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Strengthening the alloys with elastic softening in shear modulus C'

S. Kuramoto [a,*], N. Nagasako [a], T. Furuta [a], Z. Horita [b]

[a] Frontier Research Center, Toyota Central R&D Labs., Inc., Nagakute, Aichi 480-1192, Japan
[b] Department of Materials Science and Engineering, Kyushu University, Fukuoka 819-0395, Japan

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ABSTRACT

A multifunctional titanium based alloy, Gum Metal, has very low C' (=$(C_{11} - C_{12})/2$), which is similar to shape memory alloys (SMAs). The Peierls stress would be relatively low in such low C' alloys, however, it has been reported that dislocation activity in Gum Metal is suppressed up to its ideal shear strength. Recently, a Fe–Ni–Co–Ti alloy with very fine grain size processed by severe plastic deformation (SPD) has also been reported to have similar mechanical properties to Gum Metal. In the present paper, some recent discussions on elastic and plastic behaviors in these alloys were summarized. The reduced C' enhances elastic anisotropy and significantly decreases the ideal shear strength. It also results in significant core spreading of screw dislocations which can raise the critical shear stress for dislocation glide, if such cores interact with other neighboring ones, solute elements or solute clusters. Mechanical responses to loading were also discussed in Gum Metal and the SPDed Fe–Ni–Co–Ti alloy using stress–temperature diagram, which has been often used to explain the behavior of SMAs.

1. Introduction

It has been generally known that shape memory alloys (SMAs) often have very low shear modulus, C' (=$(C_{11} - C_{12})/2$), especially at the temperatures near martensite start (M_s) temperature [1,2]. This elastic softening promotes the shuffling of atoms in the specific crystal orientation during the martensitic transformation. At the same time, the elastic softening also suggests that the crystal structure of these alloys has relatively low resistance to dislocation glide, that is, they have very low Peierls stress. A multifunctional titanium based alloy, Gum Metal [3–5], has similar elastic properties to SMAs and its Peierls stress would be very low like SMAs. However, it has been reported that dislocation activity in this alloy is suppressed up to its ideal shear strength [6]. Recently, a Fe–Ni–Co–Ti alloy with very fine grain size processed by severe plastic deformation (SPD) has also been reported to have similar mechanical properties to Gum Metal [7,8]. The common characteristic feature in these two alloys is they are ductile in spite of having very high strength. The reason for this unusual combination of mechanical properties may be attributed to the deformation mechanism at ideal shear strength [9,10].

The martensitic transformation behavior in SMAs has been intensively investigated in relation to the elastic properties [1], but it seems that few researches have been made on plastic deformation behavior in SMAs with a focus on their characteristic elastic properties where C' is significantly reduced. In these alloys, shape memory effect (SME) or pseudoelasticity (PE) can be seen if the stress required for the transformation is lower than the one for dislocation glide [11]. Therefore, it is important to control the stress required for dislocation glide to obtain the alloys with excellent SME of PE. In the present paper, some recent discussions on elastic and plastic behaviors in low C' alloys, including SMAs, Gum Metal and the SPDed Fe–Ni–Co–Ti alloy, are summarized, and mechanical responses to loading in these alloys will be discussed using stress–temperature diagrams which have been often used to explain the required conditions for SME or PE [11]. In addition, mechanism to suppress the dislocation activity in Gum Metal and SPDed Fe–Ni–Co–Ti alloy is discussed in relation to elastic properties.

2. Materials and methods

In the present paper, elastic and plastic behaviors in the two low C' alloys, Gum Metal, Ti–23.7%Nb–0.7%Ta–2%Zr–1.2%O, and Fe–18.1%Ni–34.9%Co–9.3%Ti alloys (at.%) are discussed in comparison with several conventional SMAs. Billets of these alloys were hot forged and subsequently formed into round bars of 15 mm diameter. They were then solution treated at 1173 K for 3.6 ks for Gum Metal and at 1373 K for 86.4 ks for the Fe–Ni–Co–Ti alloy in an argon atmosphere, quenched in water. The solution treated bar of Gum Metal was cold-worked by 90% in a rotary swaging machine. Disk specimens of 10 mm diameter and 0.8 mm thick were machined from the solution treated bar of the Fe–Ni–Co–Ti alloy, and they were processed with high-pressure torsion (HPT), one of typical methods for SPD, at a rotation speed of 1 rpm under a compression stress of 6 GPa, for 10 turns at room temperature. Details in sample preparation procedure have been reported elsewhere [4,8]. Both of them have bcc crystal structure and exhibit high strength and high tensile ductility after cold working. Mechanical properties of these two alloys are summarized in Table 1. Elastic constants in Gum Metal have been estimated from Young's moduli of single

