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FOCAL POINT
"Shape Memory Alloys"

PSEUDOELASTICITY

K. Otsuka† and K. Shimizu‡

SYNOPSIS. Pseudoelasticity, in which relatively large strains attained on loading beyond the elastic limit recover completely or nearly completely on unloading at a constant temperature, has recently been found in various alloys, which may or may not involve a martensitic transformation. Although various kinds of pseudoelasticity have been found, all occur either in association with a stress-induced transformation or by reversible movement of twin boundaries without a phase change. The former is termed transformation pseudoelasticity and the latter twinning pseudoelasticity in the present review. The latter is further subdivided into various categories depending on the nature of driving forces and mechanisms involved, and are discussed in some detail, including up-to-date information.

1. INTRODUCTION

Normal metals and alloys usually deform plastically once an applied stress exceeds the elastic limit, and the plastic strain does not recover upon unloading. However, there are some materials in which an apparent plastic strain upon loading recovers completely or nearly completely upon unloading, the strain ranging from a few percent up to 20 percent (see Figs 1 and 3). In the present paper we term such non-linear elasticity characterised by a closed stress-strain curve as pseudoelasticity, irrespective of the nature of the driving force or mechanism. Such an effect was first observed in the early 1950s in a Cu-39.7 at.% Zn alloy undergoing a stress-induced martensitic transformation and its reversion [1] and in the martensitic state of Au-47.5 at.% Cd alloy under certain conditions [2]. In the latter case the behaviour was termed "rubber-like". Since 1970 various types of pseudoelasticity have been found and the purpose of the present paper is to classify the types of pseudoelasticity

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and to review the subject briefly in the light of up-to-date information.

According to present knowledge, pseudoelasticity occurs either in association with martensitic transformation or by the reversible movement of twin boundaries. We term the former transformation pseudoelasticity and the latter twinning pseudoelasticity. The latter also usually occurs in the martensitic state of the alloys concerned, but in some cases it occurs in non-transforming materials as well. Twinning pseudoelasticity can further be subdivided into different categories, as shown in Table 1, according to the nature of the restoring force upon unloading. Various terminologies for pseudoelasticity have appeared in the literature and are quite confusing. In the present paper we follow the one that was recently proposed by the present authors [3]. The comparison of the present terminology with the previous one is given in Table 1, and the advantage of the present one is discussed in Ref. [3]. In the following description, we assume that readers have some knowledge of the characteristics of the martensitic transformation, especially thermoelastic martensitic transformation [4-7].

TABLE 1. Classification of Pseudoelasticity

Present Terminology	Previous Terminology
I. Transformation pseudoelasticity	Superelasticity* [5, 8, 9]
II. Twinning pseudoelasticity (i) T.P. by stabilisation (ii) T.P. by elastic interaction (iii) T.P. by disordering (iv) Other T.P.	Rubber-like behaviour [5, 8, 9] Ferroelasticity [11] Bending pseudoelasticity [12]

* This has been used only for pseudoelasticity due to a matrix-to-martensitic transformation.

2. TRANSFORMATION PSEUDOELASTICITY

(a) *Transformation Pseudoelasticity Associated with Matrix-to-martensite Transformation*

It is well known that martensitic transformation is induced even above the M_s temperature, when an external stress is applied (i.e. stress-induced transformation). The critical stress to

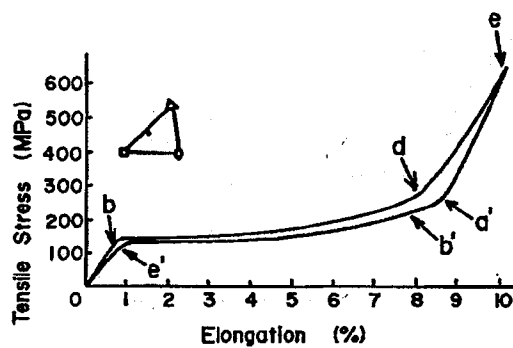
induce martensite increases linearly with increasing stress according to the Clausius-Clapeyron equation [13-14],

