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# An extraordinary enhancement of wear resistance in a multi-modal-laminated alloy

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ABSTRACT

An enhanced wear resistance in vacuum has been achieved in a multi-modal-laminated TiZrAlV by using room-temperature rolling combined with subsequent thermal treatment. The sample exhibits a higher wear resistance than the nanostructured counterpart and offers a ~30% wear mass reduction as compared with the coarse-grained counterpart. The high wear resistance can be attributed to the combination of high strength and high ductility provided by the multi-modal-laminated structure. This study demonstrates that multi-modal structure can be adopted to enhance the wear resistance of nanostructured metals and alloys for engineering application.


## 1. Introduction

Nanostructured (NS) metals and alloys are expected to exhibit high wear resistance because of their high strength (or hardness) [1–5]. However, many reports have revealed that the wear properties of NS materials are not improved or even worsened even though their strength and hardness have been increased significantly compared with their coarse-grained (CG) counterparts [6–11]. This phenomenon may be due to the poor ductility of NS materials, which facilitates the removal of materials from the surface via brittle fracture during sliding wear [6–9,12]. Therefore, wear resistance of NS materials may be increased by enhancing their ductility while maintaining their high strength.

However, strength and ductility usually exhibit an inverse relationship (i.e., increasing the strength sacrifices the ductility and vice versa). Fortunately, by introducing coarse grains into the NS matrix, some multi-modal-structured (MMS) materials have been produced and exhibit significantly enhanced ductility while possessing high strength [13–14]. The enhancement of ductility results from the enhanced strain hardening capability due to the existence of coarse grains. Moreover, the multi-modal distribution of grain sizes, rather than a uniform grain size distribution, may cause the deformation of grains via complex strain paths as demonstrated by previous studies on fcc Cu, which is also beneficial for dislocation storage and strain hardening [13]. These findings indicate the possibility of producing highly wear-resistant NS materials via forming multi-modal structure. Although many MMS metals and alloys with both high strength and high ductility have been produced [13–16], the wear properties of MMS materials are rarely investigated.

The current work aims to study the effect of the multi-modal structure on the wear properties of a material. An enhanced wear resistance in vacuum has been achieved in a multi-modal-laminated (MML) TiZrAlV fabricated by severe plastic deformation (SPD) combined with subsequent thermal treatment. The effect of the MML structure on wear properties is discussed.

## 2. Experimental methods

40.2Ti–51.1Zr–4.5Al–4.2V (wt.%; henceforth denoted as TiZrAlV) was prepared by melting pure Ti (99.7 wt.%), Zr (Zr + Hf > 99.5 wt.%), Al (99.5 wt.%) and V (99.9 wt.%) using a ZHT-001 consumable electrode vacuum arc furnace. Then, the ingot was rolled at 950 °C to produce sheet samples. The sheets were solution treated at 850 °C, which is above the β-transus temperature of the alloy (~720 °C), for 1 h. Subsequently, the sheets were water quenched to keep a large fraction of soft β phase and make them more deformable at room temperature (RT). Experiment details were given in Ref. [17]. To form a nanostructure, the quenched sheets were rolled at RT with a reduction of ~2% per pass. A total reduction of ~93%, i.e. a rolling strain of ~2.65, and a strain rate of $\dot{\varepsilon} = 1.5\ \mathrm{s}^{-1}$ were achieved. To form a multi-modal structure, the

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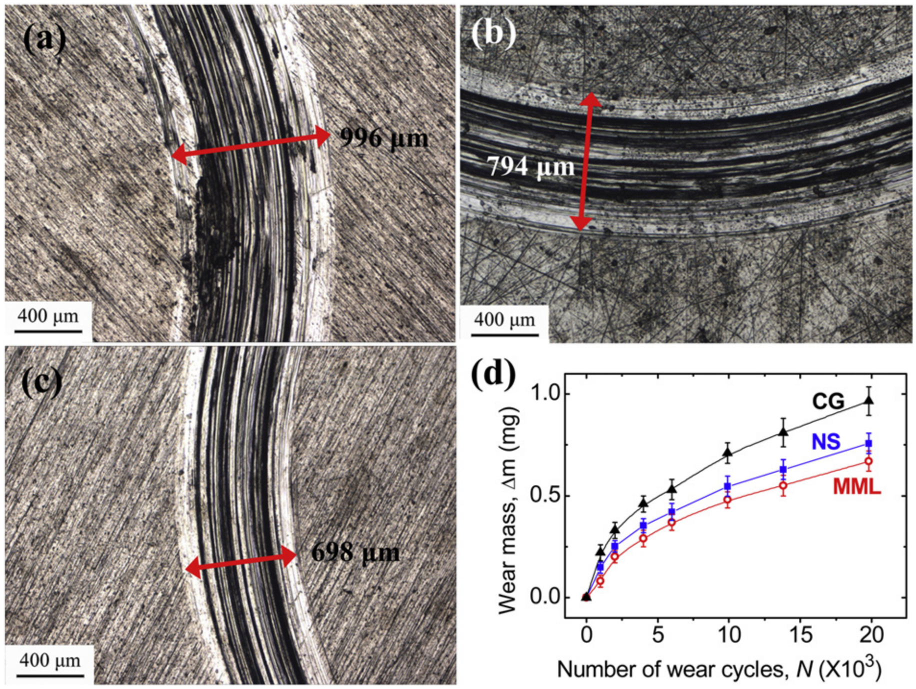


