

MICROSCOPIC EXPERIMENTAL ANALYSIS OF FRACTURE TOUGHNESS IN FRACTURE OF COPPER FOILS

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ABSTRACT

The effect of thickness on the fracture toughness J_C of copper foils was investigated experimentally. Specimens with thicknesses ranging from 0.02mm to 1mm were loaded in tension till fracture. The digital speckle correlation method (DSCM) was used to evaluate the strain fields around the crack tip, allowing determination of the J integral. The fracture toughness defined as the value of the J integral at cracking initiation was shown to depend on the material's thickness. Metalloscope results showed that microscopic structure of different specimens with different thicknesses is one factor affecting the fracture toughness.

1 INTRODUCTION

Nowadays, with the rapid development of modern technology, thin foil materials have found many applications in the fields of microelectro-mechanical systems (MEMS), integrated circuits, etc. The mechanical behavior of such materials may be different from that of bulk materials due to size effects. Therefore, models and conclusions appropriate for bulk materials may not be applicable when analyzing foil materials. Certain essential problems and phenomena occurring during the fracture process of foils should be explored by experiments in order to provide a better understanding of fracture mechanisms, especially their difference from bulk materials. For example, the effect of the thickness of the foils on the fracture behavior remains an open issue.

During last decades, several investigations of size effect have been carried out both experimentally and theoretically. For example, Judelewicz et al [1] and Arzt [2] have demonstrated that size effect on the material properties of foil materials was attributed to dimensional and microstructural constraints. Choi et al. [3] analyzed size effect on the mechanical properties of thin polycrystalline metal films, and developed a model that correctly predicts the observed influence of film thickness and grain size on stress evolution during thermal excursions. Pardoen et al. [4-5] investigated size effect on the fracture toughness of aluminum thin plates of 1-6mm thickness from tensile testing of double edge notched tension (DENT) specimens. Their research showed that thickness indeed influences fracture toughness, and the critical J integral and critical crack tip opening displacement (CTOD) constitute equivalent measures of fracture toughness at small thickness. From the above review, we note that most of the existing work has focused on size effect of plate material or thin films supported by a substrate. However, at present, many modern electronic devices or packages involve thin and free-standing films (usually much thinner than 1mm) for which the mechanical and fracture behaviors are critical in analyzing the performance of whole structure. And as to size effect for fracture behaviors of metallic foils, little work has been reported in the literature. Wang et al. [6] measured and calculated the fracture toughness of copper foils with thicknesses ranging from 20 μm to 1mm by the DSCM. In this paper, metalloscope is used to observe the microstructure of different specimens with different thicknesses. Results show that together with thickness, microstructure is one main factor affecting the fracture toughness.

2 EXPERIMENTAL PROCEDURE

2.1 Specimen

The specimens employed in this study were made of T2 copper foil with thicknesses ranging from 20 μm to 1mm. All were produced by the same processing technology, and thus had the same chemical composition and content. The Young's modulus E and Poisson's ratio μ of the material were about 108.5GPa and 0.334, respectively. A Ramberg-Osgood relation was used to fit the uniaxial stress-strain data which were measured by the CSS-44100 experimental machine. The functional form is written

$$\frac{\epsilon}{\epsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \left(\frac{\sigma}{\sigma_0} \right)^n \quad (1)$$

where α is the strain-hardening coefficient and n is the strain-hardening exponent, σ_0 and ϵ_0 are the flow stress and strain, respectively. By the least square method, we obtain $\alpha=0.0288$ and $n=15.47$. Good agreement was found between the fitted curves of the Ramberg-Osgood equation and the original uniaxial stress-strain curves as shown in Figure 1. The thin foils were processed with different thicknesses and double-edge cracks. The dimensions are shown in Figure 2. The crack on

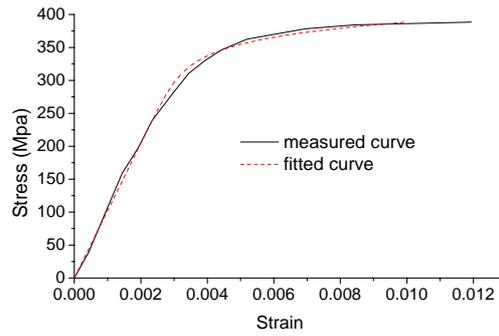


Figure 1: Stress-strain curve of the material

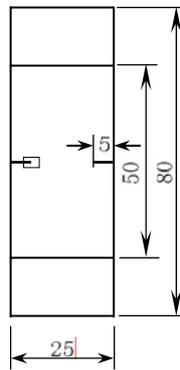


Figure 2: Dimensions of specimen and cracks

each specimen was made as follows: a line-incisor with a radius of 0.1mm was used to make an initiatory crack and then a sharp razor was used to make the crack tip. The radius of the razor was approximately 25 μm . The validity of this pre-cracking method has been justified by Pardoen et al. [4].