$$d\sigma/dT = -(\Delta H/T\Delta\epsilon),$$

where σ is a critical stress, T temperature, $\Delta\epsilon$ the strain associated with the stress-induced transformation, and ΔH the enthalpy change associated with the transformation. Now, suppose that a specimen is tensile tested at a temperature above A_f . The specimen deforms elastically at first until a critical stress (determined by the above Clausius-Clapeyron equation) is reached. Then the stress-induced martensitic transformation starts and proceeds with increasing strain. If then the stress is relieved, the reverse transformation must occur

upon unloading, since the test temperature is above A_f where the martensitic phase is completely unstable in the absence of stress. Thus, if the reverse transformation is crystallographically reversible, as is usually the case for thermoelastic transformation [7], the strain recovers upon unloading. This is what we see in Fig. 1 [14]. It is obvious from the foregoing that the driving force for transformation pseudoelasticity lies in the difference in the free energies between the two phases as a function of stress. In this sense the effect is quite similar to the shape memory effect, where the reverse transformation is caused by heating a specimen to temperature above A_f . In fact, almost all alloys exhibiting thermoelastic martensitic transformation (such as Cu-Zn [15], Cu-Zn-X [16, 17], Cu-Al-Ni [14, 18], Au-Cd [19], Ag-Cd [20], Ni-Ti [21-23], In-Tl [24-26] and Cu-Au-Zn [27]) exhibit transformation pseudoelasticity as well as the shape memory effect. The former occurs when a stress is applied at a temperature above A_f , while the latter occurs when a specimen is deformed at a temperature below A_s and subsequently heated to a temperature above A_f . At temperatures between A_s and A_f both effects occur and are complementary. Although transformation pseudoelasticity occurs both in single crystal and polycrystals, it is pronounced and easy to analyse in single crystals. Thus, in what follows the results for single crystals will be discussed unless otherwise stated.

(A)



(B)

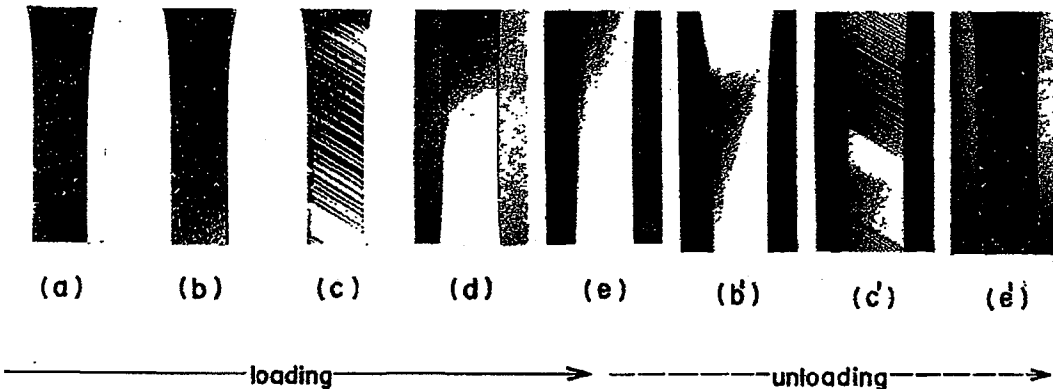


Fig. 1. The transformation pseudoelasticity associated with the $\beta_1 \rightleftharpoons \beta'_1$ transformations in a Cu-28.2 at. % Al-4.2 at. % Ni alloy single crystal. (A) represents a stress-strain curve and (B) photomicrographs corresponding to (A). Parallel lines in the photomicrographs, (b) and (c), represents traces of stress-induced β'_1 martensite plates, while those in (b') and (c') represent those of matrix β_1 upon reversion [14]

