Original Article

Effect of applied magnetic field on wear behaviour of martensitic steel

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1. Introduction

Many tribological systems can be found in the electromagnetic environment [1,2], such as electric motors and clutches. It should be evaluate the magnetic field influence on the wear behaviour of their constitutive components to improve the wear resistance. So the magnet–tribological interaction has been investigated last decade [3–5]. For example, the tool steel life increased when an external electric current was imposed on drilling processes [5]. The wear rate of XC48 steel dramatically decreased from $50 \times 10^{-5}$ g/m to $4 \times 10^{-5}$ g/m under an alternating current magnetic field [6]. The improved wear resistance of high speed steel [7], mild steel [8] and 45# steel [9] also has been reported under the applied magnetic field.

These results showed that the wear rate of ferromagnetic material usually decreased under applied magnetic field. Applied magnetic field promoted surface oxidation or dislocation mobility towards surface in wear which was considered by two main factors [10–14]. Most studies presented that the mechanical behaviours, such as stress relaxation [15], work hardening [16], plastic behaviour [17,18], fatigue [19], and hardness [20] changed under magnetic field by relating dislocation motion. Iida et al. [12] supposed that domain walls near the wear zones were captured by high density dislocations when the counterpart was magnetized and dragged the dislocations towards the worn surface. Zaidi et al. [13] calculated the dislocation motion velocity of ferromagnetic materials under applied magnetic field with intensity of 20 kA/m. It was about 4 times larger than the absence of magnetic field. According to analysis chemical states and morphologies of worn surfaces with and without applied magnetic field, surface oxidation promotion has been realized as another important factor in wear under applied magnetic field. Chin [6] and Csapo et al. [14] observed oxide layers on the worn surface under applied
magnetic field that became thicker and more fragile. With applied magnetic field, both wear rates of nickel and iron changed slightly in nitrogen or argon atmospheres, but obviously reduced in air [10]. Thus, the reduction of wear loss was thought to root in the improved chemisorption of oxygen on the activated surface. Summary, the improved oxidation was an important element to decrease wear rate of the material under applied magnetic field.

The explicit discussions demonstrated that two main mechanisms above based on oxidation and dislocations motion, respectively, were proposed to explain the wear behaviour under applied magnetic field. However, it is difficult to exclude the dislocation effect when we just consider the oxidation factor under applied magnetic field because of high dislocation density and mobility of coarse grained materials. Usually, as the grains become finer and finer, more and more dislocations are absorbed by the grain boundaries leading ultimately to a drop in dislocation density, so the dislocation density of metals and alloy usually decreases after nanocrystallization. And the dislocation mobility is also restricted because of the large amounts of grain boundary [21]. This difference could provide a chance to investigate the synergistic effect of hardness and oxidation in wear under applied magnetic field. In the present work, the martensitic steel has been selected as tested material (designated as CG). The average grain size is about 60 μm. The Vickers’ hardness is about 5.03 GPa as compared, surface nanocrystalline sample (30 nm) was designated as NC [22]. The dislocation density of CG was calculated to be about \(10^{10} - 10^{12} \text{m}^{-2}\). The dislocation mobility of CG and NC was investigated by conditional wear tester under applied magnetic field.

2. Experimental

The chemical compositions of martensitic steel (wt.%) are as follows: Ni, 0.12; Si, 0.25; Cu, 0.29; Cr, 0.44; C, 0.72; Mn, 0.75; Fe, balance. The CG shows acicular martensite feature with high density dislocations (Fig. 1a). The corresponding selected area electron diffraction (SAED) shows martensite structure in CG (inset of Fig. 1a). The average grain size of NC before wear test is about 30 nm (inset of Fig. 1c). The corresponding SAED indicates that the nanocrystallization surface is composed of martensite structure (inset of Fig. 1b).

The wear behaviour of CG and NC was tested by a pin on disc wear tester (CSM instruments) at 23°C. The sliding speed and applied load are 5 mm/s and 15 N, respectively. The sliding time is 30 min. The samples were polished by 600# abrasive paper. The diameter of AISI52100 pin is 6 mm. Its Vickers’ hardness is about 6 GPa.

Magnetic intensity effects on the wear behaviour of the sliding zones in an ambient environment were investigated. A magnetic field generation apparatus was run on a wear tester shown in Fig. 2a [23]. The magnetic field was supplied by a AISI52100 steel pin. The outer is twisted by enamel-insulated wire with diameter of 0.6 mm. The current through the pin is ranging from 0 to 1.5 A. Magnetic intensity can be adjusted by the direct current. The intensity near the sliding zone as
function of current is shown as Fig. 2b. The magnetic intensity linear increases as the current enhances.

