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Microstructure, Mechanical Properties, and Unlubricated Sliding Wear Behavior of Air-Cooled MnSiCrB Cast Steels

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Two medium carbon low-alloy MnSiCrB cast steels containing different Si contents (0.5 and 1.5 wt.%) were designed, and the effects of Si contents on the microstructure, mechanical properties, and unlubricated sliding wear behavior of the cast steels after air-cooling from 850 °C and subsequent tempering at 220 °C was studied. The results show that the microstructure of the cast steel containing 0.5 wt.% Si consists of granular bainite and lower bainite/martensite multi-phase. In the cast steel containing 1.5 wt.% Si, granular bainite was not observed. The microstructure consists of carbide-free bainite/martensite multi-phase. Excellent hardenability can be obtained at both low and high Si levels. The cast steel containing 0.5 wt.% Si exhibits excellent combination of strength, ductility, and impact toughness superior to the cast steel containing 1.5 wt.% Si. Also, the wear-resistance of the former steel is better than that of the latter in the unlubricated sliding wear condition. The air-cooled MnSiCrB cast steel containing low Si levels, with excellent mechanical properties and wear-resistance, is a potential high-performance and low-cost wear-resistant cast steel for unlubricated sliding wear condition.

Keywords air-cooled, low-alloy MnSiCrB cast steel, microstructure, Si, strength and impact toughness, unlubricated sliding wear

1. Introduction

Wear-resistant cast steels are widely used in civilian industry such as lining board, toothed plate, hammer, and other structural parts which require combination of strength, impact toughness and wear resistance. In the application fields of wear-resistant cast steels, Hadfield's cast steel (Fe-1.2 wt.%C-13 wt.%Mn) is widely employed as it has high impact toughness and high resistance to impact wear caused by rapid cold work hardening in high impact abrasive conditions. However, it may suffer considerable wear and deformation in non- or low-impact abrasive conditions, as in the fully austenitic solutionised form, it is soft and ductile (Ref 1-4). The demands for producing higher strength steel castings with high impact toughness and wear-resistance have encouraged some researchers to focus on the low-alloy cast steels (Ref 5-9). However, the impact toughness of the low-alloy wear-resistant cast steels is low when the hardness is higher than 50 (HRC). This is the main obstacle for the low-alloy cast steels to be used in manufacturing of industrial parts. In addition, most of the low-alloy wear-resistant cast steels are alloyed with expensive elements (such as nickel, chromium, and molybdenum) and oil-quenched to obtain high hardness. Therefore, they are expensive and harmful to the environment. With the shortage of natural resources and the demand for sustainable development, research and development of high-performance low-cost wear-resistant cast steels, with cheap elements and by simple heat treatment are required. However, the elimination of nickel, chromium, and molybdenum limits the hardenability of the cast steels, because of the difficulty to obtain martensite when the castings are large in diameter. In the case of steel castings, there is no process of deformation (such as forging, rolling, etc.). The mechanical properties of the steel castings depend mainly on the alloying scheme and heat treatment. Therefore, appropriate alloying scheme and heat treatment are of importance to obtain good hardenability and combination of strength and toughness at low cost.

In this study, the high-performance low-cost wear-resistant cast steels, the materials of our aim were based on the design idea of cheap alloying scheme and simple heat treatment. The cast steels were alloyed with manganese, silicon, chromium, and a little boron. The heat treatment consisted of simple air-cooling and tempering. This hardening heat treatment process of air-cooling must be based on certain hardenability, which is of importance for the application of air-cooled cast steels. In the MnSiCrB cast steels, the cheap alloying elements of manganese and boron have beneficial effect on the hardenability of steel (Ref 10-13). Manganese, the main alloying agent in the low-alloy MnSiCrB cast steels, is used to retard the pearlitic transformation and stabilize austenite during cooling, thus allowing a lower critical cooling rate to obtain good hardenability. Also, manganese solution strengthens the matrix in the microstructure. Chromium and boron are used to improve

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the hardenability. Silicon is the commonly used alloying element in wear-resistant cast steels as it is the most effective solid solution strengthening element in low-alloy steels. However, the effect of silicon on the toughness and wear resistance of the low-cost MnSiCrB cast steels at elevated hardness levels has not attracted much attention. In this study, two medium carbon low-alloy MnSiCrB cast steels containing different Si contents (0.5 and 1.5 wt.%) were designed, and the effect of Si on microstructure, mechanical properties, and unlubricated sliding wear behavior of the air-cooled MnSiCrB was investigated.

