Non-linear elastic properties of CuZnAl alloys near martensitic transformation

A. Biscarini, B. Coluzzi and F.M. Mazzolai

Department of Physics, University of Perugia, Perugia (Italy)

Abstract

The amplitude dependence of the dynamic Young modulus has been investigated during temperature cycling in the vicinity of the martensitic transformation. The Young modulus E is smaller at higher vibration amplitudes. On cooling, the difference ΔE between the value of E at the lowest strain ϵ_0 and at the current strain ϵ passes through a pronounced structured maximum in the transition region. On heating, ΔE shows a hardly noticeable peak, followed by a steep decrease over the reverse transition region. Non-linear effects also occur far above the martensite start temperature M_s and are the result of precursor effects.

1. Introduction

The martensitic transition has been investigated in an enormous number of systems during the past few decades and its main features, although highly sensitive to the system, are reasonably well established now. Among these is the incomplete softening of the C' elastic constant, which takes place when the martensite start temperature M_s is approached on cooling. The incompleteness of C' softening, that is of the decrease of C' occurring below M_s, contradicts the soft-mode theories of the transition, originally proposed by Zener [1].

More recent models [2–5] have taken into account the role played by anharmonic couplings of the C' shear homogeneous strain with inhomogeneous shuffling strains, and have been able to account for first-order structural transitions without the need for complete softening of C'.

Experimental evidence of anharmonic effects which occur in the vicinity of the martensitic transition has occasionally been reported in the literature [6, 7]; however, the amount of information available so far is inadequate to support directly the above anharmonic models. Thus, a program has been undertaken for the systematic investigation of non-linear elastic effects in the vicinity of the martensitic transition. Preliminary results monitored on cooling have been reported elsewhere [8]. Here, data obtained during temperature cyclings will be presented and discussed.

2. Experimental details

The atomic composition of the alloy used in the present work was 67.83 Cu, 19.03 Zn and 13.4 Al. After melting, the material was homogenized at 1073 K for about 4×10^4 s, then machined to the form of rectangular bars of dimensions 1.5 mm $\times$ 5 mm $\times$ 46 mm. Prior to any measurements, the samples were treated at 1050 K for 1200 s, then quenched in boiling water. The elastic energy dissipation coefficient Q^{-1} was deduced from the decay of free resonant vibrations. The amplitude of these vibrations was changed by changing the excitation voltage applied to an excitation electrode kept at a constant distance from the sample. The Young modulus was derived from the resonant frequency of the bar, which was about 2350 Hz.

3. Results

The temperature dependence of the elastic energy dissipation coefficient Q^{-1} and of the Young modulus E monitored during a temperature cycle is shown in Fig. 1. As can be seen, pronounced asymmetric peaks occur in the Q^{-1} (T) curves over the temperature regions where the parent phase–martensite (P–M) and martensite–parent phase (M–P) transition take place on cooling and on heating respectively. Concomitant depressions (elastic softenings) are displayed by the $E(T)$ curves.

