ALLOYS FOR HIGH-PRECISION TECHNOLOGY

EFFECT OF DEFORMATION AND EXTERNAL LOAD ON THE CHARACTERISTICS OF THE REVERSIBLE SHAPE MEMORY EFFECT IN ALLOY 80G15D2N3Kh

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Alloys with the shape memory effect have recently found application in engineering. Specifically, parts made of such alloys can be actuating members in structures of thermoregulators and thermorelays. It is known that the shape memory effect is realized in alloys with a thermoelastic martensite transformation. When heated, specimens strained in a martensite state recover their initial shape partially or completely as a result of a reverse martensite transformation. If an external load is applied in thermocycling, the shape will be changed both in heating and in cooling, i.e., recovered in the reverse martensite transformation and deformed under the effect of the external load in the direct martensite transformation. This change in shape is commonly said to be reversible. The aim of the present work consists in analyzing the effect of deformation in the martensite state prior to thermocycling and of an external load during the thermocycling on the reversible change of shape in Mn–Cu-base alloys.

Under a certain treatment a reversible change of shape in alloys with shape memory is observed without application of an external load (the effect is known as reversible or double-sided shape memory). In this case deformation in the direct martensite transformation occurs under the action of internal stresses or defects of the crystal structure. One way to attain the reversible shape memory effect consists in repeating many times a cycle that consists in deformation in a martensite state, heating, and cooling. Double-sided shape memory is manifested most clearly in Mn–Cu alloys in which the high-temperature face-centered cubic (f.c.c) γ-phase transforms into a face-centered tetragonal (f.c.t) phase by the mechanism of a thermoelastic martensite transformation. In these alloys the reversible change of shape is considerable even after the first cycle (deformation in the martensite state → heating → cooling) [1].

We studied alloy 80G15D2N3Kh (15% Cu, 2% Ni, 3% Cr, the remainder Mn), which possesses an optimum set of mechanical and thermosensitive properties after hardening from 900°C in water and tempering at 450°C for 2 h [2]. Tempering at 450°C promotes a metastable equilibrium of two isomorphic f.c.c phases (γ1 and γ2) with different compositions and increases the temperature of the martensite transformation to 160°C [3]. After tempering, a band 200 × 10 × 1 mm in size was subjected to a plastic bending deformation. The degree of deformation of the outer fibers was varied by changing the bending radius of the hardened plate R0 and was calculated by the formula \( \epsilon_0 = (1/R_1 - 1/R_0)(h/2) \), where \( R_1 \) is the final radius of curvature of the specimen (\( R_1 = 15 \) mm) and \( h \) is the thickness of the band. The helicoid spring obtained after the deformation was placed in the installation depicted in Fig. 1. The shaft was rig-

Fig. 1. Diagram of an installation for measuring the turning angle of a helicoid spring in loading by a static moment and heating: 1) helicoid spring (specimen); 2) shaft 5 mm in diameter; 3) carrier; 4) load; 5) gauge for measuring the turning angle; 6) bearings; 7) flexible steel line for transmitting the rotation to the turning angle gauge; 8) casing.

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Fig. 2. Change of shape of helicoid springs of alloy 80G15D2N3Kh in heating and cooling (indicated by arrows) after deformation with \( \varepsilon_0 = 2.7\% \) (\( \varepsilon \) is the deformation of the outer fibers): (a) not loaded; (b) under a load; (c) after removing the load; (d) recovery of the shape in the first heating; (e) reversible change in shape in a specimen not loaded; (f) the first heating and cooling, respectively, after applying the load; (g) reversible change in shape after three cycles of heating and cooling under the load; (h) the first cooling after removing the load.