**Fig. 1.** Metallographic images of surface morphologies of (a) as-quenched, (b) as-rolled and (c) A3-treated TiZrAlV samples after a 4000-cycle friction–wear test. The variation of wear mass of the as-quenched (CG), as-rolled (NS) and A3-treated (MML) samples with the increase in number of wear cycles is shown in (d).

rolled sheets were subjected to subsequent heat treatment (A3), which is composed of a one-step recrystallization annealing (675 °C for 10 min) and a two-step aging treatment (625 °C for 2 h + 300 °C for 1.5 h).

To study the effect of microstructure on wear properties and avoid the effect of oxidation, friction–wear tests were performed on the TiZrAlV samples in vacuum by using a ball-on-disk GTM-3E tribometer with a turbo-molecular pump ($p < 10^{-4}$ Pa). Round samples with a dimension of Φ18 mm × 0.5 mm were employed as disks against a 6-mm-diameter GCr15 steel (GB/T 18254-2002, China) ball with a Vickers hardness of 720–780 HV. In the friction–wear test, the applied load was 4 N, the wear diameter was 7 mm, and the rotation speed was 200 rpm. To obtain the variation of wear mass with the number of wear cycles, separate friction–wear tests were performed for each point (Fig. 1d). Uniaxial tensile tests were performed on the samples with a cross-section of 2.0 × 0.35 mm$^2$ and a gauge length of 5.0 mm by using an Instron 5948 Micro-Tester at a strain rate of $10^{-3}$ s$^{-1}$ at RT. The tensile direction was parallel to the rolling direction. The

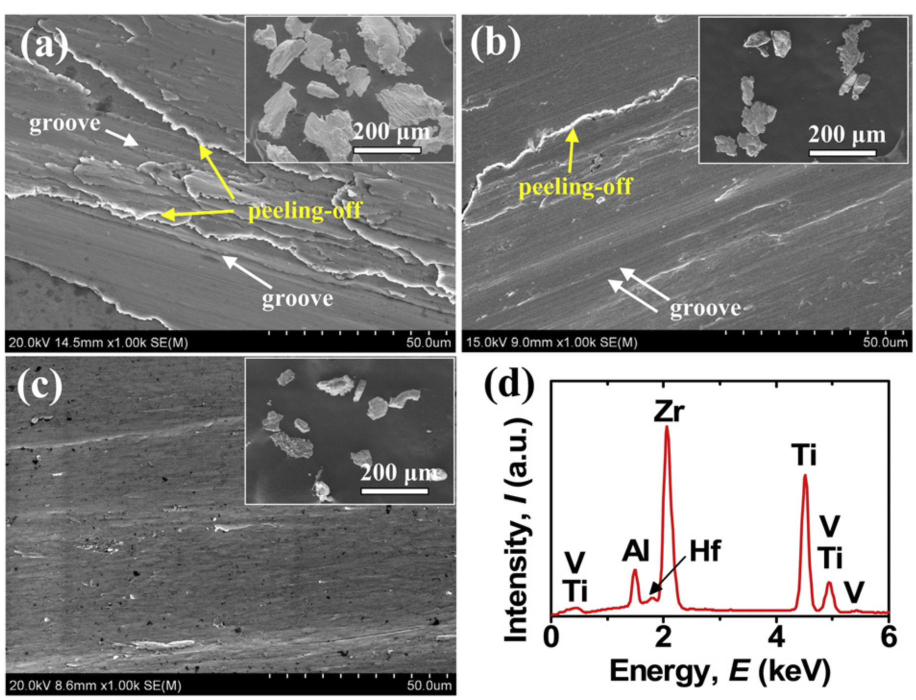


**Fig. 2.** FESEM images of surface morphologies and wear debris (insets) of (a) as-quenched, (b) as-rolled and (c) A3-treated TiZrAlV samples after a 4000-cycle friction–wear test. The EDS spectrum of wear debris of as-quenched sample is shown in (d).