip. The samples were carefully aged to have a pair of similar yield strength but different strain hardening exponent, and a pair of similar strain hardening exponent but different yield strength. Micro-hardness map was converted to plastic strain field via micro-indentation of same materials at various uniaxial compression levels. The contour plot of plastic strain for each pair was compared for to identify the individual effects of yield strength and strain hardening exponent. It was found that work hardening behavior of the material is relatively more influential in determining the plasticity spread in the z -direction (i.e., the loading direction) than in the x -direction; whereas, elastic limit (yield strength) of the material affects the plasticity spread in both loading and lateral directions.

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