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Friction and Wear Mechanism of Unlubricated 304L Austenitic Stainless Steel at Room Temperature

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Abstract: To explore wear mechanism of stainless steel used in nuclear pump, the wear properties and the worn surface characteristics of unlubricated 304L austenitic stainless steel on itself were investigated in air at room temperature. The experimental results demonstrated that the wear rate of the material decreased with the increase of the wear time. The friction coefficient fluctuated severely when the applied load was 120 N. At 120 N the wear rate was much higher than that of the applied load of 70 N. At 70 N the wear rate did not show much difference from that of 30 N. The wear mechanism was adhesive and abrasive wear under different load at the initial stage of the wear test. Then, the main wear mechanism changed with the wearing time and the applied load.

Key words: 304L; dry sliding friction; wear property; wear mechanism

1 Introduction

AISI 304L austenitic stainless steels are widely used in nuclear industry because of their high strength and corrosion resistance. In nuclear pump components, many friction pairs are the same austenitic stainless steel. It has important practical significance to investigate the wear properties of 304 L austenitic stainless steel on itself in order to insure the service life of nuclear pump components. The previous work had studied the wear properties of AISI 304 stainless steel, which had the similar wear properties with the 304 L. The phase transformation of austenite (γ) to martensite (M) of 304 austenitic stainless steel was found in the literatures[1-9]. M. Hua[10] and others found that the wear rate decreased with the increasing load and sliding speed. The wear coefficient and weight loss decreased with increasing humidity. A beneficial effect of grain refining was also shown with respect to large grain steel in that the finer grain steel produced less initial weight loss[11]. It seemed that different mating materials was likely to give rise to completely inverse friction behaviors of the SUS 304 stainless steel[10], but the friction and wear of 304L austenitic stainless steel mating material on itself have been reported rarely.

The wear properties of 304L austenitic stainless steel mating material on itself and the evolution of wear mechanism were researched in detail.

2 Experimental

2.1 Materials

AISI 304 stainless steel samples were used as the substrate. The chemical composition is shown in Table 1. The specimens were etched in 10% oxalic solution by electrolysis for revealing the detail features of microstructure. The microstructure was austenite with a few twins by a MEF-4A type optical microscope (Fig.1). An MV-1000B microhardness tester with an applied load of 300 g and loading time of 15 s was used to measure the Vickers microhardness of the specimen. The average value was 162.1 HV.

2.2 Procedure

A MMW-1A type wear-testing machine was employed to evaluate wear resistance of austenitic stainless steel samples. The rubbing-pairs were the ring with diameter of 28 mm and thickness of 10 mm, as well as the disc with diameter of 31.7 mm and thickness of 10 mm. The average surface roughness of the specimens was 0.023 μm determined by a surface profilometer of Newview5022 after abrading with 1500 grit SiC papers. Before and after each test,

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Table 1 Chemical compositions of 304L/wt%

Element	C	Ni	Cr	Si	Mn	Mo	Cu	S	P	Fe
304L	0.03	18.20	8.00	0.42	0.96	0.13	0.52	0.022	0.001	Remainder

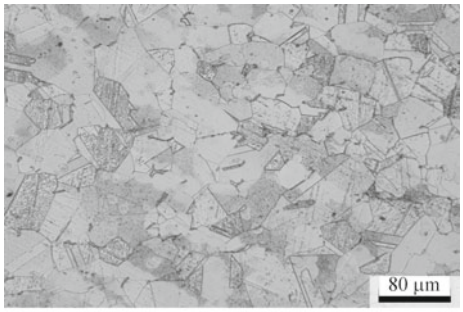

Fig.1 Metallograph of 304 L stainless steel

the specimens were ultrasonically cleaned 30 min in acetone solution, then dried 30 min in drying oven. Tribological tests were performed with a sliding velocity of 60 r/min and the load of 30, 70 and 120 N at room temperature, respectively.

The worn surface were examined with a JSM-5600LV scanning electron microscope (SEM). The transformed M from γ on the worn surface and in the subsurface layer was detected by a D/MAX-2400 X-ray diffractmeter (XRD) and optical microscope.

