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Study of microstructure, mechanical properties and impact-abrasive wear behavior of medium-carbon steel treated by quenching and partitioning (Q&P) process

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ABSTRACT

In the present work, a high performance martensite-austenite steel was produced by utilizing optimized quenching and partitioning (Q&P) process, and its impact-abrasive wear behavior was investigated in comparison with commercial Hadfield steel (Mn13Cr2) under 2 J and 4 J impact energies. Tensile tests, scanning electron microscope (SEM), transmission electron microscope (TEM) and X-ray diffraction (XRD) were applied to characterize mechanical properties, microstructure evolution, and wear mechanisms of the two steels. Experimental results revealed that the Q&P steel with martensite matrix and retained austenite (RA) had higher strength properties and better impact-abrasive wear resistance than Mn13Cr2. During impact-abrasive wear tests, wear mass loss was less under higher impact energy for both steels, and the Q&P steel owned less wear mass loss than Mn13Cr2. The main strengthening mechanisms were newly formed martensite twins (RA to martensite transformation) and high density dislocations for the Q&P steel, and the interactions of twinning and dislocation structures were for Mn13Cr2, respectively.

1. Introduction

Impact-abrasive wear is a common material failure type that widely happens in transportation, mining, metallurgy and mineral processing industries, which leads to security and reliability problems of engineering components and also significant economic and environmental losses due to shortened working life of equipments [1,2]. Therefore, wear resistant materials are desiderated in many important engineering fields. The famous Hadfield steel has been extensively used for over 120 years because of its excellent wear resistance. This material owns high toughness, good impact energy absorption ability, and mainly excellent work hardening capacity [3,4]. As the austenite based Hadfield steel has low stacking-fault energy and multiple dislocation slip systems, micro and nano twins can easily form to improve work hardening capacity [5], resulting in reinforced abrasive wear resistance of the steel. However, the Hadfield steel has relatively low strength and hardness properties [6], and it usually suffers high weight loss and shows short service life under impact-abrasive wear such as rock-crushers, stronger materials with better impact-abrasive wear resistance are expected to be produced.

In general, improvements of matrix strength and surface hardness contribute to enhanced abrasive wear resistance of steels, which means that the martensitic or bainitic steel grades are progressive candidates, because of their high hardness and strength properties [2,7]. Besides, multiphase steel with retained austenite (RA) usually shows excellent mechanical properties, good combination of strength and toughness can be achieved in martensitic or bainitic steel grades with the RA components [8,9]. For example, the low temperature bainitic steel owns very high hardness (600–670 HV) and excellent crack propagation retarding capacity, because it has very thin bainite plates and very fine scale dispersion of RA films between the plates [10]. It makes the low temperature bainitic steels have good prospect in wear resistant applications like gears [11]. As for martensitic steels, quenching and partitioning (Q&P) steel has the potential to provide the required high hardness and strength [12]. With appropriate fraction of fine scale austenite distributed between the martensitic laths in Q&P steel, improved plasticity is easily achieved through the transformation induced plasticity (TRIP) phenomenon [13], and it is favorable to increase stain hardening capacity and toughness of the steel as well [14]. It is further researched that introducing RA in the hard bainitic or martensitic matrix is beneficial to overcome its brittleness, which is an important factor determining service life of equipment under high speed and large impact load [15].

In 2003, quenching and partitioning process proposed by J. Speer

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et al. [16] is now widely applied to produce martensitic steel with a combination of high strength, high toughness and good plasticity. The Q&P treated steels with martensite matrix have high strength properties. They can be further strengthened by the phase transformation of RA, which make these steels suitable candidate for engineering equipment under impact-abrasive wear conditions [14]. Controlling of RA volume fraction, chemical components and morphologies are very important for improving integrated performance of these steels [17–19]. In this paper, a newly designed Q&P steel with 0.5 wt% C and other suitable elements, such as Si, Mn, Cr, Mo and co-addition of Ti and Nb was investigated. Systematic Q&P conditions, including quenching stop temperature and partitioning time, were firstly optimized carefully to obtain the best combination of microstructures (martensite + RA) and mechanical properties. After that, impact-abrasive wear tests were performed on both experimental Q&P steel and the contrastive Mn13Cr2, a series of characterization methods were utilized to investigate mechanical properties, microstructures evolution, and wear mechanisms of the two steels.

2. Materials preparation and experimental procedure

2.1. Materials production

The materials for Q&P process in present study were produced by a vacuum induction melting furnace. Chemical compositions of the experimental alloy are listed in Table 1. Carbon and manganese were necessary austenite stabilizers [20], while silicon was added to restrain cementite formation [21]. Chromium improved wear resistance and hardenability in low alloy steels, as well as molybdenum did. Furthermore, micro-alloying elements titanium and niobium were utilized to restrain grain coarsening under high temperature conditions and to produce precipitation strengthening [22,23]. A dilatometry experiment was conducted on a DIL-805A dilatometer, specimen with diameter of 4 mm and 10 mm long was heated to 900 °C at 5 °C/s and austenitized at this temperature for 3 min, followed by fast nitrogen cooling at − 50 °C/s to room temperature. Dilatometry curve as shown in Fig. 1a indicated that the phase transformation temperatures A_{c1} (ferrite-cementite to ferrite-austenite point), A_{c3} (ferrite-austenite to austenite point) and *Ms* (martensite transformation starting temperature) were 750 °C, 820 °C and 215 °C, respectively.

