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Effect of multi-directional forging and annealing on abrasive wear behavior in a medium carbon low alloy steel

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ABSTRACT

A medium carbon low alloy steel was processed by multi-directional forging (MF) and annealing. Microstructural evolution is studied by optical and electron microscopy and abrasive wear resistance is researched. After MF, the microstructure was refined. The tensile strength and hardness increased obviously, while the ductility decreased sharply. MF resulted in the improvement of abrasive wear resistance. Without compromising the tensile strength and hardness much, the ductility was improved significantly after subsequent controlled annealing. Higher ductility led to abrasive wear resistance for further improvement. Higher hardness, ductility and work hardening degree were found to be responsible for higher abrasive wear resistance of ultrafine-grained (UFG) medium carbon low alloy steel.

1. Introduction

UFG materials processed by severe plastic deformation (SPD) exhibit higher hardness and strength compared to their coarse-grained (CG) types [1,2]. Wear resistance is one of most key mechanical property for UFG materials in order to evaluate their potential for use as engineering components. In recent years, the wear resistance of UFG materials has attracted the growing interest of specialists in materials science. Some investigations indicated that UFG materials have superior wear resistance to their CG counterparts [2–4]. However, other studies suggested that the wear resistance of UFG materials is inferior to that of CG types [5,6]. Those studies are quite interesting and valuable. In addition, for the wear of UFG Hadfield steel by hard abrasives the previous work by the present authors [7,8], the hardness increasing and grain refinement by shot peening could not improve wear resistance.

The wear properties of metals and alloys have significant effects on the serviceability and durability of machine components. Moreover, wear of material causes huge economic loss, especially the abrasive wear [9]. For this reason, it is significant to study the effect of mechanical properties and microstructure of UFG materials on abrasive wear. In the abrasive wear, the ductility of materials is an important parameter in controlling the wear rate [10]. It is well known that the SPD materials generally exhibit disappointingly low ductility [6,11,12]. Producing UFG metals and alloys with very high strength and hardness is increasingly feasible but strength alone is insufficient for engineering applications if the material does not provide sufficient ductility and wear resistance. However, MF has been recently used to process Mg alloys and provided ultrafine grain size and high strength without compromising ductility [13,14]. A combination SPD and thermal treatment may be for processing UFG materials with high strength and high ductility [15–18]. Therefore, the ductility of SPD steels could be improved by subsequent controlled annealing without compromising the hardness much then it is likely that improved abrasive wear behavior will be obtained.

Medium carbon low alloy steels is an important wear-resistant material that they are widely used because of ease to manufacture and low cost. For instance, grinding balls and drill tools are made of medium carbon low alloy steels. In this work, a medium carbon low alloy steel was subjected to MF and annealing treatment. Evolution of the microstructure was analyzed, mechanical and abrasive wear properties were studied in comparison with coarse-grained sample. On this basis, the effect of the microstructure, hardness, ductility, and work hardening on abrasive wear behavior in ultrafine-grained materials will be discussed in detail. This will provide fundamental insight into the mechanisms that govern the abrasive wear resistance of UFG materials.

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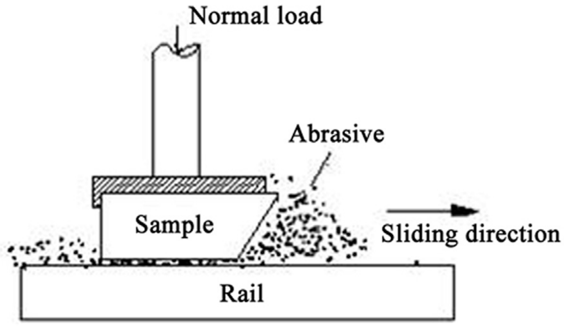

Fig. 1. Schematic of wear geometry for abrasive wear.

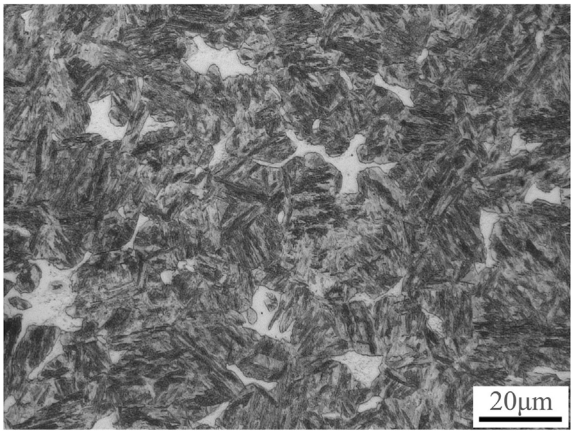

Fig. 2. Cross-sectional optical microstructure of subcritical quenching sample.