3 Results and discussion

3.1 Microstructue and phase analysis

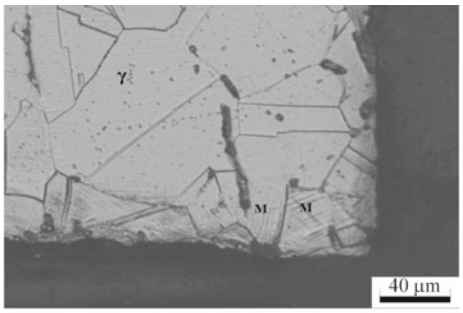

Fig.2 Metallograph of friction induced martensite on worn surface

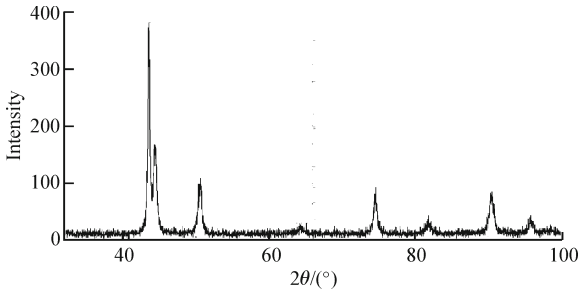

Fig.3 X-ray pattern of 304L stainless steel worn surface

Fig.2 is the metallograph of friction-induced transformation of austenite to martensite beneath the wear trace of 304L after the wear test. Fig.3 and Fig.4 show X-ray diffraction patterns of worn surface and wear particles of 304L stainless steel, respectively. The presence of the martensite peaks are observed in Fig. 3 and Fig. 4. It was obviously that the existence of martensitic transformed from austenite on the worn surface after wear test.

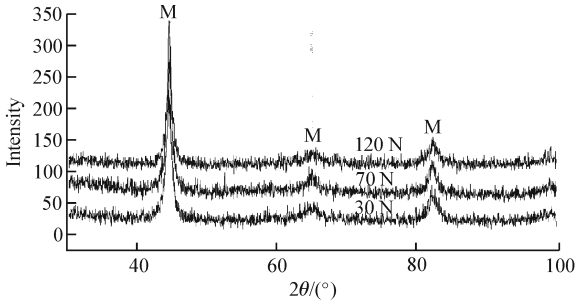

Fig.4 X-ray patterns of 304L stainless steel wear particles for wear test 180 min

The effect of the stress and the strain during the wearing test made M_s much higher than its nominal number, which were beneficial to transformation from austenite to martensite. Slip bands, twinning and grain boundaries were easy to induce stress concetration in plastic deformation of metastable austenite, which was positive to the martensite nucleation. The additional energy of metastable austenite was given by the external force that increased the mechanical driving force from austenite to martensite. Stress-induced martensite was observed in the near-surface of the worn material (Fig.2). Refined grain was observed on worn surface layers in the study of Hua and Wei[10], but it was not found in this study.

3.2 Friction and wear properties

Friction coefficient as a function of the sliding time for wear test 180 min under different load are shown in Figs.5-7, which shows the wear loss and wear

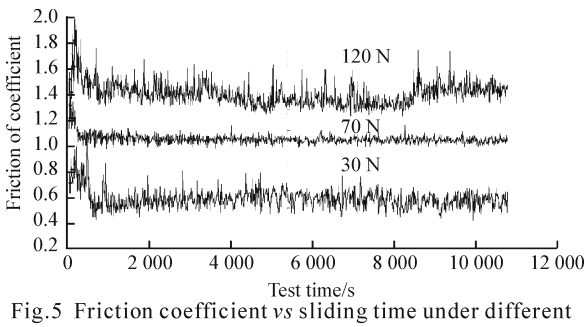

Fig.5 Friction coefficient *vs* sliding time under different loads for wear test 180 min

rate as a function of the sliding time.

At the initial stage of the wear test, there were lots of asperities on the wear surface of specimens, which made the real contact area of the wear-pairs much smaller than its nominal counterpart. The contact pressure was relatively higher than its theoretical counterpart, so that the plastic deformation easily occurred on the asperities. It was easily known that the wear coefficient (Fig. 5) and wear loss were relatively higher at the initial stage of the wear test (Fig. 6).