The worn traces were detected to evaluate the wear volume \( V \) by using a Zeiss optical microscope (Axio; CSM, 700). The wear rate origins from \( W = V/NL \) (\( N \) is applied load, \( L \) is total route). \( V \) is the wear volume loss in \( \text{mm}^3 \). \( V = S \times 2\pi r \), \( S \) is cross-sectional area of wear trace (\( \text{mm}^2 \)) and \( r \) is circular motion radius (\( \text{mm} \)). Every experimental parameters were tested at least three. The cross sections of hardness near the worn surface of the CG and NC were detected by averaging 10 measurements (Winsor; CT) with 50 \( \times \) m. Compositions and features of the worn surfaces of CG and NC were observed by a scanning electron microscope, respectively (SEM, VEGA 3) that carried energy dispersive spectroscopy (EDS; INCA Energy).

### 3. Results and discussion

Fig. 3a shows wear rates of NC and CG as function of applied magnetic intensity. Both the wear resistance of NC and CG enhance under applied magnetic field compared without magnetic field. The wear rate decreases as the applied magnetic intensity increases. Fig. 3b depicts decrement of wear rate \( (\beta_W) \) of NC and CG under applied magnetic field. The \( \beta_W \) is defined to be \( (W_0 - W)/W_0 \), where \( W_0 \) and \( W \) are wear rates of martensitic steels without and with magnetic field, respectively. The wear rate of both CG and NC decreases slightly after the magnetic intensity increases to above 2.23 kA/m. Obviously, the decrement of wear rate of CG is larger than NC (Fig. 3b). The wear rate of CG with applied magnetic field reduces by about 25–35%, while the wear rate of NC just reduces by about 5–15%. It suggests that the applied magnetic field can improve wear resistance of martensitic steel, especially for coarse grained material. The hardness of contact track increased due to the repeated sliding and applied magnetic field on NC and CG surfaces [12, 24]. The hardness of un-worn samples of NC and CG are 7.2 and 5.03 GPa, respectively. Since the worn surface goes through work hardening in wear [25, 26], the hardness of surfaces increases to 7.9 GPa and 5.6 GPa after wear tests without applied magnetic field, respectively (Fig. 4a). The sub-surface hardness evolution in wear with and without applied magnetic field (2.23 kA/m) also has been showed as Fig. 4a. Red solid circle and square presented the hardness of CG from worn surface down to about 10 \( \mu \text{m} \) is larger than in the absence of magnetic field. This increment just occurs near worn surface (about 3 \( \mu \text{m} \)) for NC. Both the worn surface hardness of NC and CG increases with the applied magnetic intensity (Fig. 4a). Like \( \beta_W \), the increment \( \beta_H \) of hardness is defined to be \( (H_0 - H)/H_0 \), where \( H_0 \) and \( H \) are worn surface hardness without and with magnetic field, respectively (Fig. 4b). Worn surface hardness of CG observably increases under the applied magnetic intensity of 2.23 kA/m, and then changes slightly with the increase of magnetic intensity. The increment of NC is further less than CG. It is according with the wear rate varieties

### Fig. 3 – Wear rates (a) and decrement of wear rates (b) of NC and CG as function of applied magnetic intensity, the error is less than 5%.

### Fig. 4 – (a) Hardness versus distance from surface to matrix, inset of a and b: hardness and its increment as function of applied magnetic intensity, respectively, the error is less than 5%.
of NC and CG without and with applied magnetic field (Fig. 4b). It should be noted that there are some retained austenite in the 1090 steel. The retained austenite would be transformed into martensite during friction and wear [27,28], that results in enhancing the hardness and improving the wear resistance of 1090 steel. In this case, the effect of applied magnetic on the phase transformation has been ignored. Namely, the phase transformation of retained austenite that enhances the hardness of worn surface is identical for all the wear conditions.

Fig. 5 presents the SEM images of NC and CG in wear with and without applied magnetic field. Worn surfaces of CG are basically covered by oxide films under both conditions (Fig. 5a and b). Excluding density oxide film, many dark oxide particles have been found for CG under applied magnetic field (Fig. 5b). The grain size of oxide particle is below 3 \( \mu \)m according to the statistic of the worn surface (Fig. 1b marked as oxide particle). Zaidi et al. [23] and Iida et al. [29] presented that the debris under the applied magnetic field was high strength and hardness. These hard debris could produce fine wear debris, which was easily oxidized. Whilst the fine oxidized wear particles would accelerate oxidation of other wear particles and contact zones. In this case, it is believed that due to worn surface hardness increase, the fine debris with high hardness form easy, thereafter produce fine oxide particle. Lots of grooves and cracks are depicted on worn surface under absence of magnetic field, which is showed as Fig. 5a. Close examination presents that some pores also occur on the worn surface of CG without magnetic field. Both groove and pore become mild and fine under applied magnetic field (Fig. 5b). Worn surfaces of NC are covered by lesser oxide films, and many fresh zones are found under both with and without applied magnetic field (Fig. 5c and d). For with and without magnetic field, these results presented the similar tribo-oxidation reactants can be observed for NC. Few micro-grooves on both worn surfaces of NC also demonstrate character of ploughing wear like as CG. The content of crack and pore on worn surface under applied magnetic field increases compared with absence of applied magnetic field.

