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Improved wear resistance by phase transformation of surface nanocrystalline 1090 steel prepared by sandblasting technique

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ABSTRACT

A surface nanocrystalline 1090 steel has been fabricated by using sandblasting technique. The surface average grain size was about 78 nm. The high strain rate and strain in sandblasting were main reasons for surface nanocrystallization. The wear resistance of 1090 steel was considerably enhanced as grain size decreased. The microstructure and hardness of contact zones before and after wear tests have been examined by XRD, SEM and TEM. Except the higher hardness, the results demonstrated that parts of ferrite transferred to cementite and martensite. It was additional beneficial for improving the wear resistance of 1090 steel as the grain size decreased.

1. Introduction

Nanocrystalline metals and alloys have attracted much attention, because of the small grain size and high grain boundary volume fraction compared with coarse grained counterparts [1]. Lots of methods have been developed for production nanocrystalline metals and alloys, including consolidation of nano-scale powders to bulk sample, electrodeposition, devitrification of amorphous materials, and sever plastic deformation [2–5], but most of them are limited to small-scale synthesis, which restricts the engineering and industrial applications. Surface modification treatment is an important method to obtain large-scale nanocrystalline metals and alloys. Among of these techniques, sandblasting is an effective way to generate nanocrystalline surfaces [6]. The high density dislocations near the surface resulting from sandblasting would be rearranged by suitable annealing, and formed nanocrystalline structure. Such a nanocrystalline surface would have no abrupt change in structure and composition between the surface and substrate.

Grain size nanocrystallization can usually improve the wear resistance of materials due to higher hardness and tribo-chemical activity [7,8]. Besides grain size factor, phase transformation in wear is used to improve wear resistance of steel. Since martensite has high work hardening rate and statistic elongation to be maintained at the high stress, the wear resistance of steel would be improved when parts of austenite phase transferred to martensite phase [9]. Lee et al. [10] indicated that the high wear resistance of FeCrCSi alloy was mainly attributed to the strain-induced martensitic phase transformation in wear. The martensite phase transformation was also observed in the white layers, which formed in the secondary deformation zones during the high speed cutting of high strength steel [11]. Zandrahimi et al. [12] reported that the martensite content transferred from austenite in wear depended on the applied load. These results demonstrated that the martensite phase transformation of steel usually happened in wear, which was designed to improve the wear resistance. Although considerable interesting in friction and wear behavior of nanocrystalline metals and alloys, few researches focus on the phase transformation of nanocrystalline materials in wear.

In the present work, surface nanocrystalline 1090 steel was prepared by using sandblasting at room temperature combined with post-annealing. The microstructure and hardness of surface nanocrystalline 1090 steel before and after wear tests has been investigated. Especially, the martensite phase transformation behavior of the surface nanocrystalline 1090 steel in wear has been examined.

2. Experimental

The 1090 steel with Vickers' hardness of 3.3 GPa is applied in the present work, the chemical compositions (wt.%) are as

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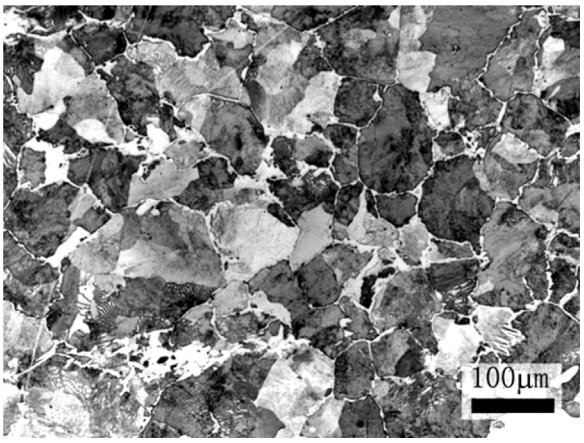

Fig. 1. Optical microscope image of received sample.

follows: C, 0.72; Si, 0.25; Mn, 0.75; Cu, 0.29; S, 0.008; N, 0.007; Cr, 0.44; Ni, 0.12; Nb, 0.022. The received samples were composed of pearlite and ferrite (Fig. 1). The steel ingot was cut into small pieces with the dimensions of $20 \times 20 \times 5$ mm^3. The samples surfaces were polished with 600# grit paper. In the sandblasting process, the sample was bombarded by the hard and high-energy sand particles with speed in the range of 50–200 m/s driven by the airflow. The following parameters during the sandblasting process were selected: the pressure of airflow was about 0.3 MPa, the temperature was 23 °C, the sand particles were diameter of 220 μm and the processing duration was 30 min. After sandblasting, the samples were annealed in Ar atmosphere at 500 °C with 30 min. These samples were designated as blasted sample.

