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The effects of neutron irradiation on oxidation behavior, microstructure and transformation temperatures of Cu–12.7 wt.% Al–5 wt.% Ni–2 wt.% Mn shape memory alloy

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Abstract

The effects of neutron irradiation on oxidation behavior, microstructure and transformation temperatures of CuAlNiMn shape memory alloy have been investigated. It is seen that irradiation leads to observable changes of structure, and decreased temperatures of the martensite ⇔ austenite phase transformation.

Oxidation followed an Arrhenius relationship. An increase in activation energy of the oxidation reaction is observed due to applied irradiation.

Keywords: Shape memory alloy; Neutron irradiation; Phase transformations; Oxidation behavior

1. Introduction

As a smart material, shape memory alloys (SMAs) have attracted much attention [1,2]. Their unusual properties are due to reversible changes of the crystal lattice under the influence of temperature, pressure, magnetic and electric fields, irradiation, etc. [3–8]. SMAs are considered to be useful for fission and fusion materials. Therefore, it is important to investigate effects of irradiation on their physical properties. Neutron irradiation may cause structural distortions in SMAs, and the restoration phenomena from irradiated state to an unirradiated state may also occur during irradiation and facilitates the martensitic transformation [9,10]. Oxidation of SMAs is also important for high temperature applications.

This paper presents the effects of neutron irradiation on oxidation behavior, microstructure and transformation temperatures of neutron irradiated Cu–12.7 wt.% Al–5 wt.% Ni–2 wt.% Mn shape memory alloy.

2. Experimental

The alloy used in this work was Cu–12.7 wt.% Al–5 wt.% Ni–2 wt.% Mn, and *e*/*a* ratio is 1.57, supplied The Scientific and Technical Research Council of Turkey. The alloy was solution treated in the β-phase field (for 30 min at 900 °C) and immediately quenched in iced brine to obtain the β-type martensitic structure. Then, specimens with different dimensions were cut from the alloy. Neutron irradiation experiments were performed at Istanbul Technical University, Institute of Nuclear Energy with a thermal neutron flux (8×10^{12} neutron cm^{-2} s^{-1}, $E > 1$ MeV) for 3.6 and 7.2 kiloseconds (ks). DSC measurements were performed by a computer-controlled Shimadzu DSC-50 at 10 °C/min between 20 and 90 °C. Thermogravimetry measurements were performed by a computer-controlled Shimadzu TGA-50 at

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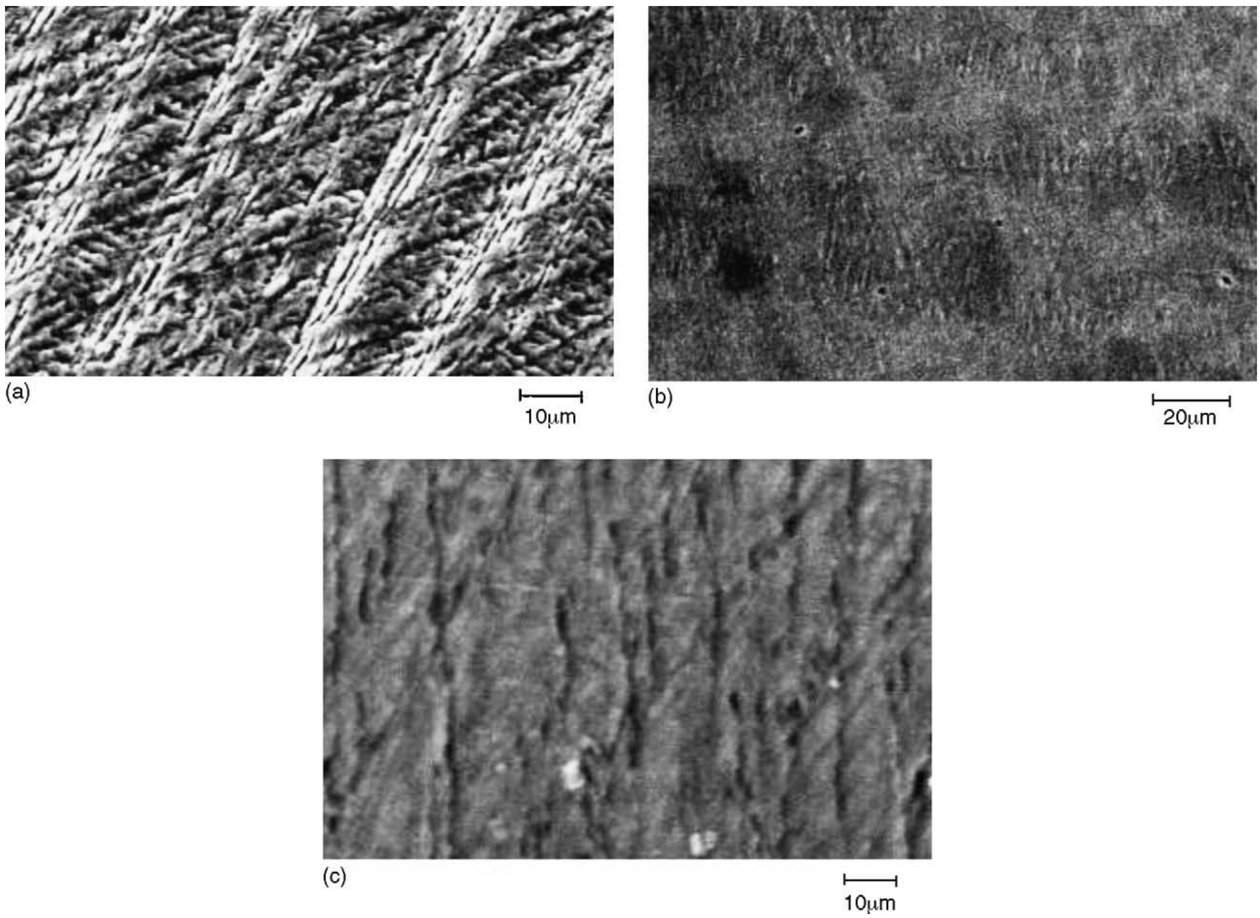

Fig. 1. Martensite morphology (a) thermal treatment, (b) neutron treatment for 3.6 ks and (c) neutron treatment for 7.2 ks.