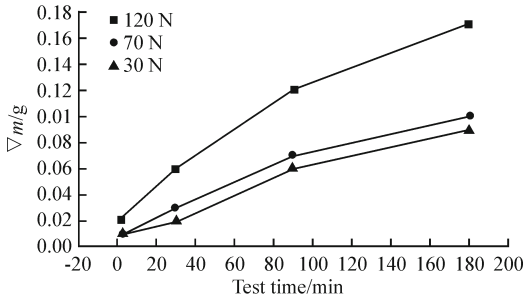

Fig.6 Variation weight loss *vs* sliding time under different loads

In order to display and comparison clearly, the friction coefficient curves of 70 N and 120 N were plotted by shifting 0.5 and 1 upwards respectively in Fig. 4. With the advance of wear test, the wear coefficient tended to be stabilized in a small range (Fig.5) and the weight loss and wear rate were obviously samller (Figs.6-7), which could be attributed to the follows: the formation of work-hardening layer on the worn surface; the transformation from austenite to martensite; the debris on the wearing surface, which detached from the substrate. The debris can break up to sufficiently small sizes and oxidized rapidly because of the friction heat. The oxidized particles, which were agglomerated to be a lubricated layer[12], could protect the surface against subsequent wear loss.

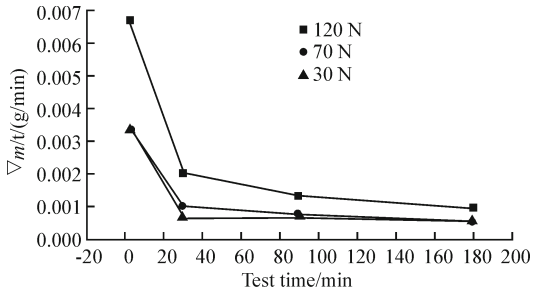

Fig.7 Variation weight velocity *vs* sliding time under different loads

As can be seen in Fig.7, the wear rate of 120 N was almost twice than that of 70 N. The wear rate of 70 N did not show significant difference from that of 30 N. Compared with 30 N load, 70 N had the seriously strain-hardening, the higher residual compressive stress[13] and the higher phase transformation from austenite to martensite[1]. The wear rate of 120 N was relatively higher than that of 70 N and 30 N loads, though it had the similar performance as 70 N. The reasons could be concluded as follows. When the applied load was 120 N, the crack initiated easily at the interface between the austenite and the harder friction-induced martensite. And the fatigue delamination were pulled out from the parent material surface as shown in Fig. 8. But this phenomenon was not found at 70 N and 30 N. The formation of the harder martensite worn debris may subsequently accelerate the wear rate.

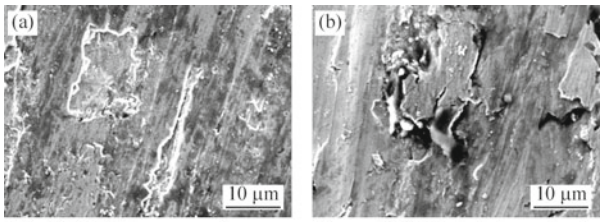

Fig.8 SEM images of worn surface of 304 L stainless steel, after wear test 180 min under 120 N load