Fig. 6 shows the sub-surface character of CG and NC without and with applied magnetic field. 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 on the worn surfaces in dry wear [30–32]. In the present work, the deformation depth is about several microns for all samples (Fig. 6). Some severe deformation zones occur below grooves for CG under absence of magnetic field (Fig. 6a). The deformation zones suffer repeated stress in wear. It results in mismatch and spun off in the matrix, then the pores on the worn surfaces form. The size of pore is estimated to be about 5–10 \( \mu \)m according to Fig. 6a. It is in accordance with the size that showed as Fig. 5a. Uniform deformation layer forms for CG with applied magnetic field, and the deformation depth is able to found as about 3–5 \( \mu \)m (Fig. 6b). Some cracks are marked as white.

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**Fig. 5** – SEM images of the worn surfaces of NC and CG with and without applied magnetic field: (a) CG, 0 kA/m; (b) CG, 2.23 kA/m; (c) NC, 0 kA/m; (d) NC, 2.23 kA/m.
Fig. 6 – SEM images of the cross-section of NC and CG under absence of and applied magnetic field: (a) CG, 0 kA/m; (b) CG, 2.23 kA/m; (c) NC, 0 kA/m; (d) NC, 2.23 kA/m.

arrows in Fig. 6c, which suggests that the deformation depth of steel decreases when the grain size reduces to 30 nm. Like deformation of CG under magnetic field, the local deformation zone is not found in the sub-surface of NC (Fig. 6d).

Why the wear resistance increment of CG under applied magnetic field is larger than NC (Fig. 3b)? An observably character that the increment of worn surface hardness under magnetic field for CG is larger than NC (Fig. 4b). So it is believed that the worn surface hardness varied with applied magnetic field may play key role to reduce the wear rate. The dislocation density of CG is about $10^{14}$–$10^{18}$ m$^{-2}$ according to the statistic of TEM observations, while the density of NC is only about $10^{10}$–$10^{12}$ m$^{-2}$ (Fig. 1). This character is sketched as Fig. 7a and d. Many experiments indicated that the dislocation motion can be effectively inhibited by grain boundary in NC, but not in CG [33]. The dislocation moves toward the surface in the wear test because of repeated friction stress [34]. According to Hertz contact theory, the maximum contact stress $p$ of CG and NC is 1140 MPa and 1230 MPa, respectively, at load of 15 N in wear, respectively [35]. In response to the high repeated external stress, dislocations move through crystals towards the surfaces (Fig. 7b and e). So hardness of sub-surfaces of both NC and CG increases in wear (Fig. 4).

Owing to the local dislocation accumulation for both CG and NC, it should result in heterogeneous deformation layer (Fig. 7b and e) in wear without applied magnetic field, which is consistent with observation of sub-surfaces of CG and NC (Fig. 6a and c). The dislocations mobility will be synergetic affected by the applied magnetic field [11,15,36,37]. When the worn surface goes through repeated stress under applied magnetic field, the effective scattering cross section of the electron is quite large since the electron’s trajectory becomes helical [38,39]. The applied magnetic field makes the singlet transfer to triplet, which may result in a lower binding energy. So the dislocations break away from obstacles easier. As a result, the applied magnetic field prompts the dislocation motion towards worn surface uniformly (Fig. 7c and e). It is also consistent with observation of sub-surfaces of CG and NC with applied magnetic field (Fig. 6b and d). Since dislocations move towards the worn surface, hardness of worn surface of NC and CG increases with applied magnetic field. Whilst higher dislocation density and lower grain boundary volume fraction of CG are helpful to prompting dislocation motion, the hardness increment of CG is larger than NC under applied magnetic field (Fig. 4b).

It should be noted that the worn surface shows different roughness after repeated friction stress. The crack occurs in the between dislocation accumulation zones and other zones. The heterogeneous sub-surfaces are easier to form large wear debris. So the roughness of worn surfaces of both NC and CG under applied magnetic field is smaller than without magnetic field. This view is also indirectly by other investigations. For example, lida et al. [40] indicated that smoother worn surfaces with finer wear particles are produced under the applied
magnetic field. Since applied magnetic field induce finer wear particles, Stolarski et al. [41] also observed that wear surface roughness of carbon steel decreased.

4. Conclusions

The wear behaviour of martensitic steel has been investigated with applied magnetic field. Both wear rates of NC and CG decreased as the applied magnetic intensity increased. While the decrement of wear rate of CG was larger than NC. Although both the worn surfaces hardness of NC and CG increased as the applied magnetic intensity increased, it was more effectively for CG than NC. The oxidation condition varied with applied magnetic field depends on the dislocation density. Namely, the higher dislocation density is the key factor for improving the wear resistance of the 1090 steel. The applied magnetic field could decrease the binding energy of dislocation, and make more dislocations move towards the surface during friction and wear. So higher dislocation density and lower grain boundary volume fraction of CG are helpful to prompting dislocation mobility under applied magnetic field, it resulted in more increment of worn surface hardness and wear resistance of CG than NC.

Conflicts of interest

The authors declare no conflicts of interest.

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Fig. 7 – Sketch of dislocation move towards the surface of martensitic steel in wear with and without magnetic field. Yellow, grain boundary; green, dislocation; blue, deformation and dislocation accumulation zones. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)