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* Corresponding author.
E-mail address: kuramoto@mosk.tytlabs.co.jp (S. Kuramoto).

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Table 1
Mechanical properties of Gum Metal and Fe–18.1%Ni–34.9%Co–9.3%Ti.

	Gum Metal	Fe–Ni–Co–Ti
Young's modulus (GPa)	55	144
Ultimate tensile strength (MPa)	1100	2730
Tensile elongation (%)	10	9.4

crystals grown in ⟨1 0 0⟩, ⟨1 1 0⟩ and ⟨1 1 1⟩ directions [12,13]. The calculated elastic properties in Ti–Nb [14] and Ti–V [10,15] binary alloys, which show similar lattice softening in Gum Metal, are also used to discuss the effect of electronic structure on the elastic and plastic behaviors in the low C' alloys.

3. Elastic and plastic behaviors of low C' alloys

What happens in the alloy with low C'? In this section, general characteristics in elastic and plastic behaviors in low C' alloys are summarized with some specific examples. Elastic softening in C' results in reduced elastic moduli along specific crystallographic orientations. Shear moduli in the crystalline solids with cubic crystal structures are given by

$$G_{0\,01} = C_{44}, \tag{1}$$

$$G_{01\,1} = C' = \frac{C_{11} - C_{12}}{2}. \tag{2}$$

where G_{001} and G_{011} are shear moduli along ⟨0 0 1⟩ on {0 0 1} and along ⟨0 1 1⟩ on {0 1 1}, respectively. In addition, G_{111}, shear modulus along ⟨1 1 1⟩ on {0 1 1}, {1 1 2} or {1 2 3}, given by

$$G_{1\,11} = 3C_{44}\frac{C_{11} - C_{12}}{C_{11} - C_{12} + 4C_{44}}. \tag{3}$$

is also important because this orientation is the easiest slip direction in bcc crystals.

The elastic constants of Gum Metal have been reported by Hara et al. [12]; C' and C_{44} were estimated as 12.5–13.5 GPa and 29–36 GPa, respectively. Thus, shear moduli in these directions are calculated using the averaged values of the elastic constants; G_{001}, G_{011} and G_{111} are 33, 13 and 16 GPa, respectively. In Fig. 1, elastic constants, C' and C_{44} are compared in several SMAs [2] and Gum Metal [12]. The anisotropy factor, A (=C_{44}/C'), is also plotted in the figure. The SMAs have generally low C' ranging from 5 to 20 GPa. On the other hand, C_{44} varies in the range of 20–130 GPa, and A also changes from 2 to 15 due to the variations in C_{44}. Gum Metal has a set of elastic constants similar to the one in Ti–Ni base SMA.

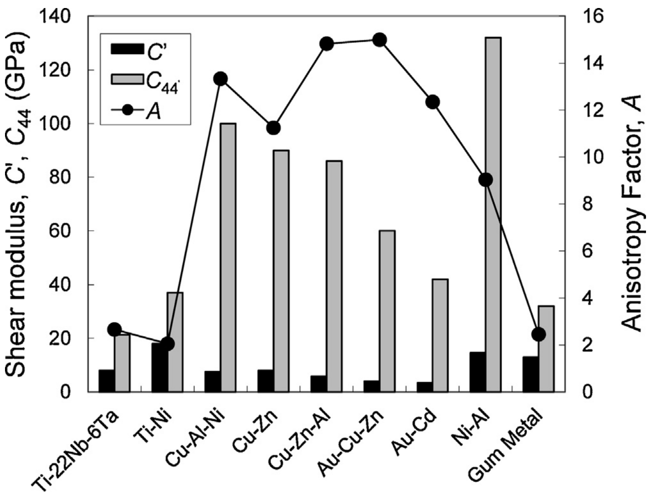

Fig. 1. Elastic constants (C', C_{44}) and anisotropic factor (A) for several bcc-based SMAs [2] and Gum Metal [12].