Figure 1 is typical of the stress-strain curve associated with transformation pseudoelasticity in a single crystal usually having a plateau region like easy glide for slip in a single crystal. This occurs because only one variant is usually stress-induced in this stage. By comparing the end of the plateau region with the associated photomicrograph, it is found to correspond to the completion of the stress-induced transformation. Thus the elongation between b and d in Fig. 1 represents the pseudoelastic one obtained by the stress-induced transformation. The elongation can be calculated from the following equation, which is similar to that given by Schmid and Boas to correlate an elongation with the shear strain for slip:

$$\epsilon_o = [(m_1^p \sin \chi_o)^2 + 2m_1^p \sin \chi_o \cos \lambda_o + 1]^{\frac{1}{2}} - 1 + m_1^n \sin \chi_o$$

where λ_o is the angle between the tensile axis and the shear direction d_1^p , χ_o the angle between the tensile axis and the habit plane, m_1^p the magnitude of the component of the shape strain parallel to the habit plane, and m_1^n that of the shape strain normal to the habit plane. Figure 2 [9] shows the result of the calculation for the pseudoelastic elongation as a function of crystal orientation for the $\beta_1 \rightarrow \beta_1'$ transformation (β_1 and β_1' represent the matrix and martensite phases, respectively) in a Cu-28.2 at. % Al-4.4 at. % Ni alloy. It is shown by an accurate measurement that the observed values agree fairly well with those calculated, but that the former ones are slightly larger since the lattice invariant shear in the martensitic transformation also contributes to the elongation.

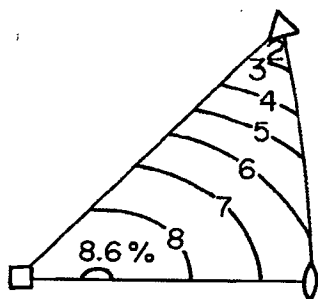


Fig. 2. Orientation dependence of the pseudoelastic elongation associated with the $\beta_1 \rightarrow \beta_1'$ transformation calculated for a Cu-Al-Ni alloy [14]

The stress hysteresis as a function of temperature and strain rate is of interest both in relation to the transformation mechanism and from a practical point of view. In Cu-Al-Ni alloys it is found to be inversely related to temperature, with one exception [3]. It is also found that the reciprocal of the hysteresis decreases linearly with the logarithm of the strain rate [3]. Both these relations can be explained by the surface dislocation theory developed by Sumino [28].

(b) Transformation Pseudoelasticity Associated with

Martensite-to-Martensite Transformation

Of recent interest in transformation pseudoelasticity is the finding of multistage pseudoelasticity and the clarification of its origin. Busch *et al.* [29] found a remarkable two stage pseudoelasticity in a Cu-Al-Ni alloy in 1966, but they could not identify the origin of the second stage. Arneodo and Ahlers [30] found a similar but somewhat different two-stage pseudoelasticity in a Cu-39.4 at. % Zn alloy, and found that the second stage proceeded by formation of plate-like products within the single crystal martensite region formed in the first stage. Clear evidence that the second stage in a Cu-28.0 at. % Al-4.4 at. % Ni alloy single crystal was due to martensite-to-martensite transformation, subsequent to matrix-to-martensite transformation, was first provided by the present authors [31-35] and Brown *et al.* [36-37], from a thorough investigation utilising neutron and X-ray diffraction and optical microscopy of stressed samples. Russian workers [38] obtained a similar result using an X-ray rotating crystal technique.

Figure 3 shows a series of stress-strain curves as a function of temperature, obtained from a Cu-28.0 at. % Al-4.2 at. % Ni alloy single crystal with an orientation close to $[001]_{\beta_1}$. The curves change drastically with test temperature relative to the characteristic temperatures. At temperatures below A_f , three-stage yielding is observed. Although the strain obtained in the first stage does not recover upon unloading, those in the second and third stages do recover upon unloading, as evidenced by the stress-strain curve in the second cycle, indicated by dotted lines in Fig. 3. Apparently three different pseudoelastic loops are observed as

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