Research Article

Formation of Nanocrystallized Structure in Worn Surface Layer of T10 Steel against 20CrMnTi Steel during Dry Rubbing

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T10 steel slid against 20CrMnTi steel on a pin-on-disc wear test rig. Optical Microscope (OM), scanning electron microscope (SEM), and High Resolution Transmission Electron Microscope (HRTEM) methods were used to analyze the microstructures in the worn surface layers. The microstructures in the worn surface layers of pins and discs were all severely plastically deformed. Furthermore, the ultrafine and even nanoferrite structure (10 nm to 100 nm) was observed when the normal load reached 60 N. The mechanism of forming nanocrystalline structure in the sliding friction induced deformation layer (SFIDL) was elucidated as the result of the simultaneous and recursive actions of (i) severe shear deformation and (ii) friction heat on the contact surface.

1. Introduction

Nanocrystalline materials show extraordinarily high hardness and/or yield strength, so some metal engineering scientists have paid attention to them [1–3]. When the grain size decreased to the nanometer level, the nanocrystalline metals have the distinctive mechanical properties in comparison to their coarse-grained counterparts, resulting in the attractive application prospects [4–6]. The revealing of the subsurface structure evolution is quite useful in understanding the friction and wear behavior of crystalline materials. Therefore, many scholars made strenuous efforts to research the worn surface microstructural evolutions of the ductile materials, such as aluminum [7], magnesium [1], and copper alloys [8].

Undoubtedly, to study evolution of the microstructure in sliding surface layer of carbon steel with test conditions is beneficial for one to understand and optimize the surface properties. Furthermore, the researches on the evolution of microstructure can explore the possible modification techniques to enhance service lifetime of the parts. Unfortunately, the limited research has been carried out on the formation of carbon steel ultrafine structure induced by dry sliding subsurface deformation.

In this study, the friction and wear properties of normalized T10 steel pin against quenched and tempered 20CrMnTi steel disc were conducted on a pin-on-disc wear test rig. The microstructural evolution in the sliding friction induced deformation layer (SFIDL) was analyzed. The possible mechanism of forming ferrite ultrafine structure in the sliding friction induced deformation layer (SFIDL) was elucidated.

2. Methods

2.1. Materials and Wear Test. The pin was made of T10 steel containing 0.98%C, 0.40%Mn, 0.35%Si, 0.011%S, 0.013%P, and balance Fe, and the disc was made of 20CrMnTi steel containing 0.2%C, 1.2%Cr, 0.1%Ti, 0.2%Si, 0.25%Cu, 0.04%S, 0.04%P, 0.95%Mn, and balance Fe, respectively. Their hardness of pin and disc specimens was about 180 HB and 357 HB, respectively. Their surface roughness of the pin and disc specimens was Ra 0.03–0.09 μm and Ra 0.05–0.1 μm , respectively.

The MM-W1 disc-on-pin wear test rig was used in a laboratory environment to carry out the dry sliding friction test. The sliding speed was 0.29 m/s, the test time was 7200 s, and the selected normal loads were 40 N, 50 N, and 60 N,

respectively. The pin and disc specimens after test were cross-sectioned cut.

2.2. Observation of Worn Surface and Friction Induced Surface Layer. Metallographic specimens were EDM-wire-cut along the sliding direction of slid SFIDLs, which were then cool-inlaid with tooth acrylic resin, grinded and polished with SiC sand paper, and then etched with a 4% nitric acid alcohol solution. Removed the tooth acrylic resin and ultrasonically cleaned via acetone solution. The worn surfaces were protected by electroless Ni plating. The so-prepared specimens were subsequently analyzed by a VHX-600 Optical Microscope (OM) and a HITACHI S-570 scanning electron microscope (SEM) with a 20 kV energy spectrum.

