Materials Science and Engineering A 521–522 (2009) 109–112

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

# Anelasticity of polycrystalline indium

K. Sapozhnikov[a,*], S. Golyandin[a], S. Kustov[b]

[a] A.F.Ioffe Physical-Technical Institute, Politekhnicheskaya 26, 194021 St. Petersburg, Russia
[b] Dept. de Física, Universitat de les Illes Balears, Cra Valldemossa km 7.5, E 07122 Palma de Mallorca, Spain

ARTICLE INFO

*Article history:*
Received 26 June 2008
Accepted 1 October 2008

*Keywords:*
Anelasticity
Indium
Internal friction
Lattice defects

ABSTRACT

Mechanisms of anelasticity of polycrystalline indium have been studied over wide ranges of temperature (7–320 K) and strain amplitude ($2 \times 10^{-7}$–$3.5 \times 10^{-4}$). Measurements of the internal friction and Young's modulus have been performed by means of the piezoelectric resonant composite oscillator technique using longitudinal oscillations at frequencies of about 100 kHz. The stages of the strain amplitude dependence of the internal friction and Young's modulus defect, which can be attributed to dislocation – point defect and dislocation – dislocation interactions, have been revealed. It has been shown that thermal cycling gives rise to microplastic straining of polycrystalline indium due to the anisotropy of thermal expansion and to appearance of a "recrystallization" internal friction maximum in the temperature spectra of amplitude-dependent anelasticity. The temperature range characterized by formation of Cottrell's atmospheres of point defects around dislocations has been determined from the acoustic data.



## 1. Introduction

Indium and indium-based alloys have attracted particular attention as high-damping materials [1,2], specifically as components of high-damping composite materials [3,4]. However, internal friction (IF) of indium is poorly known. The available data [1,5–8] are inadequate to draw justified conclusions about mechanisms of the IF. The present work is devoted to the study of the anelastic properties of polycrystalline indium over wide temperature and strain amplitude ranges.

## 2. Experimental details

IF and effective Young's modulus (YM) of indium were measured over wide ranges of temperature (7–320 K) and oscillatory strain amplitude ($2 \times 10^{-7}$–$3.5 \times 10^{-4}$) by means of the piezoelectric resonant composite oscillator technique [9] using longitudinal oscillations at frequencies of about 100 kHz. A computer-controlled setup [10] enabled us to measure the temperature spectra of the IF and YM simultaneously at two values of the strain amplitude and to follow the amplitude-independent and amplitude-dependent anelastic effects in a single thermal cycle. The strain amplitude dependence of the IF and modulus defect was measured at room temperature and 7 K in isothermal conditions and at different temperatures during heating in certain thermal cycles. During the measurements, the oscillatory strain was first increased and then decreased (forward and reverse runs). The thermal cycling was performed in a He atmosphere at a heating/cooling rate of about 1–2 K/min.

Polycrystalline indium of better than 99.99 wt.% purity was supplied by Electrozinc, Russia. According to data of chemical analysis, Pb is the main impurity (0.006 wt.%). Traces of Cu, As, Cd, Sn, Zn, Fe have been also found. Rod-shaped samples with cross-section of about 1 mm × 1 mm were spark cut from an ingot. It was impossible to make the measurements over the entire temperature range with a single sample, since YM of indium varied by a factor of about 2.5. Thus, the measurements were first performed in a low-temperature range (7–180 K) with a sample 8.3 mm long. Then the sample was shortened to 6.0 mm and the measurements were performed in a high-temperature range (130–320 K).

## 3. Results

The strain amplitude dependence of the IF and modulus defect of indium measured at room temperature is shown in Fig. 1. One can distinguish two stages of the dependence. The IF and modulus defect are completely reversible at strain amplitudes lower than $\sim 10^{-4}$. At higher strain amplitudes, a steep rise of the IF and modulus defect occurs, which is accompanied by their positive amplitude hysteresis (the reverse run is higher than the forward run). The variations in the IF and modulus defect caused by the high-amplitude measurements are rather stable as they recover very slowly with aging at room temperature (curve 4).

