Proceedings of the 5th International Symposium on Steel Science (ISSS 2017)
Nov. 13-16, 2017, Kyoto, Japan: The Iron and Steel Institute of Japan

Effect of diffusion annealing on microstructure and mechanical properties of ultra-high strength martensitic wear-resistant cast steel

Zhongzheng Pei[1], Renbo Song[1*], Jie Xu[1], Li Wang[2]

[1] School of Materials Science and Engineering, University of Science and Technology Beijing, Beijing 100083, China
[2] School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan 114051, China

Abstract: The microstructure-properties relationship, fracture mechanism and wear behaviour have been systematically investigated in an ultra-high strength martensitic wear-resistant cast steel subjected to diffusion annealing, quenching and tempering. The steel exhibited tensile strength of 1529 MPa, yield strength of 1277 MPa, hardness of 55.2 HRC, Charpy impact toughness of 32.2 J/cm^2 for quenching at 950 °C and tempering at 250 °C, tensile strength of 1982 MPa, yield strength of 1457 MPa, hardness of 54.1 HRC, Charpy impact toughness of 285 J/cm^2 in case of diffusion annealing at 1250 °C, quenching at 950 °C and tempering at 250 °C. The diffusion annealing effectively eliminated casting segregation and contributed to higher toughness. The chromium and manganese carbides after diffusion annealing treatment led to fine martensite laths, which facilitated the increase of strength. The pin-on-disk wear test was used to study the wear behaviour of the ultra-high strength martensitic wear-resistant cast steel and a conventional Hadfield steel (Mn13Cr2) in comparison. The results revealed that the martensitic steel after diffusion annealing treatment obtained more shallow and narrow scratches than the steel without diffusion annealing in the test. Both of the martensitic steel showed effectively higher wear resistance than Mn13Cr2 steel.

1. INTRODUCTION

Wear is one of the main damage forms in cone crusher liner material. However, the conventional Hadfield steel cannot be guaranteed for long service life. In recent years, low alloy martensitic wear-resistant steel is widely concerned [1-5]. A new-type of ultra-high strength martensitic wear-resistant cast steel is trialed in this paper. In order to get the best mechanical properties, the process of diffusion annealing, quenching and tempering is expected. In this work, the microstructure and mechanical properties of the martensitic steel were investigated. A pin-on-disk wear test was carried out to compare the wear resistance of the martensitic steel (with and without diffusion annealing) and a conventional Hadfield steel (Mn13Cr2), which provides references for cone crusher liner materials.

2. EXPERIMENTAL

The ultra-high strength martensitic wear-resistant cast steel (martensitic steel) and conventional Hadfield steel (named Mn13Cr2, GB/T 3077–1999 standard) for the experiments was melted by vacuum induction furnace and cast to a 20 kg ingot. The chemical composition of the martensitic steel is listed in Table 1 Samples with a dimension of 15 ×35 ×60 mm^3 were cut from the ingot for heat treatment experiment. The martensitic steel samples were diffusion annealed at 1250 °C for 5 h followed by furnace cooling. Then, the samples with and without diffusion annealing were austenitized at 950 °C for 1.5 h followed by water quenching and tempering at 250 °C for 3 h. For Mn13Cr2 steel, the samples were heated at 1000 °C for 1 h and water quenched to the room temperature as the present industrial technology.

Table 1. Chemical composition of ultra-high strength martensitic wear-resistant cast steel (wt. %).

C	Si	Mn	Cr	Mo	Ni	B	S	P	Fe
0.55	1.48	1.78	3.87	0.64	1.25	0.0085	0.020	0.007	Bal.

* Corresponding author. E-mail: songrb@mater.ustb.edu.cn, telephone: +86 10 82377990.

Comparisons of mechanical properties for the martensitic steel were made by tensile, hardness and Charpy impact test. Tensile tests at room temperature were carried out by CMT4105 electronic universal experiment machine according to GB/T 228.1-2010. Hardness tests were performed on TH320 rockwell hardness tester. The toughness was tested by ZBC2452-B pendulum impact testing machine with 10 × 10 × 55 mm^3 unnotched samples.

The microstructure was observed by optical microscopy (OM, Zeiss Axio Scope. A1), scanning electron microscopy (SEM, Zeiss EVO 18) and transmission electron microscope (TEM, JEOL 1010). The samples for OM and SEM were polished and etched by 4 vol% nital. The TEM samples were mechanically pre-thinned to thin foils and twin-jet electropolished using 20 vol% perchloric acid +alcohol solution at 20 V, -20 °C. The TEM accelerating voltage was 200 kV.

The wear resistance of martensitic steel and Mn13Cr2 were investigated by vertical universal friction and wear testing machine (MM-W1A) [6]. The schematic representation was exhibited in Fig. 1. Before and after each test, the pins and discs were cleaned with acetone in an ultrasonic water bath for 5 min to eliminate potential impurities and then dried. The lost mass of the pins was weighed every 30 min by balance with a sensibility of 0.0001g. All the tests were carried out with 80 N loads, in room temperature, a testing period of 90 min with a sliding speed of 300 r/min. The disk is composed of 45 steel with a hardness of 57.9 HRC.

