Improvement in wear resistance of TiNi alloy processed by equal channel angular extrusion and annealing treatment

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Abstract

In the present paper, the equal channel angular extrusion (ECAE) and subsequent annealing treatment are applied to the Ti-50.6at.%Ni alloy. The microstructure and pseudo-elasticity of TiNi alloy after ECAE and annealing treatment are investigated, and the wear behavior of the alloy under dry sliding condition is studied. The results indicate that ECAE technique contributes to refine the microstructure and improve the pseudo-elasticity of the TiNi alloy. The wear of TiNi alloys increases with load. Moreover, the ECAE processed TiNi alloy exhibits higher resistance to wear compared with the as-received TiNi alloy. For as-received TiNi alloy, adhesion and delamination were main damage mode under low load, while deep plough tracks were observed under high load. The slight adhesive wear was primary wear mode for the ECAE processed TiNi alloy under both low and high loads.
Keywords: equal channel angular extrusion (ECAE), pseudo-elasticity, shape memory alloy, wear.

1 Introduction

Recently, a number of investigations have demonstrated that TiNi alloy has high resistance to wear in different wear conditions compared it to many conventional wear-resistant materials such as steels, Ni-based and Co-based tribo-alloys [1–5]. This makes TiNi alloy attractive for application in many environments. Extensive researches have confirmed that the high wear resistance of TiNi alloy

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is mainly attributable to its special martensitic phase transformation [6-8] which is also called pseudo-elasticity. Liang et al. [9] has noticed strong correspondence between the wear behavior and the pseudo-elasticity. Specimens with pseudo-elasticity show higher wear resistance than those with little pseudo-elasticity.

Ultra-fine grained materials have attracted much attention from materials scientists owing to their better mechanical properties. Of several techniques developed for producing fine-grained materials by severe plastic deformation (SPD), the equal channel angular extrusion (ECAE) technique introduced by Segal et al. has been successfully applied to produce various fine-grained materials [10–14]. Many studies have confirmed that ECAE process can not only refine the microstructure, but also improve the mechanical properties of materials.

The microstructure of a material remarkably affects its mechanical properties and the wear behavior. Till now, some results on the microstructure and phase transformation behavior of TiNi alloy processed by ECAE have been reported [15,16]. However, the wear behavior of TiNi alloy processed by ECAE has not been well reported yet. The objective of this research is to understand the wear behavior of TiNi alloy processed by ECAE against GCr15 steel under dry sliding condition. The microstructure, pseudo-elasticity, and wear behavior of TiNi alloy processed by ECAE and annealing treatment are studied to evaluate the effects of ECAE and annealing treatment on the wear properties. The wear mechanisms of the TiNi alloy are discussed based on the SEM examination of the worn surfaces.

2 Experimental

Experimental materials were Ti-50.6at.% Ni alloy rod with a diameter of 25mm. The rod had been hot forged at 1123K and annealed at 773K for 2 hours. Billets for ECAE process were cut from the TiNi rod and had dimensions of 9.4 mm×9.4 mm×100 mm. The ECAE die was designed to yield an effective strain of ~1 by a single pass. The inner contact angle (Φ) and the arc of curvature (ψ) at the outer point of contact between channels of the die were both 90°, as shown in Fig. 1. Two ECAE processes were conducted at high temperature. Keeping the die at 823K, billets were preheated at 1123K for 20 min before the first extrusion, and at 1023K for 20 min before the second extrusion. During ECAE process, the billet was not rotated between passages. To obtain homogeneous and fine microstructure, the billets processed by ECAE were annealed at 500°C for an hour.

Specimens for microstructure observation, pseudo-elasticity and wear behavior measurements were cut along the extrusion direction from the TiNi billets processed by ECAE and subsequent annealing treatment. After mechanically polished and etched with a mixture solution of HF:HNO3:H2O with a ratio of 1:3:10, the microstructure of specimens was observed on a NEOPHOT-1 type optical microscope.