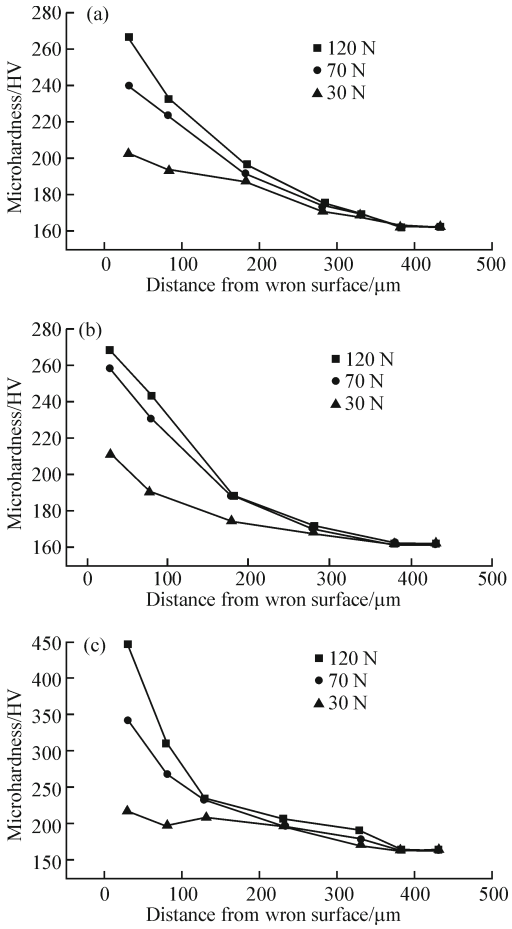

Fig.9 Microhardness versus distance, after wear test at (a) 30 min; (b) 90 min; (c) 180 min

Fig. 9 shows the relationship of microhardness and the distance away from the worn surface at 30,

70 and 120 N for different time. Because of plastic deformation and stress-induced martensite duing wear test, the unworn area revealed lower hardness than the worn area. Because of the higher amount of martensite and higher plastic deformation at higher loads, the hardness of deformed area increased with the increasing of the applied loads[14,15]. In the worn surface, the thickness of martensite transformation layer was only about 40 μm as shown in Fig.2. The microhardness of the worn surface without martensite transformation only decreased slightly. Therefore, the dominant factor of the increasing microhardness of the worn surface was the plastic deformation.

Results of microhardness versus distance showed that the thickness of plastically deformed area did not relate to the amount of applied load and wear time. The reasons were as follows: the higher load, the higher possibility of the wear lost duing wear test; more heat generated at contacting areas with the increasing of the applied load because of the low thermal conductivity of 304L stainless steel. The enhanced temperature at the contact area and low thermal conductivity of austenitic stainless steel resulted in the heat accumulation. The accumulated heat and subsequent stress relief process reduced the microhardness of austenite and martensite phases, which was consistent with the results obtained by Morteza Zandrahimi[1].

3.3 Wear mechanism

SEM images of worn surface of 304L stainless steel at 30, 70 and 120 N are shown in Figs.10-12, which showed serious damage on the surface of 304L austenitic stainless steel. At the initial stage of experiment, plastic deformation easily occurred on asperities of specimens' surface, which made the atoms of two counterparts' surface be very close to each other, so the adhesion wear occurred. The particles with higher hardness detached from deformed asperities acted as hard sliders and produced grooves. As can be seen in Figs.10(a)-12(a), there was the plough on the wear surface with lots of metallic particles in them. In the initial experiment at 30, 70 and 120 N, the dominated wear mechanism was adhesive wear. The plough of 120 N was relatively wider than that of the 30 and 70 N.

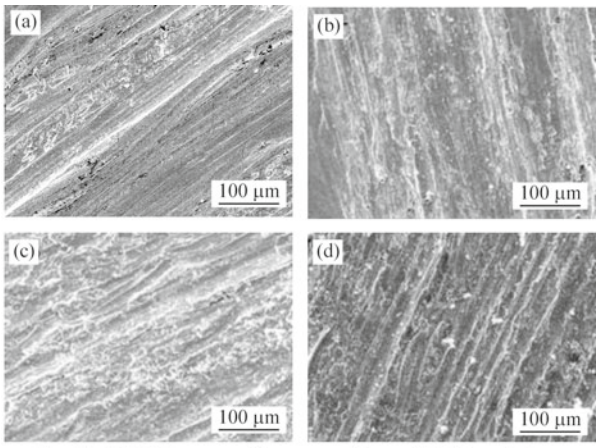

Fig.10 SEM images of worn surface of 304L stainless steel under load 30 N (a)2 min; (b))30 min; (c)90 min; (d) 180 min