For better characterization of the P–M and M–P transitions, the martensite start (M_s), martensite finish (M_f), reverse start (A_s) and reverse finish (A_f) tem-
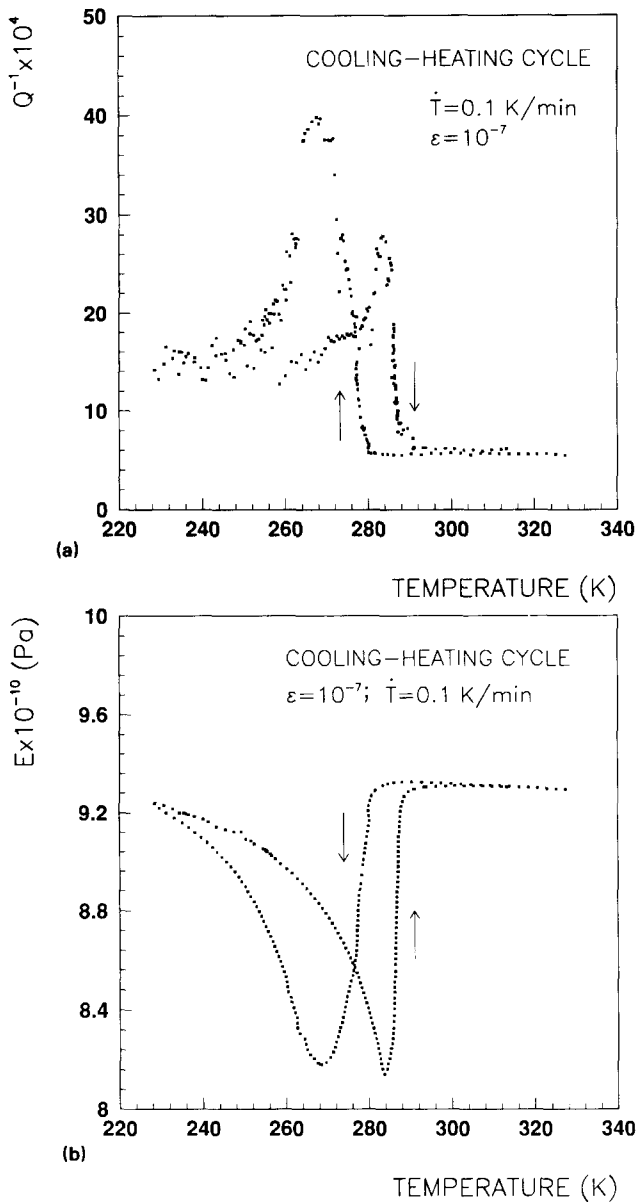
Fig. 1. Temperature dependence (a) of the elastic energy dissipation coefficient Q^{-1} and (b) of the Young modulus E during a slow cooling–heating (0.1 K min^{-1}) cycle at 2350 Hz and at a strain amplitude of about 10^{-7}.

peratures were determined by differential scanning calorimetry (DSC) [9] in a sample subjected to the same temperature cyclings as those used in the present experiment. For the thermal cycle corresponding to that in Figs. 1(a) and 1(b), the temperature values deduced from the intercept of the baseline with the tangent to the calorimetry curves at the inflexion points were $M_s = 278.5 \pm 0.5$ K, $M_f = 270.0 \pm 0.5$ K, $A_s = 282.0 \pm 0.5$ K and $A_f = 286.0 \pm 0.5$ K.

The incompleteness of the elastic softening process down to the lowest temperatures makes the determination of M_f and A_s from $E(T)$ curves uncertain. Thus, only M_s and A_f were deduced and their values

$(M_s = 278 \pm 1$ K, $A_f = 287 \pm 1$ K) were in good agreement with those derived from the calorimetry data. Therefore, it can be inferred that stresses involved in the measurements of E do not markedly affect P–M and M–P transitions.

The amplitude dependence of the Young modulus during a partial temperature cycle is shown in Fig. 2, while the difference ΔE between the Young modulus measured at the lowest strain ϵ_0 and that at the current strain ϵ is reported in Fig. 3. As can be seen, two
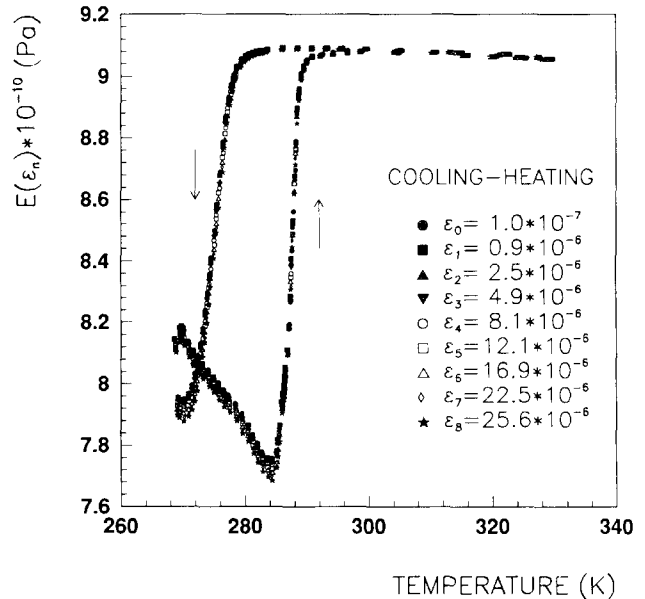

