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Recovery study on the Young's modulus of shock-loaded alloy 2024 Al

J. J. LEE, CHING H. MA
Department of Metallurgical and Materials Engineering, New Mexico Institute of Mining and Technology, Socorro, New Mexico 87801, USA

The recovery of Young's Modulus of alloy 2024 Al shock-loaded at shock pressures of 1.5 and 11 kbars was investigated at 41 and 56° C respectively. The activation energy of diffusion and the maximum percentage of recovery for the specimens as a function of shock pressures were evaluated. Based on the experimental results, some aspects of the defects in the specimens as a function of shock pressure are discussed.

1. Introduction

In recent years in our laboratory the effects of shock-loading on the Young's moduli of a number of metals and alloys have been investigated [1–3] and, in particular, the effects of shock-loading on the Young's modulus of alloy 2024 Al have been extensively investigated in a pressure range of 58 to 178 kbars [4]. In this paper, the characteristics of the recovery of Young's modulus of shock-loaded alloy 2024 Al in the shock pressure range of 1.5 to 11 kbars will be presented and discussed. From the information gained on the recovery study an understanding of the nature of defects in the shock-loaded alloy as a function of shock pressure can be gained. The recovery temperatures employed in this investigation are 41 and 56° C, respectively.

2. Experimental technique

The alloy 2024 Al used in the present study was purchased from a commercial source. It is an aluminium-based alloy containing by weight 3.8 to 4% Cu, 1.2 to 1.8% Mg and traces of Mn, Si, etc. The specimens employed in the experiments were in the form of rectangular rods $\frac{1}{4}$ in. × $\frac{1}{4}$ in. × 2 in. Before shock-loading, the specimens were annealed in a furnace with argon atmosphere at the temperature of 540° C for about 10 h and then slowly furnace-cooled. After this heat-treatment the alloy is a stable multiple-phased alloy with possibly very small amounts of solute clusterings which are prone to form in this type of alloy. Shock-loading was done by using commercial explosives of P-22 lenses with TNT pads. The specimens immediately after shock-loading were dropped in a large water tank filled with cold water, so that the effect of specimens heating during shock-loading was minimized. The recovered specimens were then kept in a freezer until later examination and evaluation, usually done the following day. The Young's modulus of each specimen was measured before and after shock-loading, as well as after isothermal recovery annealing, by a device called a "double quartz resonator", similar to the one used by Marx and Sivertsten [5]. During measurement the fundamental resonance frequency of the double quartz resonator without the specimen was first measured. Then, the longitudinal resonance frequency of fundamental mode of the double quartz resonator with specimen attached was measured. From the two resonance frequencies, the longitudinal resonance frequency of fundamental mode of the specimen was evaluated. The Young's modulus of the specimen was then calculated according to the following equation:

$$f_s = \frac{1}{2L}\left(\frac{E}{\rho}\right)^{1/2} \qquad (1)$$

where f_s, L, ρ, and E are the longitudinal resonance frequency of fundamental mode, length, density and Young's modulus of the specimen, respectively. In this investigation the value of the density of the alloy was taken from literature.

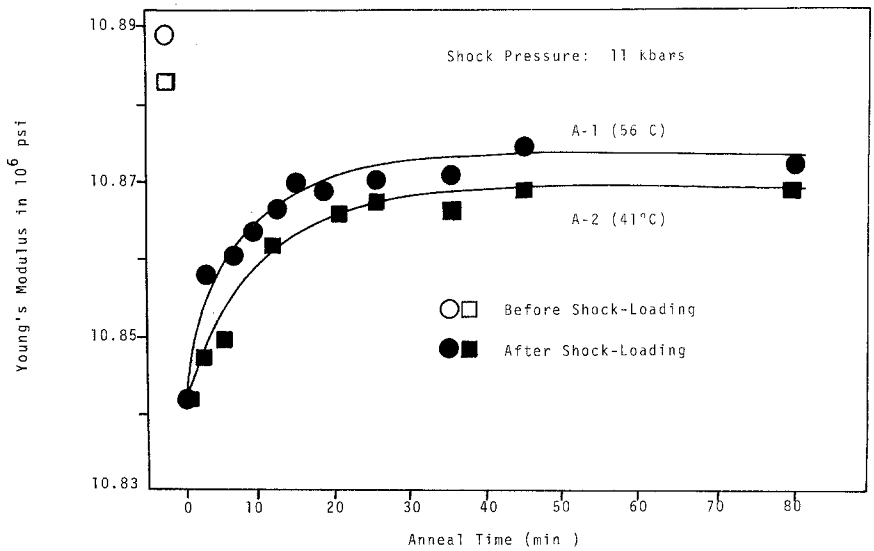

Figure 1 Recovery annealing of alloy 2024 Al after shock-loading.

