Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Materials & Molecular Research Division

Submitted to Scripta Metallurgica

RELEASE OF ELASTIC STRAIN ENERGY AS ACOUSTIC EMISSION DURING THE REVERSE THERMOELASTIC PHASE TRANSFORMATION IN Au-47.5 at.% Cd ALLOY

J. Baram, J. Avissar, Y. Gefen, and M. Rosen

May 1980

DISCLAIMER

RELEASE OF ELASTIC STRAIN ENERGY AS ACOUSTIC EMISSION DURING THE REVERSE THERMOELASTIC PHASE TRANSFORMATION IN Au-47.5 at.% Cd ALLOY

J. Baram, J. Avissar and Y. Gefen
Materials Engineering Department
Ben Gurion University, Beer Sheva, Israel

and

M. Rosen[*]
Molecular and Materials Research Division
Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

INTRODUCTION

The characteristic behavior of the acoustic emission during thermoelastic phase transformations in Au-Cd alloys has previously been reported (1-3). The estimated energy of the acoustic energy was found to be approximately one order of magnitude larger during the phase transformation on heating than on cooling. No attention has been paid, so far, as to the source of the acoustic activity during martensitic phase transformations. However, it is generally accepted that the rapid release of energy within a material generates transient elastic waves of a certain amplitude and frequency content. This acoustic emission is related to the intrinsic mechanism of the martensitic transformation.

Martensite formation occurs by a diffusionless shear mechanism involving the cooperative movement of a large number of atoms accompanied by a release of elastic strain energy. The thermoelastic martensite is typically athermal, where the amount of martensite depends on the formation temperature during cooling. Upon heating, the reverse transformation occurs by the backward movement of the martensitic interfaces, thus annihilating the elastic shape strains introduced during the forward transformation on cooling. The almost perfectly reversible mechanism, characterizing the thermoelastic martensitic transformation (4,5) is paradoxically accompanied by a high asymmetric acoustic energy balance (1-3).

The objective of this paper is to present experimental evidence concerning the acoustic energy evolved during the heating and cooling phase changes in Au-47.5 at.% Cd polycrystals. The results are examined from the point of view of the stored elastic strain energy during the martensite formation, and the frictional work that is dissipated by the movement of martensite interfaces in either direction, upon heating and cooling (6-8).

EXPERIMENTAL PROCEDURE AND RESULTS

Polycrystalline specimens of Au-47.5 at.% Cd alloy were heated and cooled through the transformation temperature range, from 10°C up to 120°C and back, at controlled heating and cooling rates. A quartz rod was used as a waveguide, and coupled to a PZT transducer with a resonant frequency in the 150-300 kHz range. The experimental procedure was described elsewhere (3). Filtered signals, preamplified at a constant gain of 40 dB, were fed into an amplitude detector that characterizes the acoustic emission signals according to their peak-amplitude. Amplitude

---

[*]On leave from the Materials Engineering Department, Ben Gurion University, Beer Sheva, Israel

distribution, with 1 dB resolution, was then performed by a Distribution Analyzer giving a definite voltage for each channel. The amplitude distribution was chart-recorded.

The correlation between the peak amplitude of the signals and the energy release at the transducer face was established by letting hardened steel balls of different mass m fall onto the quartz rod and the transducer face from different heights h. The square of the recorded peak voltage and the potential energy (E = mgh) were found to be linearly related as

$$E = (1.80 \pm 0.20) \times 10^{-6} \, V^2$$

where E and V is given in joules and volts, respectively.

The overall acoustic energy associated with the phase transformation in either direction, E_{AE}, may then be evaluated by summing up the number of pulses counted in each channel, n_i, weighted by the squared voltage V corresponding to each channel in the Distribution Analyzer.

$$E_{AE} = 1.80 \times 10^{-6} \sum_i n_i V_i^2 \quad \text{(joules)}$$

Typical amplitude distributions are shown in Fig. 1.

The amplitude threshold was set to 15 dB in order to eliminate spurious and very low amplitude signals.