2. Materials and Experimental Procedure

The low-alloy MnSiCrB cast steels were manufactured by vacuum induction melting. Aluminum, titanium, and rare earth (Ce) were added to purify and refine the cast steels. In the addition process, Al, Ti, B, and Ce were added in sequence. The steels were cast into keel blocks (shown in Fig. 1). The chemical composition of the tested cast steels, measured using wet chemical analysis, is listed in Table 1. No. 1 cast steel contains 0.5 wt.% Si, while No. 2 cast steel contains 1.5 wt.%.

The critical temperature in the heating process, measured by dilatometer method, is 796 °C for the studied No. 1 cast steel, and 805 °C for the studied No. 2 cast steel. The austenitizing temperature was selected as 850 °C for both the cast steels. High hardness was required for wear-resistant cast steels. In this study, the hardness of the cast steels was more than 50 HRC. On the basis of a series of practical trails, the hardness of the studied cast steels can reach above 50 HRC by tempering at 220 °C. Therefore, the heat treatment process was selected as air-cooling from 850 °C and subsequent tempering at 220 °C. In the heat treatment process, the keel blocks were first heated to 650 °C holding for 60 min, austenitized at 850 °C for 50 min, then subjected to air-cooling to room temperature, and finally tempered at 220 °C for 150 min. The tensile, impact, and wear test samples were all taken form the keel blocks after air-cooling from 850 °C and subsequent tempering at 220 °C.

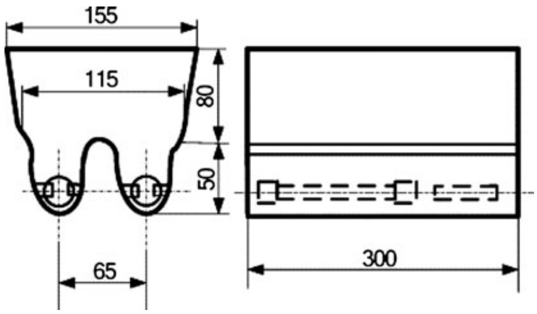

Fig. 1 Shape and dimension of Keel block

The microstructure was characterized by scanning electron microscope (SEM) using FEI Quanta 200 FEG at an accelerating voltage of 15 kV. Ambient temperature uniaxial tensile properties were determined using 60-mm gage length cylindrical tensile bars in accordance with appropriate ISO 6892:1998 standards. The number of the tested samples is three for tensile properties. The hardenability of the cast steel was tested in accordance with ISO 642:1999 standards, where the austenitizing temperature was 850 °C. The impact toughness was determined using standard-sized non-notched specimens (10 mm × 10 mm × 55 mm), broken in a pendulum-type impact machine of 300 J measurement range at room temperature. The number of the tested samples is four for impact toughness.

A pin-on-disk type of experimental set-up, falex friction, and wear-testing machine, was employed for wear study. Disks of above set-up were made of high carbon, high chromium steel, heat treated to a hardness of 62 (HRC). Cylindrical test pins of 4.8-mm diameter and 12.7 mm in length were machined from heat-treated keel blocks. The surfaces of both the test specimens and the steel disk were ground to a constant surface finish of 0.20 (c.l.a.), which were thoroughly degreased and dried before commencement of each test run. The test pins were initially weighed, and at the end of each wear test, they were wiped clear of wear particles, degreased, and reweighed. The difference in weights of the test pin, before and after the experiment, determined the weight loss. The wear tests were conducted at the load of 10 kg and sliding velocity of 0.5 mps for all the samples. All the wear experiments were conducted under non-lubricated sliding condition, at a relative humidity of 46% and room temperature of 25 °C.

The fractured surfaces of non-notched impact specimens and the worn surface of pins were analyzed by SEM using FEI Quanta 200 FEG at an accelerating voltage of 15 kV to determine the fracture and wear behavior, respectively.

3. Results and Discussion

The SEM micrographs of the MnSiCrB cast steels after air-cooling from 850 °C and subsequent tempering at 220 °C are shown in Fig. 2. It can be seen that the effect of Si on the microstructure of the MnSiCrB cast steels was significant. At lower Si content level (0.5 wt.%), the microstructure of the cast steel consists of granular bainite (B_g) and lower bainite/martensite multi-phase (B/M), as shown in Fig. 2(a). When 1.5 wt.% Si was added to the cast steel, granular bainite was not observed. The microstructure of the cast steel consists of carbide-free bainite/martensite multi-phase, as shown in Fig. 2(b). Granular bainite, which was found in low carbon and medium carbon alloy structural steels, was first put forward by Habraken (Ref 14). The microstructure morphology of granular bainite is that the second-phase islands distribute in the ferrite matrix. The second-phase islands are carbon-rich