During recovery isothermal annealing, the specimen was immersed in a water bath at a controlled temperature for a desired period and was then quickly quenched in ice-cold water. The measurement of resonance frequency of the specimen was done in a vacuum environment at room temperature. The recovery temperatures employed were 41 and 56° C, respectively. After obtaining sufficient data of Young's moduli versus isothermal annealing times at specific temperatures (either 41 or 56° C) for a specimen, another specimen which has approximately the same Young's moduli after shock-loading at the same shock pressure was isothermally annealed at another temperature in order to obtain the data of Young's Moduli versus annealing times for the purpose of construction of a pair of recovery curves such as shown in Figs. 1 and 2. Then, a horizontal line parallel to the time axis of the pair of recovery curves was drawn from an appropriate point of the vertical axis representing the Young's moduli. From the intercepts of the horizontal line on the two recovery curves the activation energy of diffusion which caused recovery phenomena is calculated using the following equation [6];

$$\ln\left(\frac{t_1}{t_2}\right) = \frac{\epsilon}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \qquad (2)$$

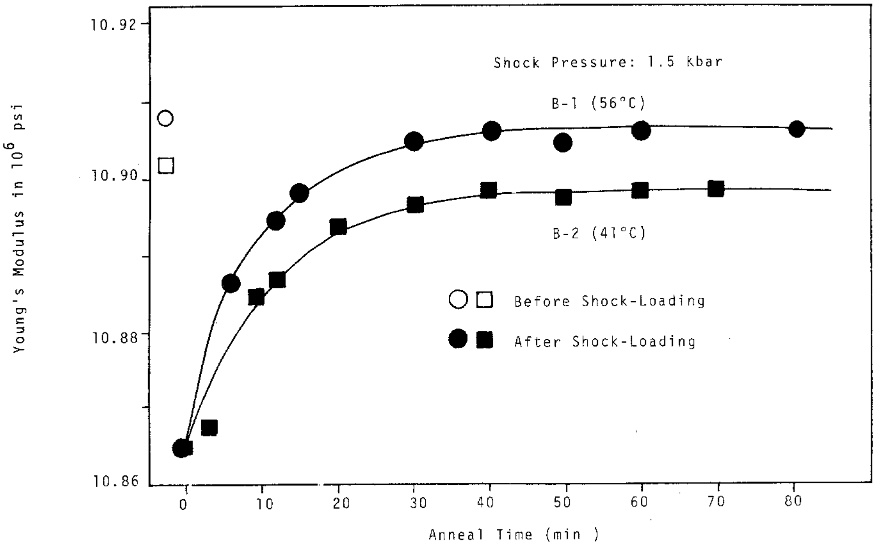

Figure 2 Recovery annealing of alloy 2024 Al after shock-loading.

TABLE I Maximum percentages recovery of Young's moduli of shock-loaded alloy 2024 Al

Specimens	Shock pressure (kbars)	Young's modulus before loading, $E_0 \times 10^6$ (psi)	Young's modulus after loading, $E_a \times 10^6$ (psi)	Max. Young's modulus after recovery $E_m \times 10^6$ (psi)	Max. % recovery $\frac{E_m - E_a}{E_0 - E_a}$
1	1.5	10.908	10.865	10.906	95*
2	1.5	10.902	10.865	10.899	92†
3	11	10.889	10.842	10.875	70*
4	11	10.883	10.842	10.870	68†

*at 56° C.
†at 41° C.

where t_1 and t_2 are annealing times corresponding to the two intercepts of the horizontal line on the two recovery curves, and T_1 and T_2 are corresponding recovery temperatures of the two recovery curves which are represented by the subscripts 1 and 2; ϵ is molar activation energy and R is molar gas constant. This method of obtaining activation energy of diffusion is commonly called the "cross-cut technique".

3. Experimental results

The experimental results on the recovery investigation of Young's Moduli of shock-loaded specimens of alloy 2024 Al at two different shock pressures recovered at 41 and 56° C are shown in Figs. 1 and 2. The estimated activation energies of diffusion during recovery of the specimens shock-loaded at 1.5 and 11 kbars are 0.31 and 0.35 eV respectively. These values were evaluated by the cross-cut technique on the basis of Equation 2. The maximum percentage recovery of Young's Modulus is shown as a function of shock pressure and temperature of recovery in Table I.

4. Discussion

4.1. Activation energy of diffusion during recovery

We suggest that the phenomenon of recovery of Young's Modulus of a specimen during recovery annealing is associated with migration of diffusing species (point defects or solute atoms) toward nearby dislocations to form clusters along them. The clusters formed along dislocations shorten the dislocation loops and thus, increase the magnitude of Young's modulus of the specimen. According to Mott [7] the elastic moduli of a solid containing dislocations are strongly affected by the average length of the dislocation loops. At a specific dislocation density in a solid, the longer the average dislocation loop length, the lower will be its elastic moduli.

In view of the magnitude of the activation energy of recovery in alloy 2024 Al shocked at pressures of 1.5 or 11 kbar, we suggest that during recovery treatment the diffusing species, which are responsible for the shortening of dislocation loops, are mainly vacancy complexes and interstitials [8–10]. In all shock-loaded metals they are very likely to contain appreciable amounts of interstitials.

4.2. Percentage recovery of Young's modulus

As shown in Table I, the maximum percentage recovery of Young's modulus is lower at both recovery temperatures for specimens shocked at 11 kbar. This rather interesting result may be explained on the basis of Mott's defect modulus theory [7] (i.e. at a specific average loop length of dislocations, a solid has lower elastic moduli if it contains higher dislocation density), and on the assumption that the average dislocation loop length is of the same order of magnitude for the recovered specimens initially shocked at 1.5 and 11 kbar, respectively. This assumption is reasonably sound because it is known that for Ni and Cu the ratio of concentration of vacancies and interstitials versus dislocation density is practically the same for specimens shocked at different pressures as long as the pressure is not higher than 200 kbar [11]. If alloy 2024 Al follows the same general trend as that of Cu and Ni, one would expect that the average loop length of dislocations should be of the same order of magnitude for specimens of alloy 2024 Al shocked at 1.5 and 11 kbar respectively. Since one is certain that the density of dislocations should be higher at specimens shocked at 11 kbar one can expect that the percentage of recovery of Young's Modulus would be lower in the specimens shocked at 11 kbar than those shocked at 1.5 kbar.

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