Tensile testing was done to investigate the effect of ECAE and annealing treatment on the pseudo-elasticity of TiNi alloy. Tensile test specimens with a reduced gage section of 1 mm thick, 2 mm wide and 20 mm long were machined

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from as-received TiNi alloy and the ECAE processed TiNi alloy. Tensile tests were performed using an Instron Universal Testing machine at room temperature (24°C). The rate of extension was 0.1 mm/min.

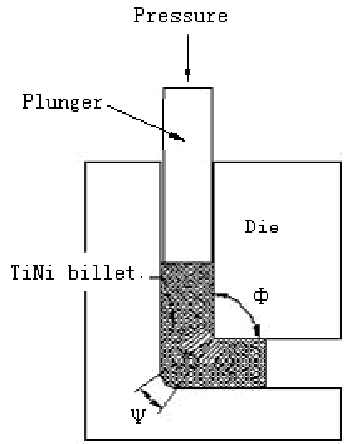


Figure 1: Schematic illustration of the ECAE process in the experiment.

The wear behavior of the Ti-50.6at.%Ni alloy sliding against a GCr15 steel ring under dry sliding condition was evaluated using a block-on-ring tribometer. The size of the TiNi block for wear tests was 20 mm×7 mm×8 mm. Wear tests were carried out at a sliding speed of 0.42 m/s and sliding time of 30 min. The applied load was ranged from 50 N to 100 N. A BP211D electron scale to evaluate the wear resistance was used to measure wear of TiNi specimens. The morphology of worn surfaces was observed using an OPTON CSM 950 scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy X-ray analysis system.

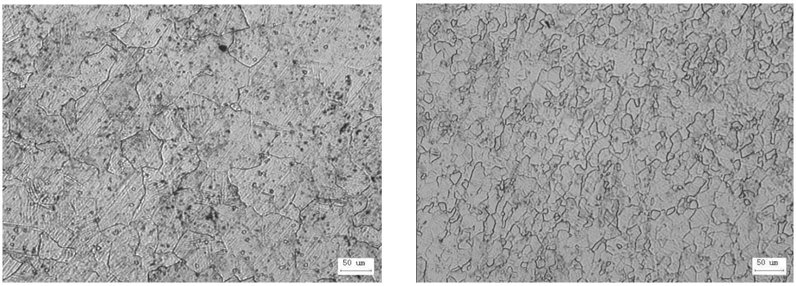
3 Results and discussion

3.1 Microstructure

For comparison, the as-received and the ECAE processed TiNi alloy were investigated. Fig. 2 shows the cross-section microstructure of the TiNi alloys. It can be seen that the microstructure of the as-received TiNi alloy (Fig. 2(a)) was coarse equiaxed structure with the mean grain size of 60 μm. After ECAE and subsequent annealing treatment, the microstructure of TiNi alloy was refined markedly, having an average grain size of approximately 5 μm.

3.2 Pseudo-elasticity

Results of the measurement demonstrated that the TiNi alloys showed pseudo-elastic characteristics, which was illustrated by $\sigma - \varepsilon$ curve of the TiNi alloys



(a) (b)

Figure 2: Microstructures of TiNi alloy: (a) as-received TiNi alloy; (b) the ECAE processed TiNi alloy.

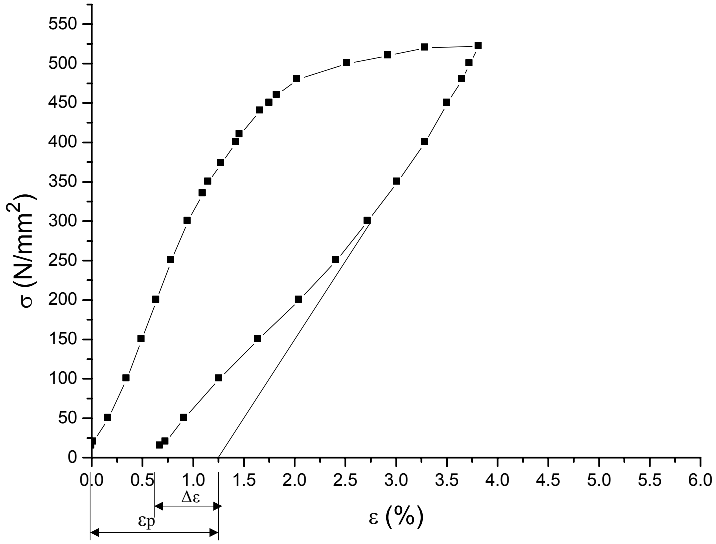


Figure 3: σ – ε curve of TiNi alloy.