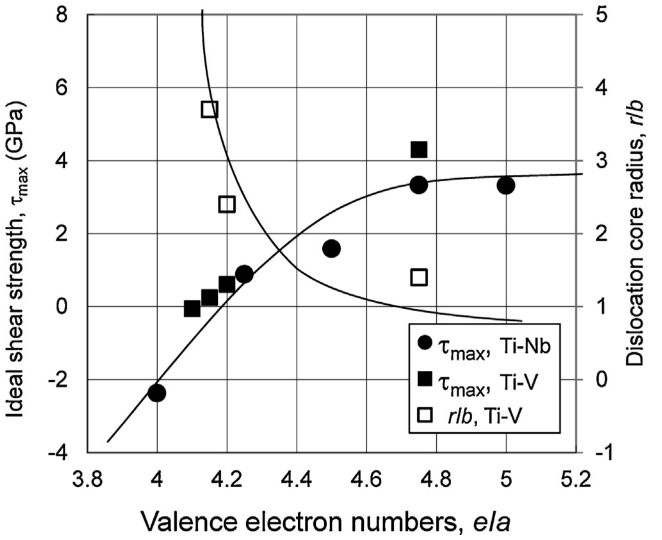

Fig. 2. Ideal shear strength and core radius of screw dislocations *vs.* valence electron number (e/a). Ideal shear strength is calculated from elastic constants for Ti–Nb [14] and Ti–V [15] binary alloys estimated by *ab initio* calculations. Dislocation core radius, r/b, was estimated also by *ab initio* calculations for Ti–V binary alloys [15].

The reduced value of G_{111} implies that the plastic deformation of the crystal can occur by dislocation activity at relatively low stress. The ideal shear strength in bcc pure metals is known to be roughly estimated by [16]

$$\tau_{\max} \approx 0.11 G_{1\,11}. \tag{4}$$

where $\tau_{\max}$ is the ideal shear strength required for plastic shear along ⟨1 1 1⟩ on {0 1 1}, {1 1 2} or {1 2 3}. The $\tau_{\max}$ of Gum Metal is estimated to be as low as 1.8 GPa from the above G_{111}. Such characteristics have been studied in the viewpoint of electronic structure using *ab initio* calculations [10,14], and it is known that the elastic properties and ideal strength strongly depend on valence electron number per atom (e/a). Fig. 2 shows the $\tau_{\max}$ values estimated by Eqs. (3) and (4) in Ti–Nb and Ti–V binary alloys with bcc crystal structure. The e/a of Gum Metal is selected to be 4.24, where the $\tau_{\max}$ is significantly reduced.

In such elastically softened condition, it is expected that dislocation mediated plasticity or martensitic transformation can easily occur. In general, the dislocation mediated plasticity is considered to occur at 1/30 to 1/10 of the ideal strength, and therefore, deformation shear strength can be estimated as 180 MPa or lower in Gum Metal. However, it has been reported that dislocation motion and martensitic transformation are suppressed up to very high stress level, and the actual deformation strength of Gum Metal is as high as the ideal strength; the resolved shear stress required to deform nanopillars of the alloy has been reported to approach its ideal shear strength during compression test [6]. In relation to this, Chrzan et al. recently reported that the elastic anisotropy also results in extensive core spreading of screw dislocations [15], which might explain characteristic plastic deformation behavior in Gum Metal at ideal shear strength. The core radii of screw dislocations in Ti–V binary alloys are plotted in Fig. 2. It is interesting that ideal shear strength approaches zero and the dislocation core radius diverge at the critical e/a of around 4.2. The effect of this core spreading of screw dislocations on plastic behavior will be discussed later.

4. Deformation diagrams for low C' alloys

Fig. 3(a) shows a schematic diagram of deformation map for SMAs, which has been often used to explain the required condition for SME or PE effects [11]. As seen in the figure, martensites are