Several runs were performed, at similar and different heating and cooling rates (between 0.5 c/min to 4.5 c/min) with specimens of various volumes (from 1/1500 to 1/550 molar volume).

The noteworthy result of the present series of experiments is the constant energy per mole value obtained when the difference of the acoustic energy during heating and cooling was calculated, namely

$$E_{AE}(\text{reverse}) - E_{AE}(\text{forward}) = 500 \pm 40 \; \text{Joule mole}^{-1}$$

It should be emphasized, in this context, that the reverse transformation considered (during heating) was always preceded by the forward transformation. The difference between the energies of the reverse and forward transformations remained constant in six different runs, and for samples of various dimensions.

Figure 1 shows that both the forward and reverse transformations generate acoustic signals with peak amplitudes in the 10-20 dB range, while the reverse transformation, on heating, exhibits a supplementary active peak at 32 dB.

DISCUSSION

The constant excess acoustic energy during the reverse thermoelastic phase transformation in Au-47.5 at.% Cd appears to be the configurational elastic strain energy stored in the specimen during the forward martensitic reaction. This stored energy is released during the heating semicycle, upon the reverse transformation, in the form of scattered acoustic waves that can be detected as acoustic emission.

The thermoelastic free-energy balance (7,8)

$$\Delta G_{ch}^{A \to M} - \eta \Delta G_{el} = -W_f \tag{1}$$

where ΔG are the chemical (ch) and elastic (el) strain free-energy changes, referred to the martensitic phase (M), and W_f is the frictional work that is dissipated during the growth of the parent (A) – martensitic (M) interfaces in the Au-Cd polycrystal. This frictional work has been shown to be dependent on the grain size (6), and is not evolved in single crystal (single interface) samples (9).

Assuming that no additional obstacles to the moving interfaces are introduced during the growth, or shrinkage, of the parent-martensite interfaces, the frictional energy (W_f) must be identical for both transformation directions. This frictional energy is apparently a source for acoustic emission, and the only one for the forward transformation, since the configurational elastic energy is stored in the martensitic phase. Therefore:

$$E_{AE}(\text{forward}) = W_f \tag{2}$$

During the transverse transformation, on heating, the detected acoustic emission energy is due to both the frictional energy (W_f) of the shrinking interfaces, and to the released configurational elastic stored energy (ΔH_{conf}). Thus:

$$E_{AE}(\text{reverse}) = \Delta H_{conf} + W_f \tag{3}$$

where the value of ΔH_{conf} should depend on the specific crystallographic features of the transformation.

For the thermoelastic martensitic transformation in Au-47.5% at.% Cd with B2 $\rightleftharpoons$ orthorhombic phase changes, the present investigation led to the conclusion that

$$\Delta H_{conf} = E_{AE}(\text{reverse}) - E_{AE}(\text{forward}) = 500 \pm \text{ Joule/mole.}$$

This experimental value for the elastic stored energy is in fair agreement with reported values of 770 Joule·mole^{-1} (10) and 370 Joule·mole^{-1} (11) for Au-47.5% at.% Cd, and with the estimated non-chemical free energy for Fe-C alloys, ranging from 200 to 1600 Joule·mole^{-1} (12).

As stated before, the frictional energy (W_f) is dissipated during the growth and shrinkage of the parent-martensite interfaces. The acoustic energy generated during the cooling semicycle is assumed to be due entirely to W_f. Resistance to interfacial motion has been found to increase with the interfacial velocity (13). The present investigation revealed this trend. Three runs performed on the same specimen at different cooling rates, yielded acoustic energies that were found to be directly proportional to the cooling rates (Table 1).

Further experiments are in progress in order to determine the effect of cooling rate, grain-size and composition on the generated acoustic energy.

TABLE 1.

Acoustic Energies vs. Cooling Rates.

