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Thin-film metallic glasses for substrate fatigue-property improvements

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ABSTRACT

Amorphous metallic films, a thin form of metallic glasses, have been attracting more and more attentions in the last two decades, due to their unique properties, compared with the conventional crystalline films, such as high strength, high toughness, large elastic limits, and high-corrosion resistance. However, the deformation mechanisms of thin-film metallic glasses (TFMGs) are still far from in-depth understanding, although some of their properties and characteristics are not as good as metallic or ceramic films. This paper will focus on reviewing and discussing the fatigue behavior of structural-material substrates coated with TFMGs. The substrates include 316L stainless steel, Al-based, Ni-based, Zr-based, and Ti-based alloys. The results show that the four-point-bending fatigue life of the substrates is greatly improved by Zr- and Cu-based TFMGs, while Fe-based TFMG, TiN, and pure-Cu films are not so beneficial in extending the fatigue life of 316L stainless steel. In comparison, the tension–tension fatigue lifetime and endurance limit of 316L stainless steel cannot be improved by the Zr- and Cu-based TFMGs. However, the TFMGs annealed at a temperature within the supercooled liquid region (ΔT) can further improve the fatigue behavior, compared to as-deposited TFMGs. The fatigue mechanisms of crystalline and bulk metallic glass (BMG) materials, together with TFMGs, are reviewed in the present work. Crystals and BMGs present 3-stage and 4-stage fatigue-deformation mechanisms, respectively. The fatigue life of medium-strength structural materials tends to be significantly improved by TFMGs. A synergistic experimental/theoretical study has shown the micro-mechanisms of the fatigue behavior of TFMGs adhered to substrates, as well as film-adhesion and thickness effects on fatigue behavior of the substrate. Furthermore, shear-band initiation and propagation under bending deformation are investigated using the Rudnicki–Rice instability theory and the free-volume models employing finite-element simulations.

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1. Introduction

1.1. Bulk metallic glasses

Since the metallic-glass (MG) phase was reported in the Au–Si alloy system by Klement, Willens, and Duwez in 1960 [1], a large number of alloy systems have been synthesized in bulk forms for the last several decades. Examples include the well-known Pd–Cu–Ni–P, Zr–Al-transition metal (TM), and Zr–Ti–Al–TM–Pd alloys [2], as well as other alloys, such as Ln-, Ti-, Mg-, Fe-, and Ni-based bulk metallic glass (BMG) systems [3,4]. As an intriguing class of potential structural materials, BMGs exhibit many excellent properties, including exceptionally high yield strength, hardness, elastic limit (~2%), and corrosion and oxidation resistance [3,5–11]. However, the application of BMGs as structural materials is severely limited by their low ductility, intrinsic brittleness, and moderate fatigue resistance at room temperature, which is mainly due to the formation of localized shear bands that quickly lead to catastrophic fracture [12–14]. There have been several approaches to improve the room-temperature ductility of BMGs, including microstructure modifications by adding dispersed inclusions in the BMG matrix [15–17] and surface modifications of the BMG [18–21], which all seek to block major shear bands, and thus inducing a more homogeneous distribution of shear bands in BMGs during deformation. Numerous studies have shown that surface modification appears to be a good approach to improve the ductility and fatigue resistance of BMGs, while keeping their amorphous structure and ultra-high strength [19,22–24].

Recently, thin-film metallic glasses (TFMGs) have been used to improve the strength and fatigue life of many structural materials, including C-2000® Ni-alloys and 316L stainless steels [25]. Moreover, the bending ductility of BMGs can be improved by introducing bilayer-MG coatings [19]. Therefore, thin-film coatings provide us a feasible approach to improve the ductility and fatigue resistance of both BMGs and crystalline materials, which could advance the application potential of BMG alloys as structural materials.

1.2. TFMGs

Currently thin-film coatings have been used extensively to improve the mechanical behavior of various substrate materials [18,19,22, 26–30], with different thin-film thicknesses [from nanometers (nm) to micrometers (μm)], especially in the field of wear resistance, hardness, and corrosion resistance, without adversely affecting their desirable bulk properties [27]. Coating components are often used in service under cyclic-loading conditions, while experiencing wear and corrosion environments simultaneously, such as on cutting saws. Therefore, the fatigue behavior of thin-film coatings is extremely important for the performance of substrate materials. An appropriate example is the widespread use of ceramic coatings, which are deposited on steel substrates to improve their fatigue strength [27]. The beneficial effects in fatigue strength are mainly attributed to the retardation of crack initiation in the substrate materials by the hard ceramic coating [27].

Numerical studies have reported that the fatigue behavior of the film/substrate system is closely dependent on film properties, such as composition, thickness, hardness, ductility, and structure, as well as film/substrate interfacial adhesion [31,32]. For instance, many ceramic coatings are susceptible to fatigue-induced fracture and delamination under high stress levels, because of their intrinsically-brittle nature, despite their high hardness and strength. Moreover, with an increase in coating thicknesses, a reduction in the adhesion of the film to the substrate may occur due to increasing residual stresses [33]. A literature review indicates that there are five film properties that could affect the fatigue-crack-initiation resistance in film/substrate materials [26]: (i) hardness—to prevent surface roughening, (ii) ductility or toughness—to retard crack initiation at the sites where persistent slip bands (PSBs) intersect with the film, (iii) cyclic work hardenability—to reduce slip localization, (iv) residual compressive stresses—to decrease film tensile stresses, and (v) film/substrate adhesion—to prevent film delamination, for which good film/substrate adhesion is the most important factor responsible for fatigue-resistance enhancement [18,19,25]. Therefore, good balance between beneficial mechanical properties of coatings and film/substrate adhesion is the prerequisite for excellent potential coating materials to enhance the fatigue behavior of substrates.

Based on the above analysis and our preliminary results, the TFMG can be a good candidate as excellent coating materials, because of their unique properties, as shown in Fig. 1 [34–49]. It should be noted that TFMGs have much higher yield strengths than ceramic and metallic (crystalline) coatings, while metallic coatings and TFMGs have larger ductility, usually indicating better adhesion with the substrate than ceramic coatings. Therefore, TFMGs should have better balance of strength and ductility than crystalline metallic and ceramic coatings, indicating that MGs can be better coating materials than most ceramic and metallic coatings. Note that two same symbols in Fig. 1 represent the upper and bottom limits of yield strength and ductility of the corresponding material. In practice, these unique mechanical properties of TFMGs have made them very popular to enhance the plasticity, strength, and fatigue life of different substrates, including steels [18,22,23,25], Ni-based alloys [18,25,50], and BMGs [19] in the past several decades. In this paper, the fatigue behavior of TFMG coatings deposited on structural materials will be reviewed and discussed.

2. Experimental techniques

2.1. Coating preparation and characterization

Two kinds of fatigue tests, including four-point-bending and tension–tension fatigue, will be conducted in the present work. The substrate materials used in the present paper are the commercial-grade 316L stainless steel with 20% cold rolling [51], HAYNES C-2000® Ni-based superalloy [52], Zr-based alloy (Zr–Hf) [53], Ti-based