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Research on friction and wear behavior of gradient nano-structured 40Cr steel induced by high frequency impacting and rolling

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ABSTRACT

Surface gradient nanostructure of 40Cr steel was prepared by using high frequency impacting and rolling. First, surface nanocrystallization mechanism was investigated through surface morphology, microstructure evolution, work hardening and residual stress. Then friction and wear mechanism of gradient nanostructured 40Cr steel was discussed by coefficient of friction, wear mass loss and worn morphology. Grain refinement process through formation of dislocation tangles, transformation of sub-grains to nanocrystals and the breakage phenomenon of the laminated structure of pearlite during high frequency impacting and rolling treatment are considered as the surface nanocrystallization mechanism. The wear mass loss of gradient nanostructured surface is far below as-received surface as the increase of applied load. The friction and wear mechanism of as-received 40Cr steel was changed from abrasive wear to fatigue wear, while fatigue wear of the gradient nanostructured 40Cr steel was not presented as the increase of applied load (10 N–50 N).

1. Introduction

Shafts are among the typical parts in mechanical structures, mainly used to support transmission parts and transmission torque. 40Cr steel is widely used in shaft parts for its excellent comprehensive mechanical properties. However, with the increasing demand of lifetime, it is quite urgent to improve the friction and wear properties of 40Cr steel shaft components.

Surface nanocrystallization induced by severe plastic deformation (SPD) is an effective approach to obtain a nanostructured surface layer [1–3] to improve friction and wear properties [4–6]. The previous studies have indicated that superior wear resistance can be attained through microstructural refinement via SPD techniques [7–11]. Liu et al. [12] investigated the wear behavior of nanocrystalline structured magnesium alloy induced by surface mechanical attrition treatment (SMAT). Results showed that the poor wear resistance of nanocrystalline (NC) layer is attributed to its low ductility and toughness under the low speed of 0.05 m/s and the wear mechanism transfers into oxidative wear leading to a low friction coefficient under the high speed of 0.2 m/s. Wen et al. [13] analyzed the effect of NC surface and iron-containing layer obtained by SMAT on tribological properties of 2024 Al Alloy and the results showed that the wear resistance of 2024 Al alloy is improved due to the combination of grain refinement, increased hardness and lubrication effect of iron-containing layer. The tribological behaviors of 316L stainless steel and medium manganese material after surface nanocrystallization under the condition of lubrication was studied by Wang et al. [14] and Ba et al. [15], respectively. Results indicated that the better friction reduction and wear resistance were exhibited on nanocrystalline layer. Mohammed [16]

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reviewed the mechanical and wear properties of the high pressure torsion (HPT) titanium and results indicated that the wear properties determining the application of Ti in medicine may be improved via SPD. Li et al. [17] found that the microstructure characterization of the further refined β-regions with ultra-refined α phase or Martensite-α′ phase was benefited to the improvement of dry sliding wear performance for the friction-stir (FS) processed surface layer. Chen et al. [18] reported that a submillimeter-thick stable gradient nanograined surface layer enables a significant reduction in the COF of a Cu alloy under high-load dry sliding. This finding is generally significant and may find tremendous potential for the technological applications in contact loading of metals.

In addition, there are still many studies about friction and wear behaviors based on SPD or surface nanocrystallization [19–22]. Most research results showed that the nano-grained layer exhibited a low friction coefficient and a better wear resistance. For example, the empirical Eq. (1) combined with Archard wear law and Hall-Petch relationship proposed by Farhat et al. [23] indicated that wear resistance can be improved by microstructural refinement.

$$W = W_0 + k\left[\frac{L}{H_0 + KD^{-1/2}}\right] \tag{1}$$

where W is the wear rate, k is termed wear coefficient, L is the wear distance, D is the grain size and W_0, H_0 and K are constants.

However, some researchers [12,24] found that the wear mechanism of nano-grained layer may be associated with sliding speed and applied load. Therefore, the high frequency impacting and rolling (HFIR) was adopted as a new SPD method based surface treatment and applied to 40Cr steel in this study. Then the wear mechanism of gradient nanostructure induced by HFIR under the condition of high sliding speed and various loads was discussed.

2. Material and experiments

2.1. Material

The material used was 40Cr steel (according to the Chinese nomenclature) with a chemical composition and the actual tested mechanical properties presented correspondingly in Table 1 and Table 2. The microstructure of 40Cr steel contains black lamellar pearlite (P) and white ferrite (F).

2.2. Specimens and HFIR treatment

The plate specimen, shown in Fig. 1, was treated by HFIR device using the parameters listed in Table 3. The principle of HFIR is ultrasonic vibration and rolling is applied when a constant extrusion between working tip and work-piece exists. The photographic view of experimental setup was shown in Fig. 2. The machining process is finished through the rotation of specimen and the radial feed of impacting and rolling head.

2.3. Experimental testing and characterization

A JEM-2010 type of transmission electron microscopy (TEM) was used to observe the microstructures at three positions (a: the top surface; b: 80 μm from the top surface and c: base material) of HFIR specimen. A Carl Zeiss EVO-18 type of scanning electron microscope (SEM) was used to examine the changes in surface morphology along the depth direction after HFIR. Hardness variation from the top surface to the interior was determined by MH-3 Vickers hardness tester with a load of 50 gf and dwell time of 15 s. The testing procedure was repeated five times at the different positions of the cross section after HFIR and the average value was finally adopted. Residual stress along the depth of HFIR specimen was measured by STRESS X3000 X-ray tester with result analysis software programmed by $\sin^2\Psi$ method (radiation Cr-Kα, diffraction angles (2θ) scanned between $-22°$ and $22°$). Because the residual stress measurement is surface sensitive, material above the target layer should be removed by chemical reducing, which will cause the rearrangement of residual stress. The corrosive liquid includes HCl and HNO_3 with the ratio of 3:1.

The dry sliding wear tests were carried out by using a computerized pin-on-disk wear testing machine (MG-2000) at room temperature (20 °C) in air and the material of abrasive disk is GCr15, at the sliding speeds of 1.2 m/s under the applied load of 10 N, 20 N, 30 N, 40 N and 50 N for a sliding distance of 216 m. Disks of 40Cr alloy under investigation were machined to 6 mm in diameter and about 13 mm in thickness. The test surface was cleaned in an acetone solution by ultrasonic wave. The loss of mass was calculated from the difference in weight of specimens measured before and after the sliding tests by the electronic balance of 0.1 mg precision. The worn surfaces and wear debris were analyzed through SEM.

Table 1
The chemical composition of 40Cr steel [24].

Material	Chemical composition (%)								
	C	Si	Mn	Cr	Ni	P	S	Cu	Fe
40Cr	0.37–0.44	0.17–0.37	0.50–0.80	0.80–1.10	≤ 0.030	≤ 0.035	≤ 0.035	≤ 0.030	Else