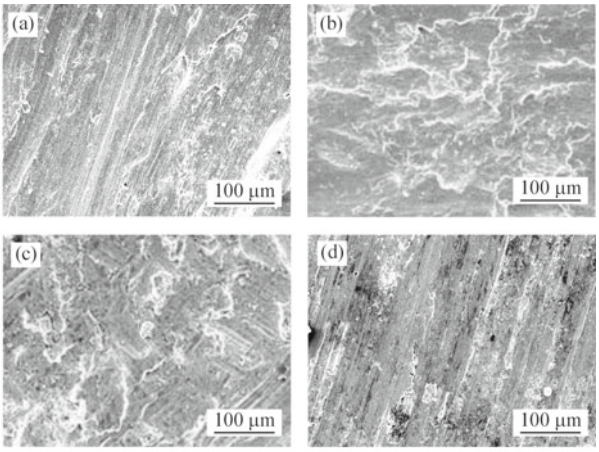

Fig.11 SEM images of worn surface of 304L stainless steel under load 70 N (a)2 min; (b))30 min; (c)90 min (d) 180 min

At 30 N for the wear test of 30 and 90 min, the adhesive occurred and abrasive ploughing appeared on the worn surface resulted from the hard abrading particles. The wear mechanism was adhesive and

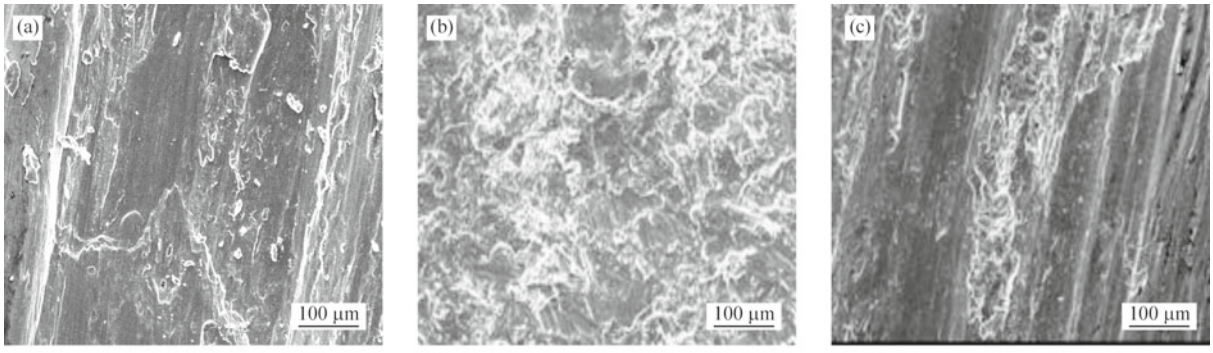

Fig.12 SEM images of worn surface of 304 L stainless steel under load 120 N (a)2 min; (b)30 min;(c)90 min

abrasive wear as shown in Figs.10(b)-10(c), whereas adhesive wear was very obvious with typical cloud-like structure.

Fig.10(d) shows that the adhesive wear for the 180 min was not significant than that of the 30 and 90 min. The main reason was the oxidized particles as lubricated layer at the interface of counterparts by friction heat[16]. The mixed wear mechanism was abrasive, adhesive and oxidation wear. Figs.11(b)-11(c) showed the plastic flow wear of the worn surface at 70 N for 30 and 90 min. The main wear mechanism was adhesive. There were lots of pittings in the plough of the worn surface for 180 min(Fig. 11(d)).The mixed wear mechanism was abrasive, adhesive, oxidation wear and pitting corrosion. At the higer load of 120 N for 30 min, the adhesive wear was the dominant mechanism (Fig. 12(b)). For 90 min, the plough was relatively wider than that of 30 and 70 N. The abrasive and adhesive wear were the main mechanism as shown in Fig.12(c). For 180 min, the fatigue cracks and fatigue delamination were shown on the worn surface in Fig.12(d). The mixed wear mechanism was abrasive, adhesive, oxidation and fatigue wear.

4 Conclusions

a) Austenite transformed to martensite beneath wear trace during the wear of 304L austenitic stainless steel mating material on itself.

b) Because of the plastic hardening, phase transformation strengthening and oxidized wear particles, the wear rate of the material decreased with the increasing of the wear time. At 70 N, the wear loss and wear rate were much lower than that of 120 N. With advancing of experiment, the wear rate of 70 N had not significant difference from that of 30 N.

c) The wear mechanism was adhesive and abrasive wear under different loads at initial stage, then the main wear mechanism changed with the time and load. Under wear test of 30 N for 30 and 90 min, the wear mechanism was adhesive and abrasive wear; for 180 min, the wear mechanism was adhesive, abrasive and oxidation wear. Under wear test of 70 N for 30 and 90 min, the wear main mechanism was adhesive wear; for 180 min, the wear mechanism was adhesive, abrasive, oxidation wear and pitting corrosion. Under wear test of 120 N for 30 min, the wear mechanism was adhesive wear; for 90 min, the main wear mechanism were adhesive and abrasive wear; for 180 min, the wear mechanism was adhesive, abrasive, oxidation and fatigue wear.

