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 $\mu$ 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

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha \left( \frac{\sigma}{\sigma_0} \right)^n$$

where $\alpha$ is the strain-hardening coefficient and $n$ is the strain-hardening exponent, $\sigma_0$ and $\varepsilon_0$ 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
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](image)

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.

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 fracture toughness. With the increase of thickness, the effect degree of these factors on fracture toughness weakens. Therefore the fracture
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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