Table 1: The γ value of TiNi alloy.

	As-received TiNi alloy	The ECAE processed TiNi alloy
γ value	40%	63%

(Fig. 3). The pseudo-elasticity was evaluated based on the value of $\gamma = {\Delta\varepsilon}/{\varepsilon_p}$, ε_p was the overall residual strain which was supposed to remain when the applied load was removed, and $\Delta\varepsilon$ was the recoverable strain which was not caused by the operation of slip systems but by stress-induced martensitic transformation. The permanent residual strain was, therefore, equal to $\varepsilon_p - \Delta\varepsilon$. The higher the γ value is, the greater the pseudo-elasticity. Table 1 showed γ value of the TiNi alloys. It can be seen that the γ value of the TiNi alloy after ECAE and annealing treatment increased obviously, which suggests that the TiNi alloy processed by ECAE and annealing treatment had better pseudo-elasticity than the as-received TiNi alloy.

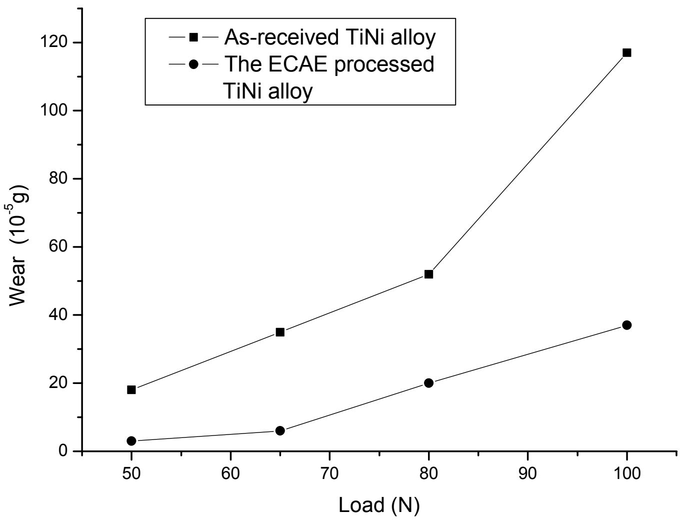


Figure 4: Variation of wear with applied load at a sliding speed of 0.42 m/s.

3.3 Wear behaviour

The effects of applied load on the wear resistance of TiNi alloys were investigated under dry sliding wear condition. The variation of wear of TiNi alloys with applied load was given in Fig. 4. It can be seen that the wear of both the as-received TiNi alloy and the ECAE processed TiNi alloy increased with applied load. This can be explained by the friction-induced thermal and mechanical effects which may increase the actual contact area and the adherence between the frictional pair as the load increased. Moreover, it was found that the ECAE processed TiNi alloy exhibited lower wear in the load range of 50 -100 N than the as-received one. This can be rationally explained by the following reasons. Firstly, the ECAE processed TiNi alloy had more fine grains than the as-received TiNi alloy, leading to the smaller stress concentration. Under the same external stress, the smaller stress concentration caused by fine grains made it difficult adjacent grains deform plastically, so the larger external stress was needed to make adjacent grains plastic deformation. It means that the plastic deformation resistance of the ECAE processed TiNi alloy is enhanced after the microstructure was refined, which reduces the initiation probability of crack and