Cooling rate (c/min):	1.25	1.85	4.25
Acoustic energy (Joule/mole):	14.7	34.5	121.4

3

REFERENCES

1. R. G. Liptai, H. L. Dunegan and C. A. Tatro, Int. J. Nondestructive Testing 1, 213 (1969).
2. A. E. Brown and R. G. Liptai, "Acoustic emission," in ASTM Special Publication 505, p. 318-331, American Society for Testing Materials, Philadelphia (1972).
3. J. Baram and M. Rosen, Met. Trans. A., (to be published).
4. N. Nakanishi and C. M. Wayman, Trans. Japan. Inst. Metals 4, 179 (1963).
5. B. S. Subramanya, G. S. Baker, D. S. Lieberman and T. A. Read, J. Aust. Inst. Metals 6, 3 (1961).
6. N. Nakanishi, M. Takano, H. Morimoto, S. Miura and F. Hori, Scripta Met. 12, 79 (1978).
7. G. B. Olson and M. Cohen, Scripta Met. 9, 1247 (1975).
8. G. B. Olson and M. Cohen, Scripta Met. 11, 345 (1977).
9. R. J. Salzbrenner and M. Cohen, Acta Met. 24, 739 (1979).
10. Y. Gefen, A. Halwany and M. Rosen, Phil. Mag. 28, 1 (1973).
11. N. Nakanishi, T. Mori, S. Miura, Y. Murakami and S. Kachi, Phil. Mag. 28, 277 (1973).
12. Z. Nishiyama, in Martensitic Transformations, edited by M. E. Fine, M. Meshii and C. M. Wayman, p. 256, Academic Press, New York, (1978).
13. K. Otsuka, C. M. Wayman, K. Nakai, H. Sakamoto and K. Shimizu, Acta Met. 24, 207 (1976).
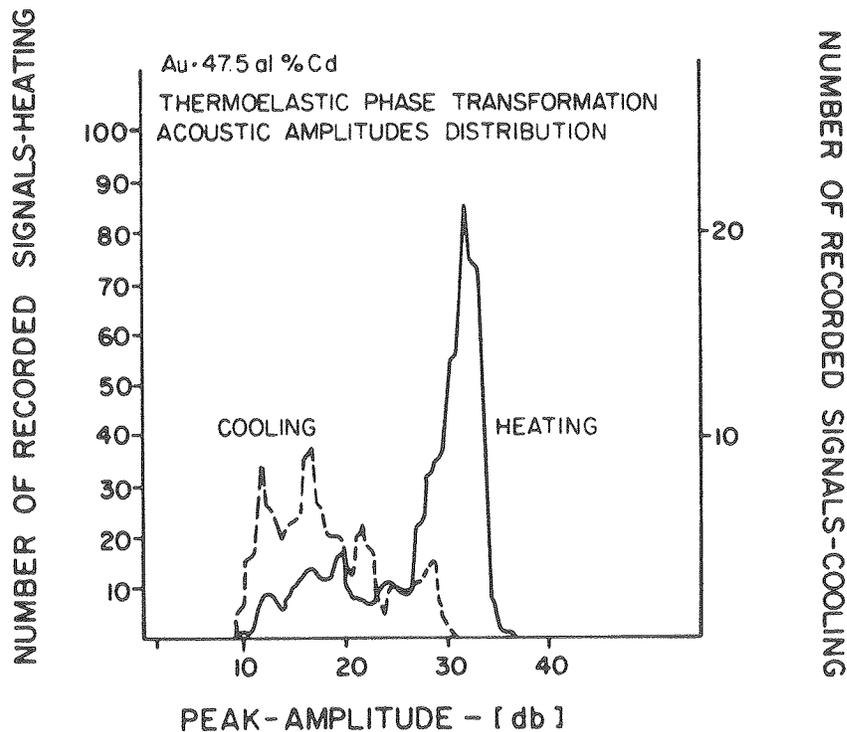
FIG 1.

Amplitude distribution during forward (2°C/min cooling rate) and reverse (1°C/min heating rate) transformations. (Notice the ordinate scale change.)