Elastic-Plastic Analysis of Deformation Induced by Thermal Stress in Eutectic Composites: II. Thermal Expansion

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In part I, a theory was developed to analyze the deformation produced in eutectic composites by temperature changes. Experimental determinations of the coefficient of expansion are used here to test the predictions of that theory. Measurements of length versus temperature in the absence of external stresses were made for Al-Al$_3$Ni, Al-CuAl$_2$, and Sb-Cu$_2$Sb eutectic composites, and for monolithic 6061 Al. Hysteresis loops in the graph of composite coefficient of expansion vs temperature are seen when the expansion coefficients of the phases are different and plastic deformation occurs. The nature of the hysteresis is shown to depend upon heating and cooling rates, prior history and the relative values of the matrix and reinforcement expansion coefficients. The theory correctly predicts these qualitative effects. In Al-Al$_3$Ni, the available component data justify a quantitative comparison of calculated and experimentally determined coefficient of expansion-temperature curves. The values compare well, further verifying the analytical approach.

In part II, an analysis for calculating the deformation of eutectic composites during temperature changes was derived. That analysis is directed principally toward the problem of thermal-cycling damage with or without applied loadings. Experimental confirmation of the theory through measurements of cycling damage is difficult, however. Presently the modes of deformation during cycling damage have not been determined positively, wide scatter exists in the available data, and measurements of internal stresses are not currently possible. As a result, meaningful quantitative comparisons of predictions and results of thermal cycling experiments cannot now be made.

Fortunately, measurements of the composite coefficient of thermal expansion can be used as a direct test of the analytical predictions. DeSilva and Chadwick measured contraction of Cu-W and Fe-B composites during cooling to verify their approach to thermal stresses. Koss and Copley have utilized this experimental method with a Co-Cr-C eutectic to determine the "stress-relaxation temperature," which corresponds to the point of initiation of plastic flow during heating in the present analysis. Thermal expansion measurements are relatively quick and simple to perform. Moreover, the measurement averages over small inhomogeneities in microstructure which may influence thermal cycling deformation but are not as yet incorporated into the analysis. It is the purpose of this paper to report measurements of the composite coefficient of thermal expansion and to compare the observed results to the analytical predictions of the proposed theory.

The coefficient of expansion of monolithic materials is usually thought to be a simple function of temperature, not related to any internal mechanical deformation or external variable such as heating or cooling rate (assuming uniform temperature is approximately maintained). As shown by the present measurements, this is not the case for composites. The normalized elongation ($\Delta L/L$)$_C$ of a composite $c$ during a change in temperature in the absence of external loading is

$$\frac{\Delta L}{L} = \int_{T_1}^{T_2} \alpha_T dT + \varepsilon_{pl}$$

where $\alpha$ is the linear coefficient of thermal expansion, $\varepsilon$ is mechanical strain, the subscript $r$ refers to reinforcement, and $T$ is temperature. An identical expression is valid for the matrix, as the composite, reinforcement, and matrix total strains are assumed identical. The (composite) coefficient of thermal expansion as measured by a device external to the sample is defined as

$$\alpha_c = \frac{\partial}{\partial T} \left( \frac{\Delta L}{L} \right)_C$$

by analogy with the definition for monolithic materials. Substituting Eq. [1] into Eq. [2], the composite coefficient of expansion is found to be

$$\alpha_c = \frac{\partial}{\partial T} \left[ \int_{T_1}^{T_2} \alpha_T dT + \varepsilon_{pl} \right]$$

The expression $\int \alpha_T dT + \varepsilon_{pl}$ comes from Eq. [2] of part I. It is simply the total strain, thermal plus mechanical, which a phase experiences during a temperature change. The change of the total-strain expression with temperature is the in-situ coefficient of thermal expansion of either phase or the composite. This total quantity is measured easily, while the individual terms cannot be readily separated. By means of the derivation of part I this total strain can be calculated directly from the material and cycling parameters.

This paper reports measured coefficients of thermal expansion for three eutectic composites. For the Al-Al$_3$Ni eutectic sufficient data exists to allow quantitative comparisons of measured and predicted coefficients of expansion. The effects of external variables on the expansion coefficient are also investigated and discussed.
EXPERIMENTAL PROCEDURE

Alloys were produced from 99.999 pct pure Al, Cu, and Sb and 99.97 pct pure Ni. These components were combined as the Al-6 wt pct Ni (rodlike Al-AlNi), Al-33.2 wt pct Cu (lamellar Al-CuAl2), or Sb-24.2 wt pct Cu* (Sb-Cu2Sb) eutectics. Melting was done in graphite crucibles with about 150 K superheat, and the melts were cast directly into graphite molds in each case. The directional solidification was accomplished by passing the mold containing the melt vertically through an induction coil at a rate of 3.5 cm per h. All melting and directional solidification was performed in flowing argon gas at 1 atm. Specimens for use in thermal cycling experiments were machined from single-grain regions of each ingot. In addition, a piece of commercial 6061 fine-grained Al was used to check the apparatus. The specimens were right-circular cylinders 2.54 cm (1.000 in.) long by 0.56 cm (0.220 in.) in diam. A small hole was drilled in the side of each specimen. A chromel-alumel thermocouple made of 0.028 cm (0.011 in.) diam wire was inserted into the hole, and the hole entrance was peened slightly to hold the thermocouple in place.

The dilatometer constructed to measure thermal expansion is drawn in Fig. 1. This instrument is nearly self-compensating with respect to push-rod expansion. Although not quite as accurate as commercial dilatometers, this device has several advantages for the present work. First, the unit is lightweight and portable. Second, it is sufficiently stable that it can be moved about with little change in the LVDT (linear voltage differential transformer) output signal. Finally, since access to only one side of the heating and cooling medium is required, the tube containing the sample can be immersed into various constant-temperature baths to provide high cooling or heating rates, while length and temperature are continuously monitored.

Heating and cooling were accomplished using a variety of methods. In each case the experimental conditions produced approximately constant rates. Low rates were obtained with the specimen inserted in a low-heat-capacity furnace. Higher heating rates could be achieved by placing the specimen into a hot furnace or bath. Higher cooling rates were reached by simply removing the sample from the heated area or by quenching into cold water. These techniques provided information on the heating- and cooling-rate dependence of expansion.

The basic data measured were length, temperature, and time. Temperature versus time was recorded on a strip chart recorder to give a permanent record of temperature-change rates. Length versus temperature was plotted on an x-y recorder. From the slope of this curve the coefficient of thermal expansion may be derived, as defined by Eq. [2].

Following the expansion measurements the samples were sectioned longitudinally, polished and examined metallographically. No evidence of fractures was found in any case.

RESULTS

Sample Calculation

The experimental plots of length change and thermal expansion coefficient versus temperature contain several unusual features. As an introduction to these figures, results of a sample computation will be briefly discussed. In part I a calculation of stresses and strains for a hypothetical composite was reported. The predicted composite length change and coefficient of expansion were calculated at the same time using Eqs. [1] and [3] and are shown in Figs. 2(a) and (b). The matrix and reinforcement coefficients of expansion are

\[ \text{Fig. 2} \quad \text{Predicted (a) length-temperature and (b) coefficient of expansion-temperature curves using theory and parameters of part I. The letters in part (b) correspond to those in Figs. 2 of part I. Arrows in this and other figures indicate the direction of the temperature change.} \]

Fig. 1—Diagram of dilatometer constructed for measurements of the composite coefficient of expansion.