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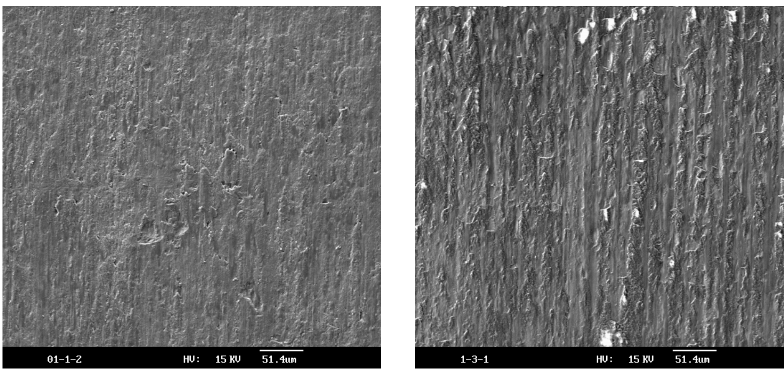
decreases stress concentration, resulting in the increase of wear resistance of the alloy. Secondly, the ECAE processed TiNi alloy has better pseudo-elasticity than the as-received one, which was recorded in Table 1. Liang et al. [9] had demonstrated the strong correspondence between the wear resistance and the pseudo-elasticity. The greater the pseudo-elasticity is, the higher the wear resistance. ECAE and annealing treatment enhanced the pseudo-elasticity of TiNi alloy, which was certainly beneficial to the wear resistance of TiNi alloy.



(a) (b)

Figure 5: Worn surfaces of as-received TiNi alloy: (a) worn under a low load of 50 N; (b) worn under a high load of 100 N.

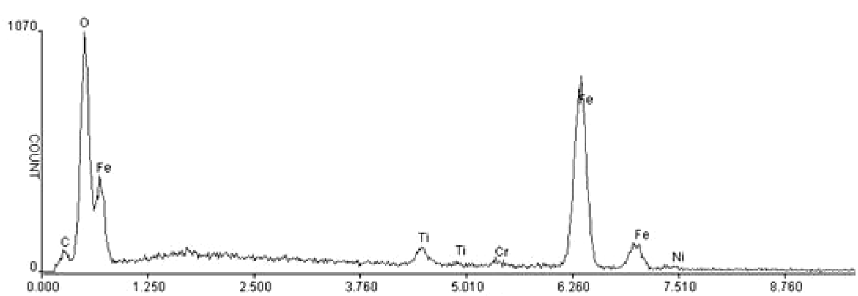
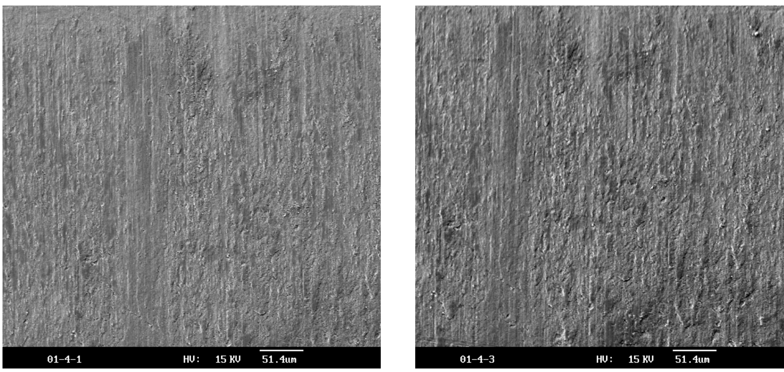


Figure 6: Results of the energy dispersive spectroscopy X-ray analysis performed on the wear tracks of the initial TiNi alloy after sliding against GCr15 steel under a load of 50 N and a sliding speed of 0.42 m/s.

The worn surfaces of as-received TiNi alloy under different applied loads were shown in Fig. 5, respectively. It can be seen that the worn surfaces of the as-received TiNi alloy had different morphologies under different applied loads. At the load of 50 N, the worn surface was smooth. However, a strong iron contamination transferred from the steel ring counterpart was observed by EDS analysis (as shown in Fig. 6), suggesting that adhesion occurred during friction.

At a higher load, deep plough tracks were observed on the worn surface of as-received alloy. Fig. 7 shows worn surfaces of the TiNi alloy with ECAE and annealing treatment. It can be seen that there is not significant difference in the worn surface between low applied load and high load. The surface scuffing was primary wear mechanism under both low and high loads. The morphological difference in worn surface of the ECAE processed TiNi alloy under different loads was not significant as that of the as-received TiNi alloy.