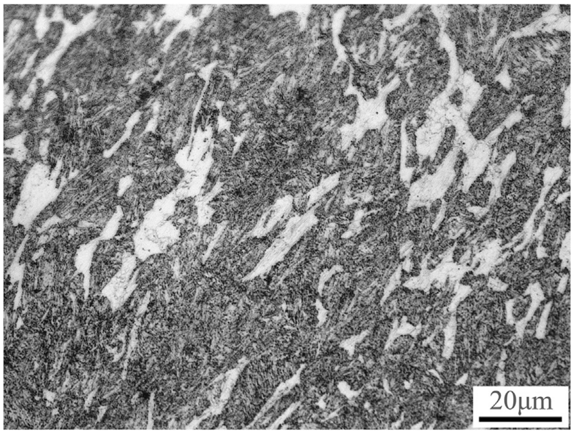

Fig. 3. Cross-sectional optical microstructure of MF sample.

2. Materials and methods

Test alloy was a commercial medium carbon low alloy steel rod with a diameter of 30 mm. The composition of test alloy is 0.36 C, 0.19 Si, 0.85 Cr, 0.56 Mn (all in weight percentage). Samples 55 mm in length were machined from the rod and subcritical quenching treated. Samples were heated at 760 °C for 150 min, and quenched into water. Before the first, second and third stage of forging, the samples were heated at 600 °C for 30 min, 10 min and 10 min, respectively. The samples were alternately forged with loading direction changed through 90° (i.e. x-y-z-x). The samples were 3 cyclic forged, every stage of forging produced 25% reductions by 3 stages at a strain rate of 5 s^{-1} by an air rammer. Finally, the samples were forged into the piece with a dimension of 26 mm × 26 mm × 57 mm. Then the forged samples were annealed at 450 °C for 150 min.

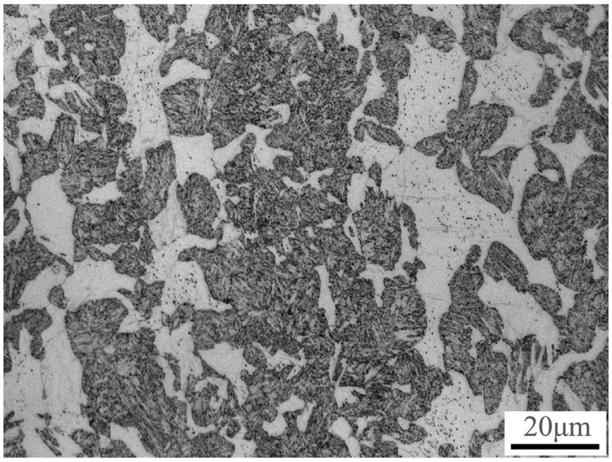

Fig. 4. Cross-sectional optical microstructure of MF and annealing sample.

The hardness was measured in the cross-sectional samples by using a HVT-100 microhardness tester with a load of 9.8 N and a loading time of 10 s. For tensile testing, all of the samples were cut into dog-bone tensile specimen with a gauge length of 15 mm, and a cross section of 2 mm × 1 mm. Tensile tests were conducted at room temperature using an Instron 8801 Materials testing machine with a constant rate of 2 mm/min. Minimum of three well reproducible tests were performed on each type of samples.

The abrasion test geometry was shown in Fig. 1. Quartz sand with nominal grain size about 250–380 μm in diameters, Vickers hardness 900–1200 HV and angular geometrical shapes were used in the three-body wear tests. The area of wearing surface was 10 mm × 15 mm with a normal load 29.4 N. The normal pressure was, therefore, 0.2 N/mm^2 and the line speed of sample was about 0.5 m/s. The reciprocal value of the weight loss after 25 min wear period was taken as the data of wear resistance.

The microstructural analyses were performed by Carl Zeiss Axio imager A2M optical microscope and Tecnai G2-F20 S-Twin transmission electron microscope (TEM, operating at a voltage of 200 kV). The worn surface morphologies were observed using a S-3400 scanning electron microscope (SEM).

Coarse-grained sample was processed by normalizing, hardening and tempering, i.e., sample was heated at 850 °C for 60 min and quenched in water, then heated at 600 °C for 120 min.

3. Results and discussions

3.1. Microstructural evolution

Fig. 2 presents the OM micrograph of the sample processed by heating to 760 °C for 150 min followed by rapid quenching into water, showing ferrite-martensite dual-phase structure. Clearly, this picture shows ferrite-martensite dual-phase structure with most martensite. Fig. 3 shows the OM micrographs of the MF sample. MF causes severely deformed microstructure as presented in Fig. 3. Obviously, predominant fine ferritic grains and a few of coarse ferritic grains exist in MF sample. During MF reheating, more carbide particles are precipitated in original martensite regions because of the carbon content of martensite is more than that of ferritic. The relatively more number of carbide particles in original martensite regions which stabilize a microstructure with a very fine grain size [19], a relatively fine grain structure formed in these regions compared to the original martensite regions. Therefore, fine ferritic grains and coarse ferritic grains coexist in the MF sample. The OM micrograph of the MF and annealing sample is shown in Fig. 4. After