To analyze whether there was any possible structure refinement on the utmost top of the slid surface, individual 0.5 mm thick slices were wire-cut along the depth direction, which were carefully thinned to a thickness in range of 30 μm –50 μm by gradually grinding off the slices from their nonslid surface. Transparent tape was used to protect the worn surface of the thinned specimens which were then punch-pressed into 3 mm diameter wafers. After single-jet electropolishing and ion thinning for 30 minutes, the specimens were analyzed via a JEM-2010 High Resolution Transmission Electron Microscope (HRTEM) equipped with a Gatan Image Filter (GIF) and selected area electron diffraction (SAED).

3. Results and Discussion

3.1. Worn Surface Layer. OM images of longitudinal cross section of T10 pins and 20CrMnTi discs were shown in Figure 1. The morphologies of SFIDLs were plastically deformed and inclined to the sliding direction in both T10 pins and 20CrMnTi discs. Beneath the worn surfaces, the ferrite and pearlite were elongated (Figures 1(a)–1(c)) and the martensite was also inclined to the sliding direction (Figures 1(d)–1(f)), which indicated that the severe plastic strain occurred as a result of friction shear stress [9]. With increased loads, higher frictional force produced larger plastic strain and greater extent of plastic deformation.

In comparison of T10 pins and 20CrMnTi discs, the morphology of subsurface layer clearly revealed that the plastic deformation degrees of pin exceeded that of disc in the sliding direction. It might be contributed to the higher initial hardness of 20CrMnTi disc, which implied that the strong strain hardening was produced and the hardness was enhanced when the normal load reached 60 N [9].

To better understand the SFIDL microstructures of pins and discs, cross sections' SEM images were shown in Figure 2. According to the method proposed by Rice et al., [10] the SFIDLs can be divided into two zones, referred to as Mechanically Mixed Layer (MML) and Plastic Deformation Layer (PDL). (i) Wang et al. [11] found that 0.45% C steels have a high density of grain boundaries and lattice dislocations in a highly nonequilibrium state in the MML, when they are rubbing against the tin alloy, which is consistent with the structure characterized by Figure 2(a). Obviously, owing to

the composite effect of shear and squeezing, the materials transferred between two mating MMLs during dry rubbing progress. Simultaneously, the MML was gradually heaped up and accumulated, eventually leading to the microcracks propagated parallel to the sliding direction during the rubbing (Figure 2(a)). (ii) Considerable plastic deformation and repetitive friction heat promoted the formation of the PDL during drastically rubbing process. The pressure and the tangential shear force tended to plastically deform the near surface material. The lamellar pearlites (Figure 2(a)) and the martensites (Figure 2(b)) were reoriented or even fractured along the sliding direction, which attributed to their ductility and brittleness. The appearance of clear plastic flow lines propagates from the worn surface to the matrix, which have been similarly described in [12].

Comparing the microstructural evolution of T10 pin with 20CrMnTi disc, the plastic deformation of 20CrMnTi disc was smaller than T10 pin (Figure 2(b)). It is worthy of notice that the harder tribopair emerges to be deformed more slightly than the softer tribopair during the rubbing process. Such finding obviously was confirmed and substantiated by the findings of Venkataraman and Sundararajan [13] and Viáfara and Sinatora [14].

3.2. Ultrarefinement and Nanocrystallization in Worn Surface Layer. Figure 3 is the TEM dark field images and SAED patterns of the T10 steel pins worn surface layers under 40 N, 50 N, and 60 N. The SAED pattern in Figure 3(a) reveals some ultrafine grains with random orientation in the worn surface layer. The SAED pattern in Figure 3(b) shows nearly continuous bcc ferrite rings, and the cementite ring is not found. It can be inferred that the cementite was possibly dissolved into the matrix or worn off. The SAED pattern in Figure 3(c) indicates that the microstructure was randomly oriented bcc grains without any cementite rings, which suggests that the cementite nearly decomposed completely. In addition, some smaller and more uniform grains in the worn surface layer were observed. Figure 3(d) shows the HRTEM image of the nanostructure ferrite in T10 pin under 60 N. The nearly equiaxed ultrafine structure, whose size of nanostructure was less than 10 nm, containing formed dislocations and some lattice distortions accommodating at the grain boundaries, could be seen in Figure 3(d). Ivanisenko et al. [15] observed ultrafine ferrite grains in the pearlitic steel via mechanical milling, which was very similar to this research.

