Analytically Speaking

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Characterization of Deposits, Coatings & Electroforms, Part 2: Mechanical Properties Measurement

Tensile Testing

Two methods are most often used to obtain the mechanical properties of deposits. One is the bulge test and the other, the uniaxial tensile test. In the bulge test, a circular piece of the deposit is clamped over a hollow cylindrical device. A fluid, usually oil or air, is pumped into the cavity of the device. The pressure of the fluid causes the deposit to form a hemispherical bulge. The pressure of the fluid and the height of the center of the bulge are measured simultaneously. In some instruments, the height of the bulge is measured with a dial gauge or an LVDT (linear variable differential transformer).

A disadvantage of having the measuring device in contact with the top of the foil is that it prevents it from reaching its full height and consequently results in a lower value of the strain. To overcome this problem, a microscope attached to a dial gauge has been used to measure the bulge height. Lasers have also been employed for this purpose. Another disadvantage of the bulge test is that, often, clamping the foil into the instrument may stretch it slightly, so as to deform it plastically. It is accordingly not possible to determine Young's modulus or the yield strength.

A stress-strain curve can be constructed from the fluid pressures and the corresponding bulge heights. The equations used to calculate the stress, σ, and the true strain, δ, are:

$$\sigma = \frac{(P-P_0)a^2}{4ht_0 \exp(-2\delta)} \quad \text{and} \quad \delta = \frac{4h^2}{3a^2} \qquad (3)$$

where h is the bulge height, a is the radius of the clamped area, P is the pressure, P_0 is the initial pressure and t_0 is the original thickness of the foil. The meaning of true strain will be discussed later.

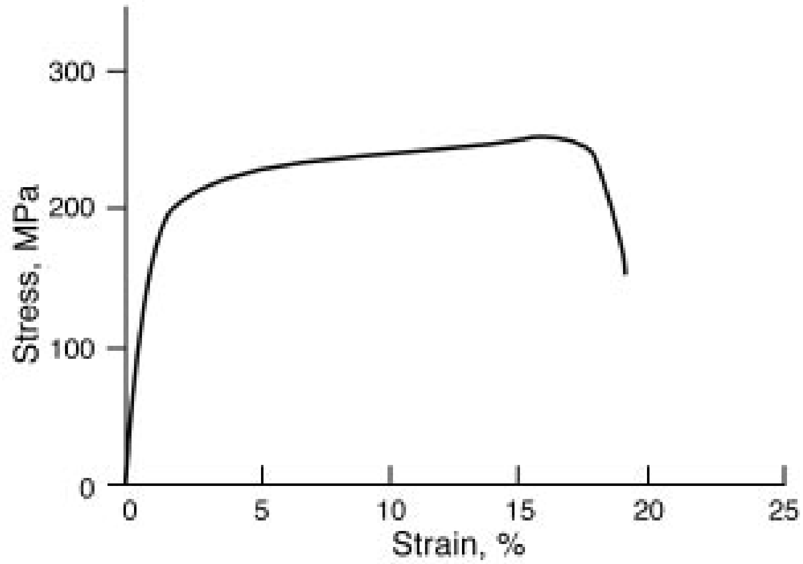

Fig. 1—Stress-strain curve of electroplated copper.

The uniaxial tensile test consists of applying a load to the specimen and measuring the change in length of a specified portion of the specimen called the gauge length. The shape of the specimen resembles a dog bone in that the middle portion is narrower than the top and bottom. The gauge length is marked on the middle portion.

ASTM Method (E 345) for testing of metallic foils specifies a two-inch gauge length and a width for the middle portion of a half-inch. If the foil is several mils thick, the width-to-thickness ratio can easily exceed 500. ASTM Method (E8), however, requires the ratio of the width to the thickness not exceed 8. There is, therefore, a problem using the standard specimen shape. Large ratios result often in the so-called "Saran-wrap" effect, where the strain is not uniform over the width. A typical value of the width-to-thickness ratio of elements of printed circuits is about 50, so this value of the ratio seems preferable. It is then necessary, however, to use a much narrower specimen.

The gauge length also must be correspondingly reduced. Consequently, the specimen becomes very small, and a mini-tensile machine must be used. Such machines have been built. One is described by Kim and Weil (see Ref.). Care must also be taken not to deform the specimen while inserting it into the tensile machine. A way to plate a frame around the specimen, that is severed after insertion, is also described by Kim and Weil (see Ref.). In their machine, the load is applied by a

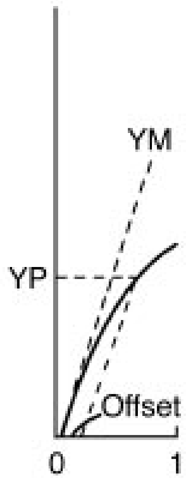

Fig. 2—Stress-strain curve of electroplated copper showing Young's modulus and the yield and tensile strengths.

computer-controlled turning of a very fine-threaded screw. The change in the gauge length is measured by the amount of light impinging on a photocell through two knife edges attached to the grips that hold the specimen in the machine.