(a) (b)

Figure 7: Worn surfaces of the ECAE processed TiNi alloy: (a) worn under a low load of 50 N; (b) worn under a high load of 100 N.

4 Conclusions

(a) After ECAE and annealing treatment, both the microstructure and the pseudo-elasticity of the TiNi alloy were improved markedly.

(b) The wear of the as-received TiNi alloy and the ECAE processed TiNi alloy both increased with load. When the load ranged from 50 to100 N, the ECAE processed TiNi alloy exhibited higher wear resistance than the as-received alloy.

(c) The wear mechanism of as-received TiNi alloy was adhesion and delamination under low load; while under high load, deep plough tracks were observed. After ECAE and annealing treatment, the surface scuffing was primary wear mechanism of the TiNi alloy under both low and high loads.

Acknowledgements

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References

[1] Richman R.H., Rao A.S. & Kung D., Cavitation erosion of NiTi explosively welded to steel. *Wear*, 181-183, pp. 80-85, 1995.

[2] Zimmerly C.A., Inal O.T. & Richman R.H., Explosive welding of a near-equiatomic nickel-titanium alloy to low-carbon steel. *Mater. Sci. Eng. A*, 188, pp. 251-254, 1994.

[3] Imbeni V., Martini C., Prandstraller D., *et al.*, Preliminary study of micro-scale abrasive wear of a NiTi shape memory alloy. *Wear,* 254, pp. 1299-1306, 2003.

[4] Jin J.L. & Wang H.L., Research on Wear Resistance of NiTi Alloy. *Acta Metall. Sinica A*, 24, pp. 66-69, 1988.

[5] Clayton P., Tribological behavior of a titanium-nickel alloy. *Wear,* 162-164, pp. 202-205, 1993.

[6] Li D.Y. & Liu R., The mechanism responsible for high wear resistance of Pseudo-elastic TiNi alloy-a novel tribo-material. *Wear*, 225-229, pp. 777-783, 1999.

[7] Li D.Y., Wear Behavior of TiNi Shape Memory Alloy. *Scripta Mater.*, 34, pp. 195-200, 1996.

[8] Li D.Y., Development of novel tribo composites with TiNi shape memory alloy matrix. *Wear*, 255(6), pp. 617-628, 2003.

[9] Liang Y.N., Li S.Z., Jin Y.B., *et al.*, Wear behavior of a TiNi alloy. *Wear,* 198, pp. 236-241, 1996.

[10] Valiev R.Z., Islamgaliev R.K. & Alexandrov I.V., Bulk nanostructured materials from severe plastic deformation. *Progress in Materials Science*, 45, pp. 103-189, 2000.

[11] Zhilyaev A.P., Furukawa M., Horita Z., *et al.*, Processing and properties of bulk ultrafine-grained materials produced through severe plastic deformation. *Diffusion and Defect Data Pt.B: Solid State Phenomena,* 94, pp. 3-7, 2003.

[12] Markushev M.V., Bampton C.C., Murashkin M.Y., *et al.*, Structure and properties of ultra-fine grained aluminum alloys produced by severe plastic deformation. *Mater. Sci. Eng. A*, 234-236, pp. 927-931, 1997.

[13] Shin D.H. & Park K.T., Ultrafine grained steels processed by equal channel angular pressing. *Mater. Sci. Eng. A*, 410-411, pp. 299-302, 2005.

[14] Son Y.I., Lee Y.K., Park K.T., *et al.*, Ultrafine grained ferrite-marten site dual phase steels fabricated via equal channel angular pressing: Microstructure and tensile properties. *Acta Mater.*, 53 (11), pp. 3125-3128, 2005.

[15] Li Z.H., Cheng X.H. & ShangGuan Q.Q., Effects of heat treatment and ECAE process on transformation behaviors of TiNi shape memory alloy. *Materials Letters,* 59 (6), pp. 705-709, 2005.

[16] Stolyarov V.V., Prokof'ev E.A., Prokoshkin S.D., *et al.*, Structural features, mechanical properties, and the shape-memory effect in TiNi alloys subjected to equal-channel angular pressing. *Physics of Metals and Metallography,* 100 (6), pp. 608-610, 2005.