The strain amplitude dependence of the IF measured at 7 K also exhibits two stages (Fig. 2). The amplitude hysteresis of the IF is lacking for measurements up to a maximum strain amplitude of about

* Corresponding author. Tel.: +7 812 2927119; fax: +7 812 2971017.
*E-mail address:* k.sapozhnikov@mail.ioffe.ru (K. Sapozhnikov).

0921-5093/$ – see front matter 
doi:10.1016/j.msea.2008.10.077

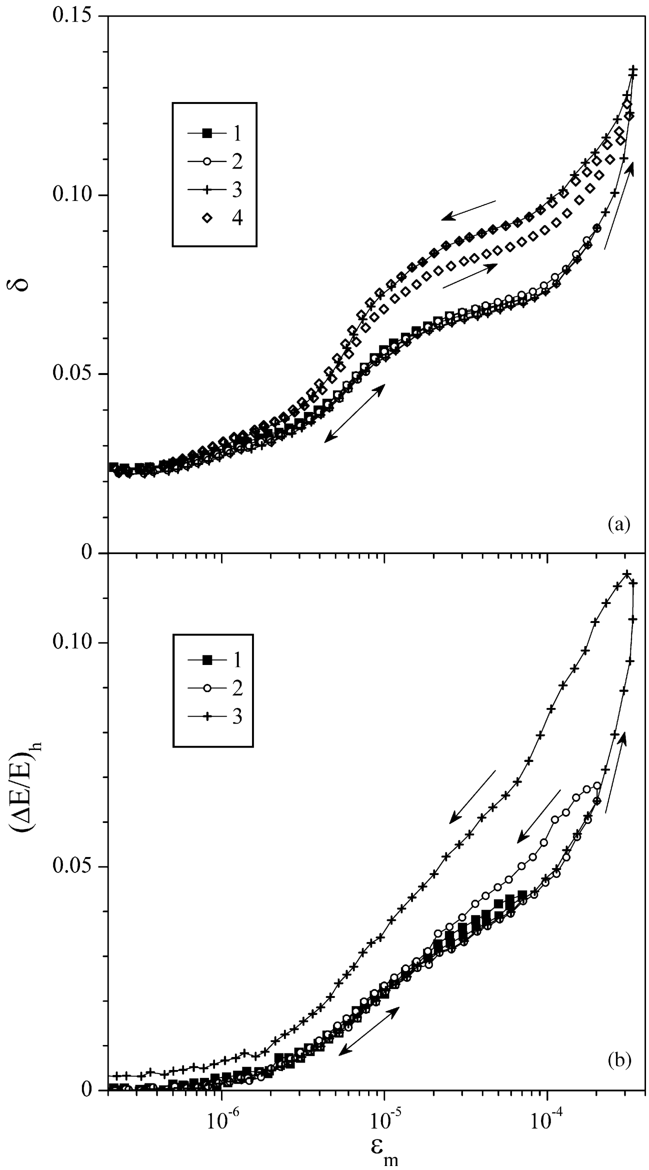


**Fig. 1.** Strain amplitude dependence of the decrement (a) and Young's modulus defect (b) measured at room temperature in consecutive runs to the maximum strain amplitude of $7 \times 10^{-5}$ (1), $2 \times 10^{-4}$ (2) and $3.4 \times 10^{-4}$ (3). Curve 4 was taken within 6 days after curve 3.