The results of a uniaxial tensile test can be expressed in two ways: One as the so-called engineering properties and the other as the true properties. The engineering stress, σ, and the engineering strain, e, are based on the original specimen dimensions and are calculated by:

$$\sigma = P/A_0 \quad \text{and} \quad e = (L_i - L_0)/L_0 \qquad (4)$$

where P is the applied force, A_0 is the original cross sectional area of the middle portion, L_i is the gauge length corresponding to each load and L_0 is the original gauge length. The true properties are based on the instantaneous dimensions. The true stress, σ_T, and the true strain, δ, are calculated by:

$$\sigma_T = P/A_i \quad \text{and} \quad \delta = \ln (L_i/L_0) \qquad (5)$$

where A_i is the instantaneous area. The true strain can be calculated from the engineering strain. The true stress can be determined only from the engineering stress and the strain, as long as the cross sectional area remains uniform over the gauge length. The equations for doing so are:

$$\sigma_T = \sigma(1+e) \quad \text{and} \quad \delta = \ln (1 + e) \qquad (6)$$

Figure 1 is an engineering stress-strain curve of electroplated copper. Because the initial part of the curve is difficult to discern, the strain axis has been expanded in Fig. 2, where Young's modulus, designated YM, is the slope of the initial part of the curve. Any corresponding values of the stress and the strain can be used to calculate the slope. For example, at a strain of 0.5 percent, the stress is about 175 MPa. Young's modulus is therefore 175/0.005 MPa or 35000 MPa, which is equal to about 5 x 10^6 psi. This value is smaller than the handbook value of Young's modulus for copper. The reason for the difference will be discussed in subsequent installments.

There are two properties that define the beginning of the plastic range. They are the proportional limit, which is the point where the curve deviates from a straight line and the elastic limit, which is the largest stress that, when removed, does not result in a permanent length change. Both of these properties are difficult to determine, however. Therefore, the yield strength is generally used to indicate the beginning of the plastic range.

The yield strength is the stress that results in a small plastic strain called the offset, and is usually 0.1 or 0.2 percent. As shown in Fig. 2, the offset is laid off on the strain axis, and a line is drawn parallel to the slope of Young's modulus. The stress where this line intersects the stress-strain curve is the yield strength. The value of the yield strength, marked YP, is about 130 MPa or about 18,600 psi. When citing a value of yield strength, the magnitude of the offset should be specified.

It can be seen in Fig. 1 that the stress reaches a maximum, then decreases. The maximum engineering stress is the tensile strength. The value of the tensile strength in Fig. 1 is about 250 MPa or 35,700 psi. The reason for the maximum is necking. The width and the thickness decrease rapidly over a small portion of the gauge length. Subsequently, fracture occurs in the necked portion.

According to Eq. (4), the engineering stress decreases when the cross sectional area decreases more than the increase in the force. Because the area must remain uniform over the gauge length for the relationship between the true and the engineering stress of Eq. (6) to hold, it cannot be used after necking has occurred. The true stress-strain curve does not show the maximum because the decrease in the cross sectional area is taken into consideration. Brittle materials generally do not show necking and the stress maximum. The tensile strength is, therefore, the one that caused fracture.

Ductility is usually defined in terms of percent elongation. It is the engineering strain at fracture. According to Fig. 1, the percent elongation is about 18 percent. If a stress-strain curve is not available, the percent elongation can be determined by fitting the two fractured pieces back together and measuring the gauge length. The original gauge length is then subtracted from this value. The difference is then divided by the original gauge length, and the result is the percent elongation. When the two fracture pieces were fitted back together, the elastic strain had been relieved. The value of the percent elongation is therefore smaller than the one obtained from the stress-strain curve. The percent elongation obtained by fitting the fractured pieces back together can also be larger because of a poor fit.

The reduction in area at fracture is a less frequently used indication of ductility. It is often difficult to measure the area of the fracture. The value of the reduction in area of electrodeposits is often much greater than the percent elongation. It indicates that many electrodeposits are quite ductile. This subject will be discussed in a subsequent communication. **P&SF**

Reference

Kim and R. Weil, Testing of Metallic and Inorganic Coatings, ASTM STP 947, H.B. Harding and G.A. DiBari, Eds., ASTM, Philadelphia, PA (1987); pp. 11-18.