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Effect of strain rate on the mechanical properties of a gum metal with various microstructures

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A B S T R A C T

In this work, a bulk gum metal (GM) was fabricated via arc melting from high purity powders. The ingots were first extruded using a conventional route followed by equal channel angular pressing (ECAP). The mechanical behavior of the extruded GM and ECAP-processed GM was studied under both quasi-static and high strain rate compression conditions to evaluate the influence of strain rate. In addition, the associated mechanical anisotropy, or the lack thereof, was investigated through loading in different orientations with respect to the extrusion or ECAP direction. Precipitous stress drops were observed under dynamic compression of both extruded and ECAP-processed GM specimens when loading perpendicular to the extrusion direction. Adiabatic shear banding (ASB) was found to be associated with the precipitous stress drops on the dynamic stress-strain curves. The details of the ASBs were characterized by optical and scanning electron microscopy, with emphasis on electron backscattered diffraction (EBSD). The mechanisms responsible for the formation of ASB were examined both from thermal softening and geometrical softening perspectives. Significant microstructure refinement within ASBs was established, and a possible grain refinement mechanism was proposed.

1. Introduction

Gum metals (GMs) are essentially a group of β-Ti alloys containing significant amounts of β-stabilizers to maintain the body-centered cubic (bcc) lattice structure. GMs have been designed by *ab initio* calculations to fulfill the requirements of three electronic "magic" numbers so that multiple "super" mechanical properties might be obtained [1–3]. Alloy compositions [1–16], such as Ti-24Nb-4Zr-8Sn-O, Ti-12Ta-9Nb-3V-6Zr-O and Ti-23Nb-0.7Ta-2Zr-O, have been identified to meet those criteria of electronic magic numbers. Additionally, substantial cold work and the presence of certain amount of oxygen have also been found to be indispensable for the reported "super" mechanical properties such as super strength, super elasticity with relatively low elastic modulus, super plasticity and so on [1,2,12,15,17]. The combination of these properties might be attributed to the formation of Zr-O clusters, which act as pinning centers that strongly inhibit the movement of dislocations during plastic deformation, giving rise to strong strain hardening [1,3]. Undoubtedly, combined with the bio-compatibility of titanium and its alloys, GMs have been regarded as a promising candidate for biomedical engineering applications, for example, as orthopedic implants as their elastic modulus can be tailored to match that of human bones [4,5,18,19].

As a matter of fact, pure Ti and Ti-alloys have been widely utilized as biomedical materials, such as artificial knee and hip-joints. Among them, Ti-6Al-4V (Ti64) is currently the most commonly

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used for load bearing applications due to its light weight, high strength, corrosion resistance and relatively low Young's modulus compared to either stainless steels or Co-Cr alloys [20–22]. However, this commercial biomaterial can slowly leach out V ions which will cause a series of symptoms [4]. Conversely, the transition elements such as Nb, Ta and Zr, etc., are non-toxic and non-allergic alloying elements. Amongst them Nb and Ta are β-stabilizers while Zr is more or less neutral. Their presence within a GM may render the GM better biocompatibility [4,5]. For example, the relatively low Young's modulus of GMs makes it much more suitable for dental and orthopedic applications. The Young's modulus of Ti64 with (α+β) two-phase microstructure is ~110 GPa, roughly four times larger than that of cortical bone (20–30 GPa). Significant mismatch in Young's modulus between artificial biomedical alloys and cortical bones creates stress shielding effect resulting in low bone density, loosening of implants, implant failure, and an increased likelihood for revision surgery. With less stress shielding, GMs with single β phase is attracting significant attention because of their low Young's modulus ranging between 55 GPa and 90 GPa. The extremely low Young's modulus (~33 GPa), quite near that of real human bone, has been reported by Y.L. Hao and co-authors who investigated the elastic deformation of Ti-24Nb-4Zr-8Sn-O [5]. As such, GMs are expected to be potential biomedical materials because of their light weight, high mechanical strength, good biocompatibility and low Young's modulus.

On the basis of first-principles calculations as well as experimental data, alloying can affect the stability of β phase in GMs. Alloying can also be used to tailor the elastic modulus of GMs along with thermo-mechanical treatment [5,6,18]. Thereby, a combinatory methodology of theoretical studies [6–8] and experimental efforts [5,11,14–16] renders it possible to fabricate β-phase GMs with desirable properties. When a compositional average valence electron number (electron/atom (e/a)) of *ca.* 4.24, which turns out to be one of the three electronic magic numbers, is reached, the shear moduli G_{011} and G_{111} have the tendency to vanish. G_{011} corresponds to shearing along ⟨011⟩ on {011}, and G_{111} corresponds to shear along ⟨111⟩ on {011}, {112} and {123}. The ideal shear strength for shearing in a ⟨111⟩ direction on a {112} plane is given by the equation $\tau_m = 0.11\ G_{111}$ [3,6,8], where τ_m is the ideal shear strength along all potential shear directions. As such, the ideal shear strength scales linearly with the shear moduli. The nearly vanishing or exceedingly small shear moduli points to relatively low ideal shear strength along those directions when e/a reaches 4.24. In addition, the resolved shear stress (RSS) required to move dislocation may exceed the ideal shear strength of GMs if the pinning obstacles distribute with appropriate spacing. In this sense, the conventional dislocation-mediated plasticity may be entirely inoperative, and GMs may fail at a very high stress level considering the competition of dislocation mobility and ideal shear [1,6,17].