Table 1 Chemical composition of the MnSiCrB cast steels (wt.%)

	C	Si	Mn	S	P	Cr	Al	Ti	B	Ce
No. 1 cast steel (low Si)	0.44	0.5	2.46	0.01	0.01	0.8	0.02	0.03	0.0038	0.08
No. 2 cast steel (high Si)	0.44	1.5	2.45	0.01	0.01	0.8	0.02	0.03	0.0036	0.08

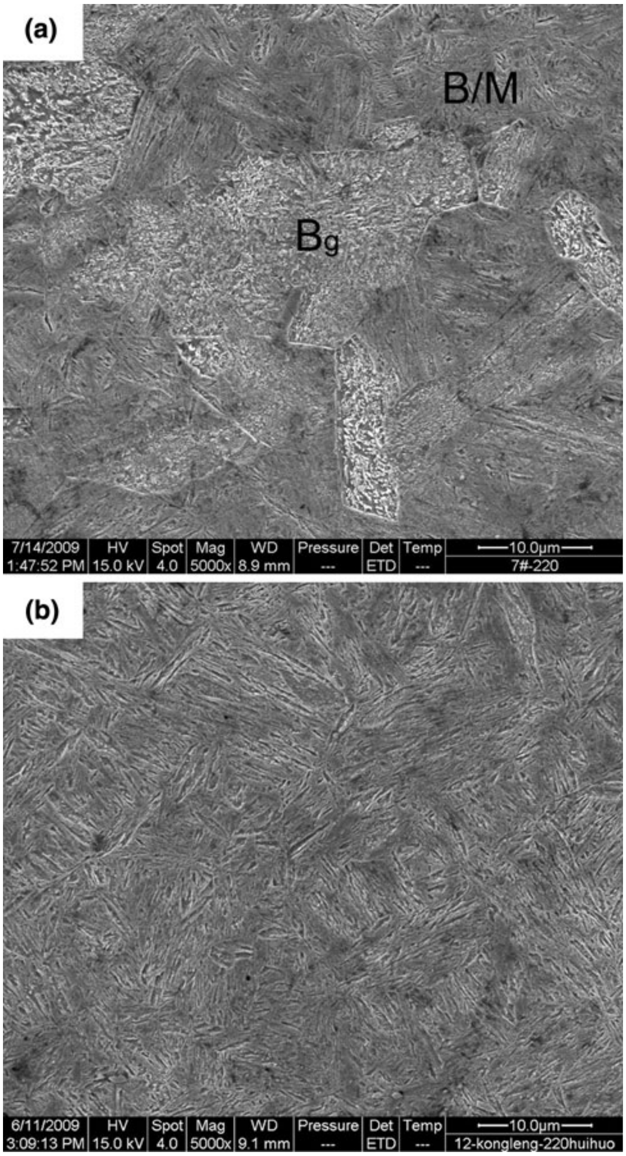

Fig. 2 SEM micrographs of the MnSiCrB cast steels after 850 °C air-cooling and 220 °C tempering, (a) MnSiCrB cast steel containing 0.5 wt.% Si, granular bainite, and lower bainite/martensite multi-phase; (b) MnSiCrB cast steel containing 1.5 wt.% Si, carbide-free bainite/martensite multi-phase

austenite left during the forming of granular bainite ferrite. It can convert into martensite in the following transformation process or retain in the form of austenite. The second-phase islands are often referred to as M/A islands. Si is the commonly used solid solution strengthening element in low-alloy steels. It is known to significantly impede the formation of cementite during bainite transformation because of near zero solubility of Si in cementite phase (Ref 15). Therefore, a large amount of Si addition to low-alloy steel retards the formation of granular bainite and improves the formability of the carbide-free bainite/martensite multi-phase. Carbide-free bainite is a mixture of fine bainitic ferrite plates, retained austenite, and some martensite (Ref 16).