2.2 Experimental Technique

The DSCM(digital speckle correlation method) as previously established is used to obtain the displacement and strain fields near the crack tip region, allowing determination of the fracture toughness, characterized by J_C and defined as the value of the J integral at cracking initiation. The process in DSCM includes recording, digitizing and processing two speckle patterns (or images) of an object in two different deformation states to yield in-plane displacement components and in-plane displacement gradients. The two speckle images of the surface of the object are usually captured before and after loading. The speckle images in the two states are known as reference and deformed speckle patterns, respectively. A small speckle area in the undeformed speckle pattern is taken as a reference subset and the speckle area corresponding to the reference subset in the deformed speckle pattern is defined as the target subset. In this case, it is essential to identify the corresponding relation between the two subsets. Differences between the two subsets include translation and distortion information about the object. The deformation measurement is performed at two different deformation stages and comparison is made for subsets between the two digital patterns. Finally, the J integral can be calculated based on the strain field in the region around the crack tip. The detailed experimental procedure can be found in [6] and the experimental method is schematically summarized in Figure 3.

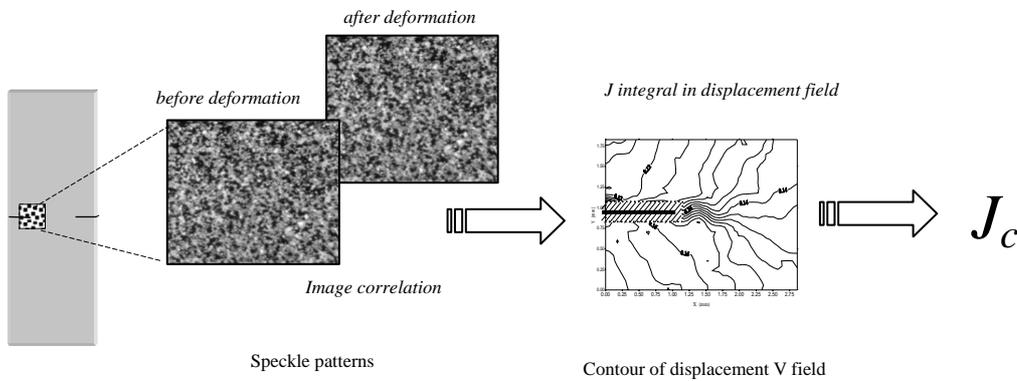


Figure 3: Schematic illustration of J_C evaluation processing

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Toughness/thickness curve

In order to study the effect of thickness on J_C , specimens with thickness $h=0.02, 0.03, 0.05, 0.1, 0.2, 0.3, 0.4, 0.6, 0.8$ and 1mm were used in our test, and each thickness was repeated four times.

The fracture toughness J_C of the specimens with thickness range from 0.02mm to 1mm is presented in Figure 4 as a function of specimen thickness, showing that J_C strongly depends on thickness. In a so-called stage I (see Figure 4), J_C is shown to increase with an increase in thickness, then to reach a maximum at the thickness $t \approx 0.3$ mm. Conversely, J_C decreases as the thickness increases within the so-called stage II (see Figure 4). Moreover, it should be noted that Figure 4 is similar to the plots presented in many textbooks such as that of Kanninen and Popelar [7]. However, most of them have no quantitative results and provide a qualitative analysis only.

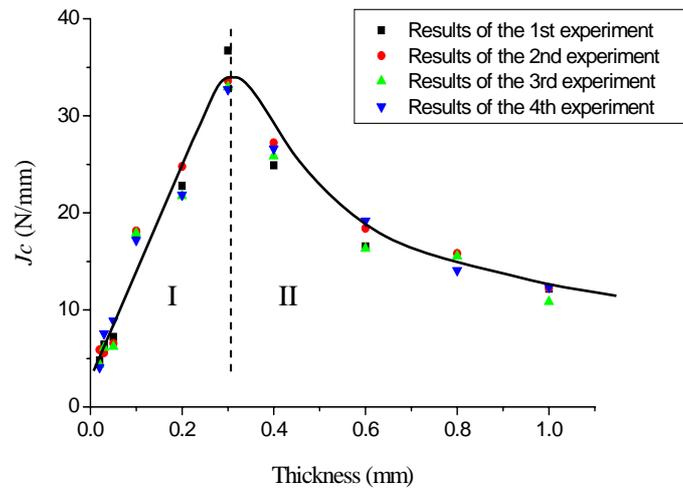


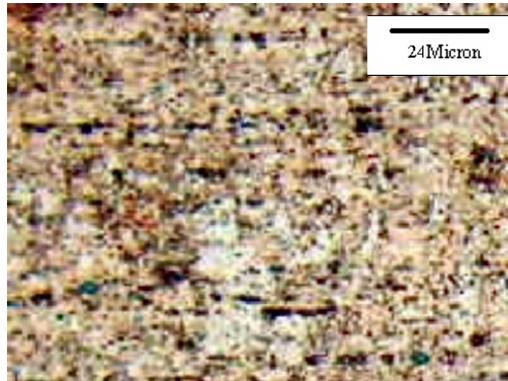
Figure 4: Relation between J_C and thickness