The as-cast ingots (230 mm × 120 mm × 120 mm) were cut into bars (40 mm × 30 mm × 60 mm) for the subsequent Q&P heat treatments. The Q&P conditions are shown in Fig. 1b, 12 groups of experiments were designed with different quenching temperatures (*Tq*) and partitioning time. Specimens were firstly austenitized at 900 °C for 30 min, followed by salt bath quenching at 80, 100, 120 and 140 °C, respectively. After that, they were partitioned at 400 °C for 15, 25 and 40 min before air cooling down to room temperature (RT). The quenching rate was > 20 °C/s and the air cooling rate was about 1 °C/s in laboratory conditions. The austenization temperature (900 °C) was determined slightly over A_{c3} to guarantee elements homogenization. The high partitioning temperature (400 °C) was determined over *Ms* to guarantee efficient and sufficient carbon partitioning from supersaturated martensite into adjacent austenite grains, ensuring high carbon content in RA and reinforced mechanical stability of RA [23].

2.2. Microstructure and mechanical properties of Q&P steel

Dog-bone like specimens were prepared with a gauge length of 25 mm and diameter of 5 mm for room temperature tensile experiments, which were performed on a CMT4105 electro-mechanical universal testing machine. Charpy impact tests were conducted on Zwick RKP-450 impact device at ambient temperature (20 °C), with sample size of 10 mm × 10 mm × 55 mm and a V-notch of 2 mm in depth. Two samples for tensile tests and three samples for Charpy-V tests were prepared for each group of the 12 different Q&P conditions. Hardness tests were performed on a Vickers tester and measured with a load of 500 gf and the holding time is 15 s. Five hardness values were measured for each testing point from the specimen surface, and three of them were averaged after excluding the maximum and minimum values.

Table 1
Chemical composition of tested steel (wt%).

Elements	C	Si	Mn	Cr	Mo	Ti	Nb	Fe
Composition	0.50	1.03	2.01	1.58	0.34	0.11	0.034	Balance

Metallographic characterization was carried out by means of scanning electron microscope (SEM) and transmission electron microscope (TEM). Moreover, X-ray diffraction (XRD) was utilized to measure RA volume fraction and carbon content.

Specimens for SEM observation were firstly machined and mechanically polished, followed by 5% nital etchant, and the microstructure was characterized by Zeiss Auriga field emission scanning electron microscope (FE-SEM). Specimens of 0.6 mm in thickness for TEM observation were firstly mechanically polished to 40 µm and punched into Φ3 mm discs, then they were twin-jet electro-polished in 5 vol% perchlorate alcohol solution at 50 V/− 30 °C for about 2 min. For the sample preparation of wear track special care has been taken by reducing the thickness from opposite side of wear track. TEM experiments were performed with JEM-2100 (HR) operated at 200 kV.

Specimens of 2 mm in thickness for XRD were firstly mechanically polished, followed by electro-polishing with 5 vol% perchlorate alcohol solution at 36 V for 10 s. The samples were leveled from opposite side of the wear track to preserve the wear track. Two samples for XRD tests were prepared for each group of the 12 different Q&P conditions. XRD measurements were conducted over a 2θ degrees ranging from 47° to 93° with a step size of 0.02° and a scanning speed of 1°/min in Rigaku D_{MAX}-RB X-rays diffractometer, operated at 40 V and 150 mA with a graphite monochromator and filtered Cu radiation (λ = 0.15406 nm).

2.3. Impact-abrasive wear tests

Impact-abrasive wear tests for the Q&P steel and Mn13Cr2 were performed on an impact-abrasive machine (MLD-10) at room temperature as shown in Fig. 2. The upper specimens (Q&P steel and Mn13Cr2) used for the wear tests were cut into 10 × 10 × 30 mm^3 with cambered surface (curvature of 50 mm) on the end face of the specimen. Lower specimen (45 steel with tensile strength of 600 MPa, yield strength of 365 MPa, Charpy impact energy of 37 J and surface hardness of 620 HV) was ring type cylindrical with external diameter of 50 mm. The abrasive materials were quartz sand and shale, the standard particles were screened with 30–50 mesh, and the flow quantity was 2 kg/min. The impact direction was perpendicular to horizontal of specimen and pointing to worn surface. The upper specimen performed reciprocating motion 200 times/min and the lower specimen rotated 200 r/min. Impact-abrasive wear tests were conducted under 2 J and 4 J impact energy conditions, and repeated three times for both Q&P steel and Mn13Cr2. The accumulated wear mass loss of upper specimen was measured per 6000–18000 rotations (30–90 min) by a precision electronic balance. Metallographic examinations were then conducted on both tested materials.

3. Results and discussion

3.1. Effect of Q&P conditions on microstructure and mechanical properties

3.1.1. Quantitative analysis of microstructure constituents

Martensite and retained austenite are designed to be the major microstructures of the experimental Q&P steel. During the Q&P process, final microstructure constituents are determined by the quenching temperature *Tq* and subsequent partitioning process, which are