The higher normal load leads to bigger shear stress and thus larger plastic deformation, resulting in ultrafine grain and sharper grain boundaries. Similar decomposition phenomena of ferrite nanocrystallization under various plastic deformation processes have been reported, such as surface mechanical attrition on tool steel [16, 17], ball drop test on eutectoid steels [5], and drill holes on steel [18]. Todaka et al. [5] suggested that the dissolution of cementite is always accompanied by the decomposition of pearlite colonies and ultrarefinement of ferrite. Therefore, the observed ferrite nanocrystalline in the present study may be the results of the ferrite nanocrystallization via severe shear deformation [19].

FIGURE 1: OM micrographs of longitudinal cross section of (a) T10 steel pin under 40 N, (b) T10 steel pin under 50 N, (c) T10 steel pin under 60 N [9], (d) 20CrMnTi steel disc under 40 N, (e) 20CrMnTi steel disc under 50 N, and (f) 20CrMnTi steel disc under 60 N [9].

FIGURE 2: SEM images of worn surface layer of (a) T10 steel pin [9] and (b) 20CrMnTi steel disc.

At present, two possible mechanisms for explaining the ultrafine structure formation exist induced by sliding friction.

(i) The effect of severe shear deformation in the worn surface induced ultrafine structure formation. Rigney et al. [20–22] insisted that the ultrafine structure could be formed when the strain is high enough during the rubbing process. Obviously, the plastic shear flowing of material containing high fractions of low-angle subgrain boundaries with high

densities of misfit dislocation entanglement located at these subgrain boundaries in the worn surface layer induces the formation of nanostructure. Ni et al. [23] revealed that grain refinement occurred by dislocation rearrangements, which was likely to happen via grain rotation and the formation of coarser grains under high strains during the deformation process. Sadykov et al. [24] confirmed that the ferrite grains could be ultrarefined up to nanometer scale by dry sliding

FIGURE 3: TEM DF images with diffraction patterns of worn surface layer of T10 steel pins under (a) 40 N, (b) 50 N, and (c) 60 N [9] and (d) HRTEM image of T10 steel pin under 60 N.

friction at high load. Kato et al. [25] suggested that the shear deformation significantly increased the equivalent strain and promoted grain refinement.

(ii) The recrystallization was due to considerable friction heat. Wei et al. [26] considered that a large amount of friction heat agglomerated during dry rubbing process, which has a great influence on the microstructural evolution of near surface layer. Wang et al. [27, 28] verified that the flash temperature on the contact surfaces could reach 1000°C or even higher via the method of finite element analysis. In addition, the friction pair was undergoing temperature cycles, generating considerable heat stress during dry sliding process for the present experimental contact condition, which also accelerated plastic deformation of subsurface layer [28]. Owing to the higher temperature, the surface layer of pin would be softened and worn, leading to the formation of fresh surface and direct contact [29].

Therefore, it is certain that the observed ultrafine and even nanocrystalline ferrite on the T10 pin worn surface

appeared to be the result of joint action of two mechanisms stated above. The ultrafine structure in the worn surface layer formed via the simultaneous and recursive actions of (i) severe shear deformation and (ii) friction heat on the contact surface.

4. Conclusions

Based on the experimental results discussed above, there are three conclusions obtained as follows.

- (1) The T10 steel pin and 20CrMnTi steel disc specimens were both formed by the SFIDLs microstructures, and the clear plastic flow lines propagating from the worn surface to the matrix were observed.
- (2) When the normal load reached 60 N, the ultrafine and even nanocrystalline ferrite was formed in the worn surface of T10 steel pin, whose structure size was in the range of 10 nm to 100 nm.

- (3) The formation mechanism of nanoferrite structure was considered to be the results of severe plastic deformation and friction heat induced by dry sliding friction.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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