3.2 Analysis and Discussion

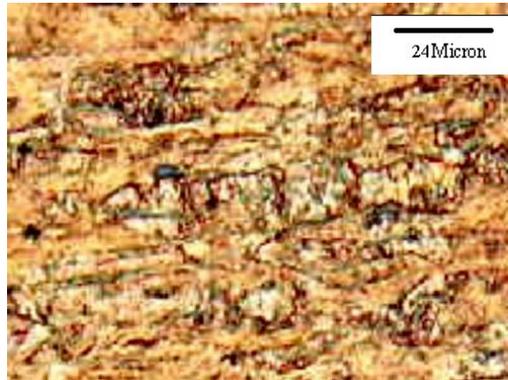
A brief discuss was made in [6] that showed the energy spent in the neck shrinking process in front of the crack tip, micro-defects of the material, and the stress triaxiality ratio may be the major factors affecting fracture behavior, and their contributions to fracture toughness will differ with different thickness of foil.

In order to investigate the relation between fracture toughness and thickness experimentally, a metallographic examination of the specimen's microstructure by a metalloscope is carried out in this work. Microstructures of different specimens with thickness 0.05mm, 0.3mm and 1mm are shown in Figure 5. From them we can see that 1) the grains are also elongated along the rolling direction and the grain flow direction is along with rolling direction; 2) With the decrease of the thickness, crystal grain size decrease too. When thickness $h=1$ mm, some big grains who are elongated along the rolling direction can be seen. When thickness equal 0.5mm, some big grains break up and turn into sub-grains. And when thickness equal 0.05mm, no obvious grain can be seem.

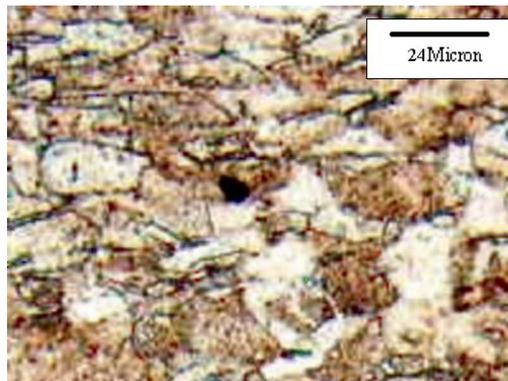
In stage I, the thicknesses of specimens were thinner. No obvious grain found in the material. The degree of brittleness is more than that of toughness. And the nonhomogeneity and some microfaults of material are the main factors that affect the facture toughness. With the increase of thickness, the effect degree of these factors on fracture toughness weakens. Therefore the fracture



(a) Thickness=0.05mm



(b) Thickness=0.3mm



(c) Thickness=1mm

Figure 5: Microstructure of foil materials with different thickness

toughness increases with the increase of thickness. In stage II, with the increase of thickness, the degree of dislocation pile up of material strengthens that result in a stress concentration. So the fracture toughness decreases with the increase of thickness at this stage.

From above analysis we can see that the microscopic structure of materials as well as thickness is main factors affecting for the fracture toughness of the metal foil.

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REFERENCES

- [1] Judelewicz M., Kunzi, H.U., Merk N. and Ilschner B. Microstructural development during fatigue of copper foils 20-100 μm thick. *Materials Science & Engineering A: Structural Materials: Properties, Microstructure and Processing*. 1994; A186 (1-2): 135-142.
- [2] Arzt E. Size Effects in Materials Due to Microstructural and Dimensional Constraints: A comparative Review. *Acta Materialia*. 1998; 46(16): 5611-5626.
- [3] Choi Y. and Suresh S. Size effects on the mechanical properties of thin polycrystalline metal films on substrates. *Acta Materialia*. 2002; 50(7): 1881-1893.
- [4] Pardoën T., Marchal Y. and Delannay F. Thickness dependence of cracking resistance in thin aluminum plates. *Journal of the Mechanics and Physics Solids*. 1999; 47(10): 2093-2123.
- [5] Pardoën T., Marchal Y. and Delannay F. Essential work of fracture compared to fracture mechanics-towards a thickness independent plane stress toughness. *Engineering Fracture Mechanics*. 2002; 69(5): 617-631.
- [6] Wang H.W., Kang Y.L., Zhang Z.F. and Qin Q.H. Size effect on fracture toughness of metallic foil. *International Journal of Fracture*. 2003; 123(3-4): 177-185.
- [7] Kanninen M.F. and Popelar C.H. *Advanced Fracture Mechanics*, Oxford University Press, New York, 1985.