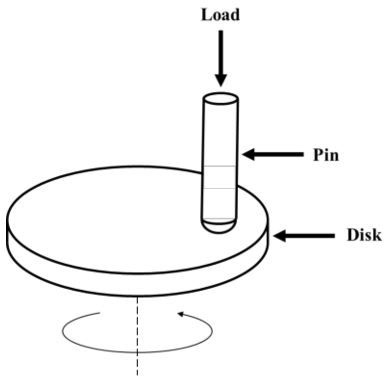

Fig. 1. Schematic representation of pin-on-disk wear test on MM-W1A.

3. RESULTS AND DISCUSSION

3.1 Microstructure

Fig. 2 shows the microstructure of the experimental steel after heat treatment, which consist of fine martensite and retained austenite. The dark and grey regions in Fig. 2a clearly show the casting segregation caused by the high Cr, Mn compositions in the martensitic steel without diffusion annealing. As for the martensitic steel with diffusion annealing, this chemical heterogeneity basically disappeared in Fig. 2b. Thus, the diffusion annealing process makes great contribution to eliminate the casting segregation.

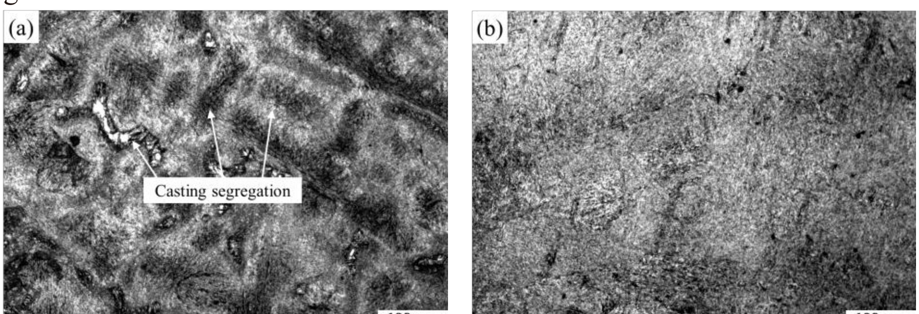

Fig. 2. OM micrographs of the martensitic steel (a) without (b) with diffusion annealing.

SEM micrograph in Fig. 3 shows the microstructure of the martensitic steel right after diffusion annealing. Due to high Cr, Mn, Ni and Mo compositions, the hardenability of the martensitic steel is so excellent that the multiphase of martensite and retained austenite could be obtained right after diffusion annealing even by furnace cooling. It can be seen in Fig. 3a that the martensitic steel represents coarse martensite laths with typical carbides distributed. The enlarged area marked in Fig. 1a and EDS analysis are shown in Fig. 3b, which indicates a typical precipitate including high content of C, Cr and Mn. These carbides precipitated during the furnace cooling process after diffusion annealing remain abidingly during the 950 °C quenching process. Thus, these carbides could accelerate the packet, block and lath divided and pin the boundaries of packets and blocks as second phase particles. Further, the martensitic steel could represent small-sized packets and blocks and eventually obtains very fine martensite laths after subsequent quenching and tempering heat treatment process. TEM micrograph in Fig. 4 shows high density dislocations, which subserve the strength, in laths of the martensitic steel with diffusion annealing.

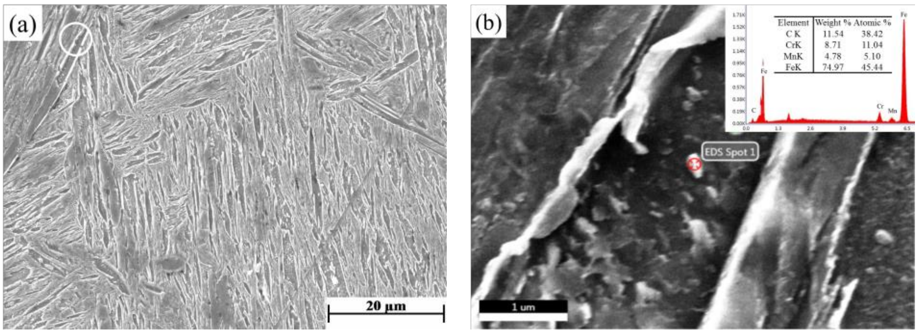

Fig. 3. (a) SEM micrograph (b) EDS results of the martensitic steel after diffusion annealing.

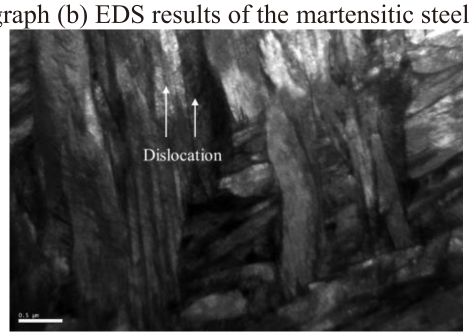

Fig. 4. TEM micrograph of the martensitic steel after diffusion annealing, quenching and tempering.