In light of the above, a dislocation-free plastic deformation mechanism has been proposed for GMs. For example, GMs have been observed to deform by giant faults which are macroscopic planar defects with large plastic strain [1]. The generation and multiplication of giant faults are supposed to be closely related to the formation of nano-disturbances [7,8], viz. nanometer scale planar areas of local shear. From the perspective of physical model, abnormal nano-disturbances are described as nanoscale dipoles of non-conventional partial dislocations with arbitrary, non-quantized Burgers vector magnitudes [7]. This mechanism, however, immediately became a subject of intense debate in the community, particularly because of the lack of convincing evidence. Later on, conventional dislocation slipping [9,12,13], twinning [10,11] and phase transformations [11,14–16] have been discovered, which have been employed to explain the peculiar mechanical behavior of GMs.

Notwithstanding the ambiguous picture regarding the plastic deformation mechanism, GMs are drawing increasing attention from researchers concerning elastic deformation, nonlinear elasticity, conventional tensile behavior, *in vitro* biocompatibility and so on. However, to the best of our knowledge, an important aspect of the mechanical behavior of GMs is missing from the literature: the high strain rate or dynamic mechanical properties [23–26] has largely been ignored. High strain rate behavior is of paramount importance in a number of applications, including implants where varying loading rate in service may well be anticipated. Under impact loading, materials are subjected to large deformation within a very short time frame, and experience a strain rate in the order of $10^3\ s^{-1}$, or even higher. Dynamic loading of visco-plastic materials usually brings forth much more complicated processes and phenomena vis-à-vis quasi-static loading (strain rate below 1.0 s^{-1}). For example, the short time frame of loading usually renders insufficient time for the heat generated from plastic work to be dissipated out of the specimen, and thus adiabatic heating may become an important issue. Localized thermal softening may eventually lead to rapid local plastic deformation and final catastrophic failure of the specimen [23–26].

In this work, titanium-based β-phase GMs with various microstructures were produced by arc melting and casting followed by conventional extrusion and then equal-channel angular press (ECAP). ECAP is among the most popular top-down technologies for the production of ultrafine grain (UFG, grain size *d* ranging from ~100 nm to ~1000 nm) and even nanocrystalline (NC, *d* below ~100 nm) [27,28]. Mechanical properties of the GM under both quasi-static compression and high-strain rate compression were investigated in order to evaluate the effect of loading rate on the mechanical behavior of GMs at large. Furthermore, loading was in different directions, i.e., extrusion and transverse directions so as to examine the anisotropy of the GM after thermo-mechanical treatment. Optical microscope and scanning electron microscope (SEM) were used to reveal the microstructure of the as-processed materials as well as the microstructure after mechanical loading. In-depth information from electron backscattered diffraction (EBSD) was obtained to assist the interpretation of the formation of adiabatic shear band in the GM under uni-axial compression.

2. Experimental procedures

The initial ingot, which was 2.0 inches in diameter and 6.6 inches in length, was made of high purity Ti, Nb, Ta and Zr powder through arc melting and casting. Table 1 lists nominal composition of the GM. The microstructure and composition of the ingot are usually homogeneous using this technique. To avoid contamination, a protective layer of Ti film was placed around the powder preform. As such the work piece was encapsulated during arc melting. A billet with a diameter of 0.79 inch was obtained via extruding the ingot at 1010 °C. Subsequently, one pass of ECAP was employed to impose severe plastic deformation to the extruded billet at 500 °C without back pressure. The ECAP facility employs a stationary constraint die with channel diameter of 0.79 inch and

Table 1
The nominal composition of Ti alloy of this work.

Elements	At.%	Wt.%	Density g/cc	Companies	Purities, %
Ti	73.3	58.77	4.51	Alfa	99.999
Nb	23	35.79	8.58	PMTI	99.9
Ta	0.7	2.12	16.68	Alfa	99.95
Zr	2	3.05	6.51	Alfa	99.5
O	1	0.27	–	–	100.00
Final alloy	100	100	5.53	–	