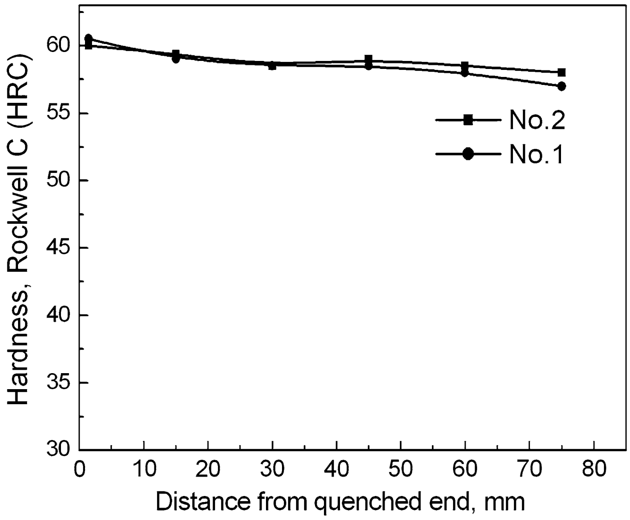

Fig. 3 Jominy hardenability curves of the investigated MnSiCrB cast steels. No. 1 cast steel containing 0.5 wt.% Si, No. 2 cast steel containing 1.5 wt.% Si

Hardenability, defining the susceptibility of steel to quenching, is the most important property for the air-cooled cast steels, because the air cooling rate is lower than that of water quenching or oil quenching. The hardenability curves obtained according to the Jominy end-quench test (Ref 17) are the most widely used in steel composition and manufacturing process design. The Jominy hardenability curves of the MnSiCrB cast steels with different contents of Si are shown in Fig. 3. It can be seen that the MnSiCrB cast steels have good hardenability at both lower and higher Si levels. The addition of 1.5 wt.% Si does not significantly change the hardenability of the MnSiCrB cast steel. As shown in Fig. 2, the microstructure of the MnSiCrB cast steel containing 0.5 wt.% Si after air-cooling was granular bainite and lower bainite/martensite multi-phase. No ferrite formed at high temperature region during heat treatment was observed. The formation of granular bainite was not detrimental to the hardness of the MnSiCrB cast steel. In the MnSiCrB cast steels, Mn, Cr, and B were all the effective elements for improving the hardenability.

The sulfide inclusion is common phase in cast steel, and it is detrimental to the mechanical properties, especially to the impact toughness. The sulfide inclusion cannot be eliminated once it is formed in cast steels as there is no process of deformation (such as forging, rolling etc.) for steel castings. In the MnSiCrB cast steels, rare earth (Ce) was used to purify and refine the cast steels. The effect of rare-earth element Ce (mixtured by La, Pr, and Nd) on the shape of the sulfide inclusions in MnSiCrB cast steel is shown in Fig. 4. It can be seen that the sulfide inclusions were globularized effectively. The earlier study (Ref 18) showed that the addition of rare-earth metals to cast steel globularized the sulfide inclusions, and this can be beneficial to the mechanical properties, especially the impact toughness.

High hardness is required for the cast steels applied in wear conditions. In order to obtain high wear-resistance, the hardness of the designed cast steels in this study is aimed to exceed 50 (HRC). Generally speaking, at high hardness levels, the ductility of low-alloy cast steels is usually low, and fracture occurs at low plastic deformation degree or even at elastic deformation region during tensile test. Therefore, none of the tensile properties was reported for high hardness cast steels. In this study, the effect of Si contents on the mechanical properties of the MnSiCrB cast steels was analyzed by tensile and impact tests. The tensile properties and impact toughness of the MnSiCrB cast steels after air-cooling from 850 °C and subsequent tempering at 220 °C are reported in Table 2. In the tensile test, percentage of reduction of area was too low, and so only the percentage of elongation after fracture (A) was used to evaluate the ductility of the cast steels. In the impact test, impact toughness (a_K) of the cast steels is characterized by using non-notched specimens (10 mm × 10 mm × 55 mm) which are usually used in industrial application for high hardness material, especially hardness cast steels and cast irons. From Table 2, it can be seen that the MnSiCrB cast steel samples with 0.5 wt.% Si have higher tensile strength (R_m = 2020 MPa on average) with good ductility (A = 5% on average). While the MnSiCrB cast steel samples with 1.5 wt.% Si have low tensile strength (R_m = 1780 MPa on average) with low ductility ($A < 1\%$). Especially, the impact toughness can reach 97-164 J/cm^2 for the cast steel with 0.5 wt.% Si and 24-61 J/cm^2 for that with 1.5 wt.% Si at the similar hardness levels. Therefore, the MnSiCrB cast steel with 0.5 wt.% Si can exhibit higher tensile strength, ductility, and impact toughness than that with 1.5 wt.% Si. Attention must be paid to the fact that the hardness values and the yield strength (characterized by proof strength non-proportional extension, $R_{p0.2}$) of the cast steels containing different Si contents are nearly identical, but the tensile strength values are very different. The difference in the tensile strength is not reflected in the corresponding difference in the hardness values. The engineering stress-engineering strain curves of three specimens of the cast steel with low Si (CS (LSi)) and three specimens of the cast steel with high Si (CS (HSi)) are shown in Fig. 5. It can be seen that the cast steel with 0.5 wt.% Si exhibits better ductility and work hardening ability than the cast steel with 1.5 wt.% Si. Fracture occurred at lower plastic deformation degree (< 1%) for the cast steel containing 1.5 wt.% Si while it occurred at higher plastic deformation degree (5% on average) for the cast steel containing 0.5 wt.% Si. Therefore, the MnSiCrB cast steel containing 1.5 wt.% Si has lower tensile strength than the cast steel containing 0.5 wt.% Si even though the former is harder than the latter.