3.2 Mechanical properties

The mechanical properties of the martensitic steel are shown in Table 2 It can be seen that values of ultimate tensile strength (UTS), yield strength (YS) and Charpy impact toughness (a_k) are 1.30, 1.14 and 8.85 times higher by the diffusion annealing process, respectively. The hardness remains nearly unchanged. Mechanical behaviors analysis can be combined with microstructure observation. The high density dislocations in the martensite laths provide the martensitic steel an ultra-high strength. The diffusion annealing effectively eliminated casting segregation. Further, the carbides of Cr and Mn prevent the martensite laths from coarsening during the diffusion annealing at a high temperature of 1250 °C. Consequently, the uniform and fine laths of the martensitic steel with diffusion annealing contributed to higher Charpy impact toughness.

Table 2. Mechanical properties of martensitic steel after heat treatment.

Heat treatment processing technologies	UTS(MPa)	YS(MPa)	Hardness(HRC)	a_k(J/cm^2)
950 °C × 1.5 h + 250 °C × 3 h	1529	1277	55.2	32.2
1250 °C × 5 h + 950 °C × 1.5 h + 250 °C × 3 h	1982	1457	54.1	285

3.3 Wear resistance comparison

Fig. 5 shows the relationship between the wear loss and wear time of experimental steels. For each materials the wear mass loss increased with increasing wear time. The unit time wear loss of Mn13Cr2 and martensitic steel without and with diffusion annealing is 0.492mg/min, 0.166mg/min and 0.092mg/min, respectively. The lesser mass loss of both martensitic steels compared to Mn13Cr2 was observed at each wear time. Fig. 6 shows the worn surface of experimental steels. The wear character of the Mn13Cr2 was a combination of furrow and desquamation, as is exhibited. As for the martensitic steels, soigne furrow were observed. Further, the martensitic steel after diffusion annealing treatment obtained more shallow and narrow scratches than the steel without diffusion annealing. As a result, it demonstrated that the wear resistance of the martensitic steel is superior to Mn13Cr2.

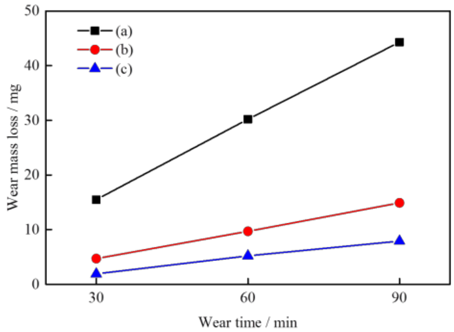

Fig. 5. Wear test results of (a) Mn13Cr2 (b) (c) martensitic steel without and with diffusion annealing.

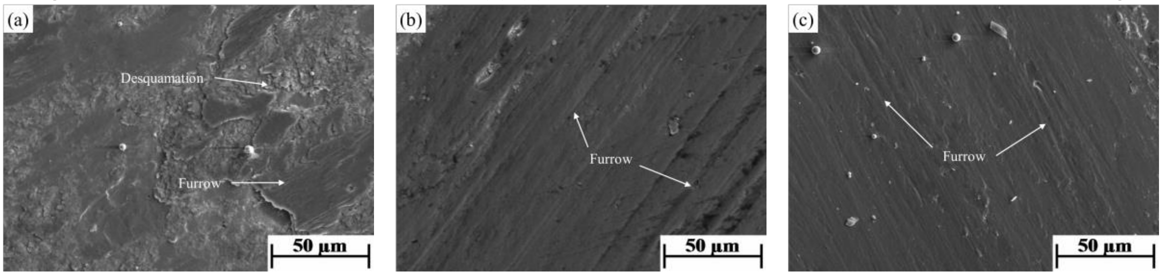

Fig. 6. Worn surface of (a) Mn13Cr2 (b) (c) martensitic steel without and with diffusion annealing.

4. CONCLUSION

From the studies of the effect of diffusion annealing process on the microstructure and mechanical properties of ultra-high strength martensitic wear-resistant cast steel, the main conclusions are drawn as follows:

(1) The steel exhibited tensile strength of 1529 MPa, yield strength of 1277 MPa, hardness of 55.2 HRC, Charpy impact toughness of 32.2 J/cm^2 for quenching at 950 °C and tempering at 250 °C, tensile strength of 1982 MPa, yield strength of 1457 MPa, hardness of 54.1 HRC, Charpy impact toughness of 285 J/cm^2 in case of diffusion annealing at 1250 °C, quenching at 950 °C and tempering at 250 °C.

(2) The diffusion annealing effectively eliminated casting segregation and contributed to higher strength and toughness. The chromium and manganese carbides after diffusion annealing treatment led to fine lath martensite, which facilitated the increase of tensile strength and yield strength.

(3) The pin-on-disk wear test results revealed that the martensitic steel after diffusion annealing treatment obtained more shallow and narrow scratches. Both of the martensitic steel showed effectively higher wear resistance than Mn13Cr2 steel.

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