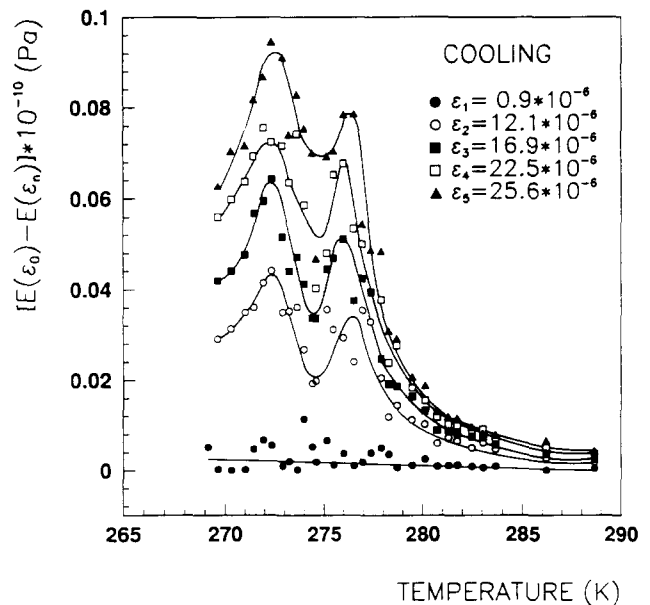Fig. 2. Partial temperature cycle taken at the strain amplitudes indicated in the figure.

Fig. 3. Temperature dependence during cooling of the difference ΔE between the Young modulus at the lowest strain (10^{-7}) and at the strains quoted in the figure.

peaks are displayed in Fig. 3 at temperatures (276 and 272 K) slightly higher than those corresponding to the points of inflexion (275 K) and of the minimum (270 K) in the cooling curve $E(T)$ of Fig. 2. An important feature of these peaks is the insensitivity of their temperatures to strain amplitude changes. This feature again suggests negligible effects of the low level measuring stresses on the P–M transition.

In Fig. 4, data taken at temperatures much higher than M_s are plotted with an enlarged scale. As can be seen, anharmonicity (ΔE) starts to increase far above M_s. Partial cycles carried out between the upper limit
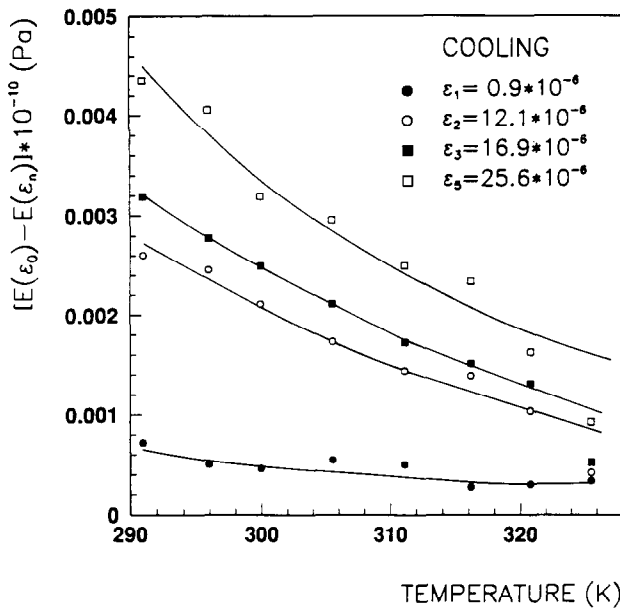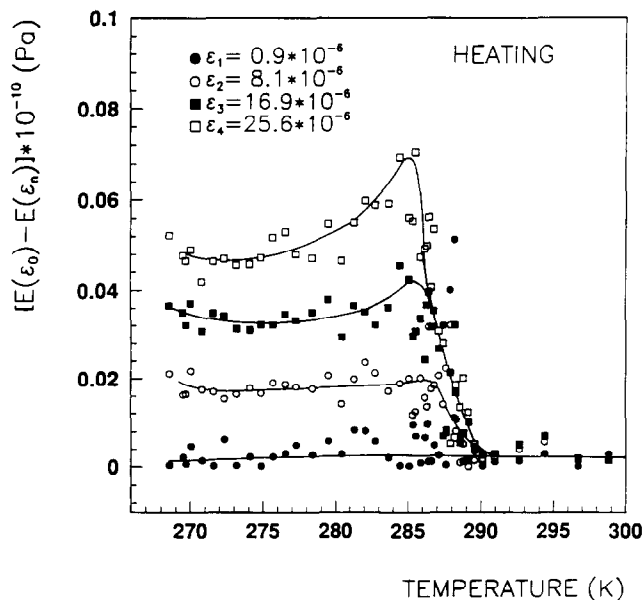
of 330 K and the lower limits of 287, 285 and 282 K display no hysteresis of the ΔE curves.