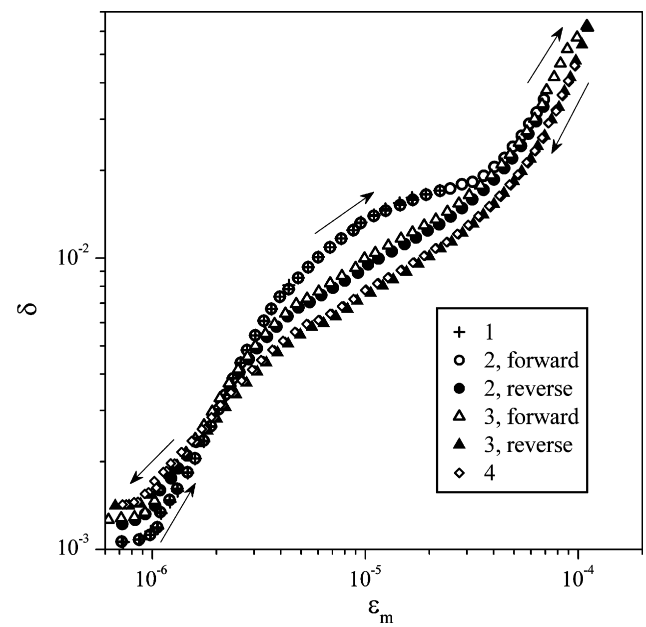


**Fig. 2.** Strain amplitude dependence of the decrement measured at 7 K in consecutive runs to maximum strain amplitude of $2 \times 10^{-5}$ (1), $7 \times 10^{-5}$ (2), $1.1 \times 10^{-4}$ (3) and $1.0 \times 10^{-4}$ (4).

$2 \times 10^{-5}$ (curve 1 in Fig. 2). For higher maximum strain amplitudes, the cross-over amplitude hysteresis of the IF, combined of negative hysteresis at high amplitudes and positive hysteresis at low amplitudes, appears provided the maximum strain amplitude is higher than that attained during previous measurements (curves 2 and 3 in Fig. 2). Otherwise the amplitude hysteresis is lacking, even though the strain amplitude range covers the high-amplitude stage (curve 4 in Fig. 2).

Fig. 3 shows temperature dependence of the IF of indium measured for two values of strain amplitude in the low-temperature (a) and high-temperature (b) ranges. The spectra at strain amplitude of $5 \times 10^{-7}$ account largely for the background (amplitude-independent) IF, whereas those at strain amplitude of $5 \times 10^{-6}$ correspond to the low-amplitude stage of the amplitude-dependent IF. A steep rise in the IF with increasing temperature at lowest temperatures gives way to a saturation (amplitude-dependent IF) or a decline (background IF) at temperatures of about 100 K (Fig. 3a). On heating, an asymmetric maximum is superimposed on the temperature spectrum of the amplitude-dependent IF at temperatures around 160 K. This maximum is lacking on cooling as well as on thermal cycling in a narrow temperature range around these temperatures. Note also a steep rise of the amplitude-dependent IF accompanied by step-like changes at the onset of cooling from temperatures of about 150 K (curve 2 in Fig. 3a) wherein the sample was held for about 10 h before cooling. In the high-temperature range (Fig. 3b), both background IF and amplitude-dependent IF pass through a minimum at temperatures of about 180–200 K. A steep IF rise is observed at higher temperatures. The high-temperature branches of the curves are represented on $T^{-1}$ – ln $\delta$ scales in the inset of Fig. 3b. One can notice that the temperature hysteresis of the amplitude-dependent IF is observed in a number of temperature ranges: (1) at low temperatures (7–70 K); (2) in the temperature range of the IF maximum; (3) in the high-temperature range wherein the temperature hysteresis of the IF is enhanced strongly by increasing the maximum temperature and the time of exposure at this temperature. In contrast to the amplitude-dependent IF, the background IF is well reproducible during thermal cycling, except for the initial transient portion of the cooling curve in Fig. 3a.

Measurements of the strain amplitude dependence of the IF at different temperatures during thermal cycling have shown that the low-amplitude stage of the dependence, which is completely reversible at 7 K and room temperature (Figs. 1 and 2), exhibits amplitude hysteresis in a certain intermediate temperature range. Fig. 4a depicts the appearance of the positive amplitude hysteresis at low amplitudes on heating in the low-temperature range. Fig. 4b shows the disappearance of the positive amplitude hysteresis at high temperatures (a slight negative amplitude hysteresis emerges at temperatures higher than 300 K). This process occurs in parallel with the onset of the IF rise.

## 4. Discussion

Although indium is prone to twinning, its plastic deformation under low stress is due to dislocation glide [11]. That is why dislocation motion will be considered below as responsible for the observed anelastic effects.