10 °C/min heating and cooling rates. Microstructures of the alloy were investigated by a JSM-5600 microscope.

3. Results and discussion

Fig. 1a–c shows micrographs of the alloy exposed to heat treatment and irradiation. Martensitic structure of the alloy is shown in Fig. 1a. Irradiation affects the microstructure of the alloy, that is, the martensitic structure has disappeared after irradiation. Irradiation is known to affect the atomic structure of the alloy and cause defects in the structure [11–13].

Transformation temperatures and enthalpies for unirradiated and neutron irradiated samples are given in Table 1. The transformation temperatures (A_s, A_f, M_s and M_f) decrease with irradiation. Enthalpies of transformation ($\Delta H_{heating}$ and

Table 1
Transformation temperatures and enthalpy changes for the martensite–austenite phase transition

Thermal cycle	A_s (°C)	A_{max} (°C)	A_f (°C)	M_s (°C)	M_{max} (°C)	M_f (°C)	$\Delta H_{heating}$ (J/g)	$\Delta H_{cooling}$ (J/g)
Unirradiated								
First cycle	56.9 ± 0.4	65.4 ± 0.2	80.2 ± 0.4	65.2 ± 0.4	54.1 ± 0.2	38.6 ± 0.4	−3.90 ± 0.13	4.13 ± 0.13
Second cycle	55.1 ± 0.4	63.8 ± 0.2	77.1 ± 0.4	67.5 ± 0.4	55.2 ± 0.2	39.4 ± 0.4	−4.67 ± 0.13	4.35 ± 0.13
Third cycle	54.9 ± 0.4	62.6 ± 0.2	76.4 ± 0.4	67.9 ± 0.4	55.8 ± 0.2	40.1 ± 0.4	−4.71 ± 0.13	4.41 ± 0.13
Irradiated for 3.6 ks								
First cycle	49.9 ± 0.4	58.1 ± 0.2	68.4 ± 0.4	49.3 ± 0.4	41.8 ± 0.2	29.0 ± 0.4	−4.82 ± 0.13	5.67 ± 0.13
Second cycle	46.3 ± 0.4	54.9 ± 0.2	65.8 ± 0.4	50.4 ± 0.4	41.4 ± 0.2	29.5 ± 0.4	−5.16 ± 0.13	5.72 ± 0.13
Third cycle	46.0 ± 0.4	55.1 ± 0.2	65.0 ± 0.4	50.7 ± 0.4	42.4 ± 0.2	31.8 ± 0.4	−5.22 ± 0.13	5.78 ± 0.13
Irradiated for 7.2 ks								
First cycle	49.2 ± 0.4	58.3 ± 0.2	67.8 ± 0.4	48.9 ± 0.4	41.1 ± 0.2	29.2 ± 0.4	−5.25 ± 0.13	5.70 ± 0.13
Second cycle	46.0 ± 0.4	54.5 ± 0.2	66.5 ± 0.4	49.5 ± 0.4	41.7 ± 0.2	27.6 ± 0.4	−5.52 ± 0.13	5.76 ± 0.13
Third cycle	45.0 ± 0.4	54.6 ± 0.2	65.1 ± 0.4	49.7 ± 0.4	40.9 ± 0.2	30.7 ± 0.4	−6.01 ± 0.13	5.81 ± 0.13

Table 2
Oxidation parameters of the alloy

	E_a ($kJ\,mol^{-1}\,K^{-1}$)	K_0 ($mg\,mm^{-2}\,s^{-1}$)	O_p ($O\,s^{-1}$)	Mass gain (%)		Mass gain rate ($mg\,min^{-1}$)	
				Heating	Cooling	Heating	Cooling
Unirradiated	56.46	9.02×10^{-5}	7.41×10^{14} (at 580 °C)	0.15	0.02	6.8×10^{-2}	0.9×10^{-2}
Irradiated for 3.6 ks	63.23	2.78×10^{-4}	8.95×10^{14} (at 510 °C)	0.17	0.05	8.0×10^{-2}	2.3×10^{-2}
Irradiated for 7.2 ks	75.51	1.44×10^{-3}	10.39×10^{14}(at 560 °C)	0.20	0.07	8.5×10^{-2}	3.0×10^{-2}

$\Delta H_{cooling}$) increase with irradiation. The mass gain, mass gain rates and oxygen rates of the alloys were determined and are given in Table 2. It is seen in Table 2 that neutron irradiation increases oxidation of the alloy.

In order to obtain the parameters of oxidation such as activation energy and oxidation rate of the alloy, Arrhenius relationship can be used in the following form:

$$K_p = K_0 \exp\left[-\frac{E_a}{RT}\right] \quad (1)$$

where K_0 is the pre-exponential constant, E_a is the activation energy, R is the gas constant and T is the temperature. E_a and K_0 values were calculated from the slope and intercept of $\ln K_p$ versus $1/T$ plot and are given in Table 2. It is found that these values change by irradiation applied.

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