Data obtained on heating (Fig. 5) show that anharmonicity is high within the martensite phase and passes through a single maximum at a temperature (285 K) which is slightly higher than the temperature of the minimum (284 K) in the corresponding $E(T)$ curve of Fig. 2. Thus, it is conceivable that this peak is associated with the lower temperature peak of Fig. 3.

4. Discussion and conclusions

The major question to be answered first concerns whether the observed non-linearity is an intrinsic property of the bulk lattice or is instead related to strain amplitude-dependent motions of martensite–martensite and martensite–parent phase interfaces. In principle, measurements carried out over temperature ranges where a single phase is present should be able to provide the correct answer to this question. In practice, however, discrimination between the two possibilities is a difficult task, because the martensite and parent phases can coexist under the effect of internal stresses, even at temperatures far above M_s and far below A_s.

Despite the above difficulties, the present high temperature results seem to show convincingly that anharmonicity is a bulk lattice effect. In fact, ΔE starts to increase at temperatures which appear exceedingly high (at least 50 K above M_s) to be associated with the presence of the martensite. Furthermore, no hysteresis has been monitored in the Young modulus and DSC data in the course of partial cyclings carried out at temperatures higher than 300 K.

Further questions to be addressed concern the source of anharmonicity below A_s, and the nature of $\Delta E(T)$ peaks of Figs. 3 and 5. In agreement with previously reported data [8], Fig. 5 shows that ΔE is virtually insensitive to temperature changes far below A_s. This feature rules out the possibility that this kind of anharmonicity is associated with the M–P transition. Most likely, it arises from strain–amplitude-dependent motions induced by the measurement stress of martensite–martensite interfaces. The gradual increase displayed by ΔE on approaching the reverse transition temperature A_s is probably the result of bulk lattice non-linearity, which causes the martensite structure to become unstable at the temperature of the peak (285 K). Similarly, on cooling, the higher temperature peak of Fig. 3 is expected to correspond to a state of instability of the parent phase at around 276 K. An understanding of the lower temperature peak is less clear; however, it seems reasonable to attribute it to a transition of the martensite formed at around 276 K into another

Fig. 4. As in Fig. 3 but at temperatures above M_s (278.5 K).

Fig. 5. As in Fig. 3 but during heating.

structure which is stable at low temperatures. Whether this transition involves lattice structure changes or alterations in the morphology of the martensite variants is still an open question.

In conclusion, the present results provide some evidence that, within the accuracy of the present experiments, the reverse M–P transition is a single-stage transition, while the direct transition takes place through two distinguishable stages.

Acknowledgments

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