The wear behavior of the samples was evaluated by sliding wear test using a ball on disc tribo-meter (CSM Instruments, Neuchatel, Switzerland) at room temperature of 23 °C and humidity of 30%. The samples surfaces were polished with 600# grit paper, and then cleaned in an acetone ultrasonic bath and dried in hot air. The Vickers' hardness of silicon nitride ball with diameter of 6 mm is about 19 GPa, and surface roughness R_a is about 0.01 μm. The wear tests were performed at a sliding speed of 5 mm/s with normal loads of 2–15 N. The running distance is 54 m. The profile of the worn surface cross section was measured by a Micro-XAM-3D surface profiler to determine the wear volume V. The wear rate was determined as $W = V/P{\cdot}s$, where P and s are applied load and total sliding distance, respectively. At least three tests were repeated for each set of testing parameters and the average values were calculated from the test data. The relative error for the friction and wear tests was less than ±10%.

The samples surfaces before and after wear tests were investigated with X-ray diffractometer (XRD, Philips X'pert) using Cu$K\alpha$ radiation, in a reflection mode at a scan rate of 1°/min. The worn surfaces of samples were cleaned in an acetone ultrasonic bath to remove the isolated wear debris before XRD test. Several samples surfaces before and after wear tests were electrochemically thinned in an electrolyte of nine parts of methanol and one part of perchloric acid with twin-jet electropolisher at room temperature and were examined with a JEOL-2010 transmission electron microscope (TEM). Morphologies of the worn traces were also observed using a Vega-3 scanning electron microscope (SEM).

The cross-sections of the samples before and after wear tests were examined by micro-indenter (Winsor, CT, USA) with maximum load of 50 mN. Each determined value was obtained by averaging 10 measurements.

3. Results and discussion

The fine grains around many dislocations in the sample surface can be observed by TEM after sandblasted at room temperature combined with annealing at 500 °C (Fig. 2). The average grain size is about 78 nm according to the statistic of the TEM images (inset of Fig. 2b). The corresponding SAED indicates that the nanocrystallization surface is composed of ferrite and cementite (inset of Fig. 2a).

The average friction coefficients of the samples after the initial running time have been presented as Fig. 3a. Both friction coefficients of the received and blasted samples increase at the low applied load, and then keep steady about 0.8 at high applied load. The friction coefficient of 1090 steel changes slightly with the grain size, while the wear resistance of 1090 steel significantly improves as the grain size decreases (Fig. 3b). The wear rate of 1090 steel reduces to about one third as the grain size decreases to nano-scale in the experimental range. Fig. 3b also shows that both wear rates of samples increase as the applied load increases.

The severe adhesion and oxidation have been broadly observed on the worn surface of the received sample at applied load of 15 N (Fig. 4a). As the grain size decreases to 78 nm, in addition the medium oxidation and plastic deformation, there are few adhesion and cracks on the worn surface of the blasted sample (Fig. 4b).

Fig. 5 shows the sub-surface morphologies after wear of received and blasted samples. Lots of researches showed that the sub-surface of metals and alloys would form gradient structure with nanocrystalline, ultrafine grain, deformation layer and matrix under the repeated contact stress onto the worn surfaces in dry wear [13,14]. In the present of work, this deformation gradient can't be observebly detected for both samples. The deformation depths of samples are about 20 μm and 30 μm, respectively (Fig. 5). It may result from the higher hardness of both samples. Typical cracks are indicated in Fig. 5a, which initiate sub-surface, but not worn surface. Iida et al. [15] calculated that the maximum shear strain-energy was located worn sub-surface with certain depth, which was considered to be the location of the crack initiation point. In addition, dislocations moved towards surface in wear [16]. By considering dislocation pileup and energy accumulation, the crack is initiated in the sub-surface (marked as black arrows in Fig. 5a and b). The spall forms when the crack extends continuous. The spall is easy to oxidation and form oxide film on the worn surface of received sample. Although the crack is observed on the worn surface of blasted sample, it is not found on the sub-surface. May the crack initiation is near to the worn surface, it can't be distinguished in here; or the phase transformation in wear (discussion below) can release the strain energy accumulation and dislocation pileup, so the crack tolerability increases.

The sandblasting process provides repeated shock load with high speed on the material surface. In the top surface layer, a very high deformation strain rate would be induced by the sandblasting. An estimated value of strain rate is about 10^3–10^4 s^{-1} in the top surface of the sample, and steeply decreases with an increase of depth from the surface [17]. The high strain rate brings in the high density dislocations, which transfers to nanostructure after proper annealing. Some cementite dissolve into the ferrite as the steel suffers from the severe plastic deformation (Fig. 6a), which also was observed other experimental [18]. Parts of cementite, which are indicated as white arrows in the incomplete nanocrystallization zone of sandblasted sample, become discontinuous (Fig. 6b). Since the local temperature of sample during large deformation even reaches above 1000 °C [19], the diffusion coefficient of carbon in ferrite improves from 4.7×10^{-23} cm^2/s at room temperature to 1.1×10^{-9} cm^2/s at 1000 °C [20]. So, parts of cementite dissolve into the ferrite after sandblasting and annealing. The un-solute cementite forms the nano-scale grains (Fig. 6, marked as red circle). The