Fig. 3. Dependence of the reversible change in shape \( \varepsilon_2 \) on the degree of deformation in the martensite state \( \varepsilon_0 \).

idly fixed to the inner end of the spring, and a constant moment of force was transmitted to the spring through the shaft. The spring was subjected to thermocycling in accordance with the rule \( 20 \text{°C} \to 180 \text{°C} \). The spring specimen was heated by an electric current. The temperature was controlled by a Chromel-Alumel thermocouple welded to the specimen. The deformation of the external fibers was controlled by the turning angle of the shaft (\( \varphi \)) using a gauge of angular displacements, i.e., \( \varepsilon = \pi \varphi h / 360 l \), where \( h \) is the thickness of the band and \( l \) is its length.

Figure 2a presents the curve of the change in the specimen shape after deformation with a degree \( \varepsilon = 2.7\% \) in the process of heating and cooling. In the first heating the initial shape is partially recovered (curve 1). At 180°C the deformation of recovery of shape \( \varepsilon_1 \) is 0.9%. In cooling, the shape determined by the initial deformation is partially recovered (\( \varepsilon_2 \approx 0.5\% \)). In further thermocycling the curve describing the change in shape stabilizes, repeating cooling curve 2 with virtually zero hysteresis (Fig. 1a). The dependence of the reversible shape memory effect \( \varepsilon_2 \) on the degree of deformation in the martensite state \( \varepsilon_0 \) is presented in Fig. 3. It can be seen that at low \( \varepsilon_0 \) the dependence is linear. At \( \varepsilon_0 > 4\% \) \( \varepsilon_2 \) does not change, which agrees with data of [1].

Fig. 4. Dependence of the reversible change in shape \( \varepsilon_2 \) and \( \varepsilon_p \) and the irreversible deformation \( \varepsilon_p \) on the load \( \sigma \); (a) the load and the deformation act in the same direction, (b) are opposite; (\( \vartriangle \), \( \blacktriangledown \), \( \blacktriangleleft \)) \( \varepsilon_0 = 0.6\%; \vartriangleleft, \blacktriangleleft \) \( \varepsilon_0 = 2.7\%; \square, \blacksquare \) \( \varepsilon_0 = 4.6\%; \blacklozenge \) \( \varepsilon_0 = 8.0\% \).

If the mentioned treatment of the specimen is followed by an additional application of an external load, the magnitude of the reversible shape memory effect changes. The direction of the application of the external load \( \sigma \) can coincide with the direction of the preliminary deformation \( \varepsilon_0 \) or it can be opposite to it. An example of a change in shape under a load with coinciding directions of \( \sigma \) and \( \varepsilon_0 \) is given in Fig. 2b. The load does not influence the recovery of the shape in the first heating (curve 3 has the same shape as curve 2), but it causes additional deformation in cooling (curve 4 in Fig. 2b). The additional deformation increases in further thermocycling, but the curve that describes the change in shape stabilizes after three cycles of heating and cooling (curve 5 in Fig. 2b). The change in shape under the load becomes smoother, but the temperature of the maximum thermal sensitivity hardly increases (curve 5 in Fig. 2b). The effect of the load can be characterized on the whole by two parameters, namely, the total degree of irreversible deformation \( \varepsilon_p \) accumulated in the stabilization process and the degree of reversible change in shape \( \varepsilon_2 \) under the load in the steady regime. Figure 4a presents the dependence of \( \varepsilon_2 \) and \( \varepsilon_p \) on the value of the external load \( \sigma \) for three groups of specimens differing in the degree of preliminary deformation in the martensite state. For all three groups application of the external load increases the magnitude of the reversible change in shape \( \varepsilon_2 \). The most substantial increase in \( \varepsilon_2 \) is observed in specimens with \( \varepsilon_0 = 0.6\% \) and the minimum increase is observed in specimens with \( \varepsilon_0 = 8.0\% \). The dependence of \( \varepsilon_p \) on the external load is approximately the same in all three groups, namely, \( \varepsilon_p \) is low at \( \sigma < 100 \text{ N/mm}^2 \) and increases markedly at \( \sigma > 100 \text{ N/mm}^2 \).