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Effects of using (Ti,Mo)C particles to reduce the three-body abrasive wear of a low alloy steel

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ABSTRACT

The use of high-grade, low alloy abrasion resistant steels has been limited due to the effects of their high hardness on their formability, machinability, and weldability. In order to increase the wear resistance of the steel without increasing hardness, a new low alloy wear resistant steel reinforced with (Ti,Mo)C particles was developed. The three-body abrasive wear behaviour of the experimental steel has been studied using a standard dry sand rubber wheel wear testing procedure under applied loads of 45 N and 130 N. Experimental observations revealed that nano- and microparticles are uniformly distributed in the martensitic matrix. The analysis of worn surfaces including longitudinal sections of the surfaces showed that the particles can effectively resist micro-cutting, due to which, the main wear mechanism of the experimental steel was through formation of pits and other indications of surface fatigues. Typically, the abrasion resistance of the experimental steel reinforced with particles was, respectively, 1.6 and 1.8 times that of a traditional low alloy wear resistant steel under applied loads of 130 N and 45 N.

1. Introduction

Wear is one of the most common failures observed in many industrial applications and the development of abrasion resistant materials is therefore advantageous both from technical and economic points of view [1]. Low alloy abrasion wear resistant steel (such as: NM 500, HARDOX 500, XAR 500, and JFE-EH 500) is widely used in the manufacture of engineering, mining and metallurgical machinery [2,3]. Generally, the abrasion resistance of steel is strongly dependent and directly proportional to the hardness. Unfortunately, the formability, weldability and processability deteriorate with increasing carbon content and hardness. Hence, to improve the wear performance without increasing the hardness and sacrificing formability, it is of great interest to improve the weldability and processability of low alloy abrasion resistant steel. Previous studies have demonstrated that metal matrix composites containing hard particles of carbides (TiC, Cr_3C_2, WC, VC, NbC, etc.), nitrides (TiN, S_3N_4), borides (TiB_2, CrB_2), and/or oxides (Al_2O3, ZrO_2, Y_2O_3) showed high abrasion resistance because of the presence of the hard particles which can resist wear and thereby protect the metal matrix [4–7]. In this case, the reinforcement was obtained through in-situ processing techniques or by using powder metallurgy processing techniques, etc [8,9]. However, these production processes are complicated and have long production cycles. Nevertheless, use of thermo-mechanically controlled processing to produce low alloy abrasion resistant steel reinforced with particles has received little attention.

TiC is a widely used reinforcement in steel due its high melting point, high hardness, low density, and good chemical stability [10–12]. In recent years, many researchers have studied the effect of TiC addition on wear resistance. Dalai et al. [13] improved the wear resistance of austenitic manganese steel by in-situ addition of TiC particles where it was not possible to achieve sufficient work hardening at low impact loads. Srivastava et al. [14–16] indicated that TiC and (Ti,W)C particles bonded strongly with the austenite matrix and were retained on the sliding surface and thereby protected the matrix. Alpas et al. [17,18] found that the wear resistance of TiC and (Ti,W)C particles-reinforced high manganese steel are related to the bearing capacity of the in-situ added particles. Since the wear resistance is related to bonding strength and bearing capacity, and the soft austenite matrix has limited bearing capacity for particles, we have chosen to develop a particles-reinforced martensitic wear resistant steel. Wei et al. [19–22] studied the wear resistance of high speed steel with high vanadium content and showed that VC distributed evenly in the austenitic and martensitic matrix can effectively resist micro-cutting of abrasive. Nevertheless, there are only few reports on TiC particles-reinforced low alloy abrasion resistant steel.

A new low alloy wear resistant steel reinforced with (Ti,Mo)C particles was obtained by thermo-mechanically controlled processing and

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Table 1
Chemical compositions of experimental steel and NM500 (wt%).

Materials	C	Si	Mn	Ti	Mo	B	S+P
Experimental steel	0.41	1.50	1.35	0.600	0.24	0.0020	≤ 0.015
NM500	0.27	0.25	1.24	0.016	0.26	0.0018	≤ 0.015

the microstructure and mechanical properties of the steel have been characterized. The three-body wear behaviour of the experimental steel was studied by MLG-130 dry sand rubber wheel wear testing machine under applied loads of 45 N and 130 N. Finally, the wear mechanism of (Ti,Mo)C particles-reinforced steel under abrasive wear condition was investigated.

2. Experimental procedure

2.1. Materials and heat treatment

The actual chemical compositions of the experimental steel (denoted as (Ti,Mo)C-reinforced steel) and NM500 are listed in Table 1. The NM500 is traditional 500HBW grade low alloy wear resistance steel, which was chose as contrast steel. Increasing the Ti and C in the experimental steel served to form a larger amount of (Ti,Mo)C particles so that the experimental steel had a similar hardness to the contrast steel, which allowed to study the effect of (Ti,Mo)C particles on abrasion resistance of materials with similar hardness. The experimental steel and contrast steel were melted using the vacuum melting furnace with the capacity of 150 kg, and then forged into 100 mm × 100 mm × 120 mm ingots. Before rolling, the ingots were heated to 1200 °C for 2 h for solution treatment, after which they were hot rolled to 12 mm thick plates by two-stage controlled rolling and followed cooled at an ultra-fast rate (~100 °C/s) to 650–750 °C, finally by air cooling to room temperature. The plates were reheated to 880 °C for 30 min in a box-type resistance furnace and water quenched to room temperature (as 880WQ). SEM, TEM, EDS, tensile and wear samples were cut from plates after 880WQ, and samples details are shown in Table 2.