References

[1] Morteza Z, Rezabateni M, Poladiet A, *et al.* The Formation of Martensite during Wear of AISI 304 Stainless Steel [J]. *Wear,* 2007, 263: 674-678

[2] Hübner W, Pyzalla A, Assmus K, *et al*. Phase Stability of AISI 304 Stainless Steel during Sliding Wear at Extremely Low Temperatures[J]. *Wear,* 2003, 255: 476-480

[3] Farias MCM, Souza RM, Sinatora A, *et al.* The Influence of Applied Load, Sliding Velocity and Martensitic Transformation on the Uunlubricated Sliding Wear of Austenitic Stainless Steels[J]. *Wear,* 2007, 263: 773-781

[4] Yang ZY, Naylor MGS , Rigney DA. Sliding Wear of 304 and 310 Stainless Steels [J]. *Wear,* 1985, 105(1): 73-86

[5] Hsua KL, Ahna TM, Rigney DA. Friction. Wear and Microstructure of Unlubricated Austenitic Stainless Steels[J]. *Wear,* 1980, 60(1): 13-37

[6] Wei XC, Li J, Hua M. Tribological Characteristics of HSLA TRIP Steel Containing Meta-Stable Retained Austen ite[J]. *Tribology,* 2006, 26: 49-53

[7] Jervis TR, Hirvonen JP. Tribology and Surface Mechanical Properties of the Oxide Film Formed by Excimer Laser Surface Treatment of AISI 304 Stainless Steel[J]. *Wear,* 1991, 150(1-2): 259-265

[8] Raud S, Garem H, Naudon A, *et al.* Wear Resistance Improvement and Structural Modifications of B+-implanted Austenitic Stainless Steel[J]. *Materials Science and Engineering,* 1989, 115: 245-251

[9] Wei XC, Hua M, Xue ZY, *et al*. Evolution of Friction-induced Microstructure of SUS 304 Meta-stable Austenitic Stainless Steel and Its Influence on Wear Behavior[J]. *Wear,* 2009, 267: 1 386-1 392

[10] Hua M, Wei XC , Li J. Friction and Wear Behavior of SUS 304 Austenitic Stainless Steel Against Al_2O_3 Ceramic Ball under Relative High Load[J]. *Wear*, 2008, 265: 799-810

[11] Bregliozzi G, Schino ADi, Kenny JM, *et al*. The Influence of Atmospheric Humidity and Grain Size on the Friction and Wear of AISI 304 Austenitic Stainless Steel[J]. *Materials Letters,* 2003, 57: 4 505-4 508

[12] Rigney D. Role of Hardness in Sliding Behavior[J]. *Wear,* 1994, 175: 63-69

[13] Poggie RA, Wert JJ. The Influence of Surface Finish and Strain Hardening on Near-surface Residual Stress and the Friction and Wear Behavior of A2, D2 and CPM-10V Tool Steels[J]. *Wear,* 1994, 149: 209-220

[14] Bi HY, Li SZ, Zhang XX. The Effect of Deformation Strengthen ing on Wear Res istance of Stainless Steel in Dry Sliding and Corrosive Environment [J]. *Tribology,* 1998, 18 (4) : 327-331

[15] Qi YH, Ma YQ, Zhang ZP, *et al.* TEM Observation of theWorn Surface Layer in Metastable Austenite Fe-C-Cr-Mn Cast Iron [J]. *Tribology,* 2000, 20 (3) : 92-96

[16] Ken'ichi Hiratsuka, Ken'ichi Muramoto. Role of Wear Particles in Severe-mild Wear Transition[J]. *Wear,* 2005, 259: 467-476