2.2. Microstructure examination

Metallographic samples (10 mm × 10 mm × 12 mm) were cut using electro-discharge machining from plates after hot rolling followed by water quenching; the samples were then polished using standard metallographic procedures. The morphology of the particles was observed using non-erosion samples and the microstructure was studied by ZEISS ULTRA-55 scanning electron microscopy (SEM) operating at 15 kV after etching the samples with 4% nitral (4 ml HNO_3 + 96 ml ethanol). Precipitation was observed using FEI Tecnai G2 F20 transmission electron metallography (TEM) operating at 200 kV. For TEM studies, 3 mm diameter samples were cut from plates after 880WQ and ground to ~45 μm thickness and electrolytically jet polished in a solution of 9 vol% perchloric acid in ethanol at −25 °C. Surface scan was carried out on JEOL JXA-8530F field emission electron probe (EPMA) operating at 20 kV.

2.3. Mechanical property tests

Vickers macrohardness was determined across the thickness of the plates using KB3000BVRZ-SA hardness tester under 10 kg load and the average value from 10 measurements was reported. The Vickers microhardness of matrix and (Ti,Mo)C particles was tested using a microhardness tester (FM-700) with 50 g and 10 g loads, respectively. Tensile tests were performed on an AG-X 100 kN tensile testing machine at room temperature with a crosshead speed of 1 mm min^{-1}. The tensile specimens were prepared as per the GB/T 228.1–2010 Chinese standard with a gauge section of 5 mm diameter, a gauge length of 25 mm and a parallel length of 40 mm. The gauge length direction perpendicular to the rolling direction. Three tensile specimens were tested for each steel.

2.4. Dry sand rubber wheel abrasion wear test (ASTM G65)

Three-body abrasive wear tests were performed using a commercially made, dry sand rubber wheel wear testing machine (Fig. 1a) (model MLG-130, manufactured by the company of Chengxin, the location of company is Zhangjiakou, Hebei, China). Modified ASTM standard test method G65 Procedure B was used [23]. The experiments were carried out at room temperature and the test parameters were as follows: rotational speed 200 rpm, normal load 130 N and a smaller load of 45 N acting against the specimen (75 mm × 25.5 mm × 7 mm), a sliding distance of 1436 m, and using quartz sand with size in the range of 200–400 μm (Fig. 1b). The sand flow rate was 300 g/min. The hardness of the rubber wheel was 60 Shore A hardness. The diameter of the rubber wheel was 228.6 mm. Each test was repeated three times and the data were treated using statistical analysis. The weight of the samples was measured to 1 mg accuracy using a SECURA225D-1CN electronic balance before and after the tests, after carefully cleaning and removing unattached abrading particles. The morphology of the samples after wear was characterized by SEM.

3. Results and discussion

3.1. Microstructures

A non-erosion specimen can exhibit the morphology and distribution of particles more clearly; the morphology of particles in (Ti,Mo)C-reinforced steel after quenching from 880 °C is shown in Fig. 2. It is found that the particles are uniformly distributed in the steel matrix and have different morphologies consisting of a mixture of columnar, cuboid, granular and polygonal particles. The size of the granular particles is generally smaller, with diameters in the range of 1–4 μm (measured by Image Pro Plus). The polygonal particles are larger and sizes can reach up to 6–9 μm. The columnar particles are longer (3–9 μm) but have smaller diameters (0.4–0.9 μm). The sizes of cuboid particles are in the range between 4 and 9 μm. The in-situ formed particles are usually unevenly distributed and segregated [7], but those in our experimental steel that was subjected to rolling, are uniformly distributed. This has the effect of reducing the void area between particles and is advantageous for wear resistance [7].

The composition of the particles was determined from surface scans

Table 2
SEM, TEM, EDS, tensile and wear samples details.

Tests	Size of samples	Heat treatment	Sample processing
SEM	Metallographic samples (10 × 10 × 12)mm	Hot rolled and 880WQ	Polished and no-etched/etched (4% nitral)
TEM	Thin foil samples Φ3 mm × 45 μm	Hot rolled and 880WQ	Electropolished (9% perchloric acid)
EDS	Metallographic samples (10 × 10 × 12)mm	Hot rolled and 880WQ	Polished and no-etched
Tensile	A25 round rod standard samples	Hot rolled and 880WQ	Lathe processed
Wear	Rectangular samples (75 × 25.5 × 7) mm	Hot rolled and 880WQ	Milling machine processed