Four typical broken non-notched impact samples are shown in Fig. 6. Examination of the fractured surfaces revealed that the fracture mechanism of the MnSiCrB cast steels with low Si and high Si is all quasi-cleavage (mixture of cleavage and dimple), but the fractured surfaces of low Si cast steel are covered with bigger and deeper dimples than that of high Si cast steel, as shown in Fig. 7.

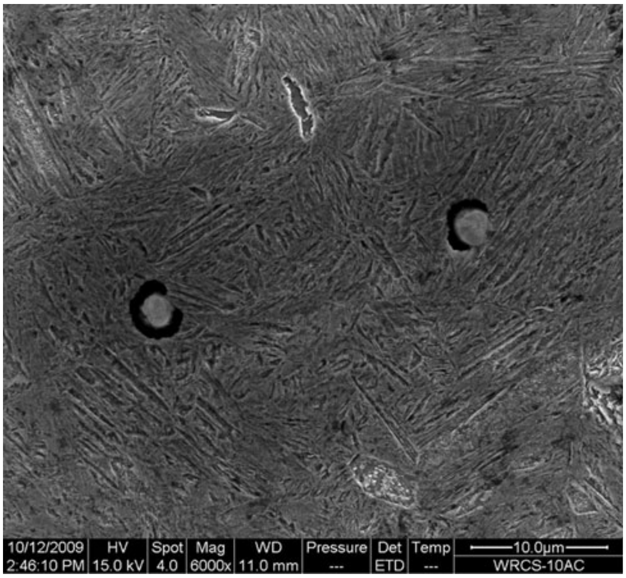

Fig. 4 Morphology of inclusion in MnSiCrB cast steel

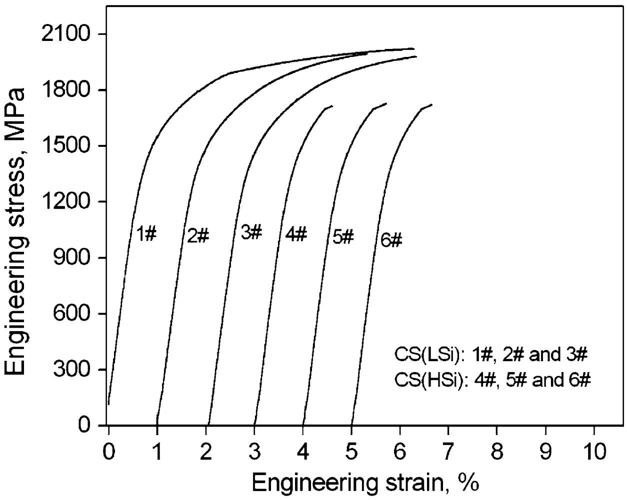

Fig. 5 Engineering stress-engineering strain curves of a No. 1 cast steel test specimen and a No. 2 cast steel test specimen, 850 °C air-cooled and 220 °C tempered, specimens of 1#, 2#, and 3# from No. 1 cast steel containing 0.5 wt.% Si, specimens of 4#, 5#, and 6# from No. 2 cast steel containing 1.5 wt.% Si

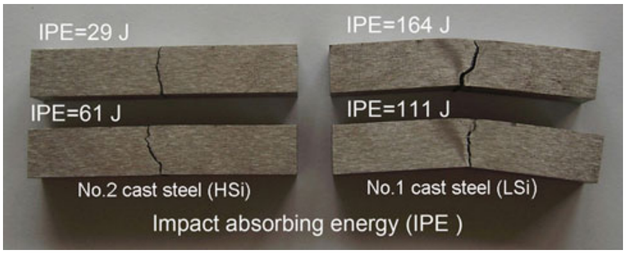

Fig. 6 The broken non-notched impact samples of the MnSiCrB cast steels containing different Si contents

Table 2 Tensile properties and impact toughness of the MnSiCrB cast steels

	Hardness, HRC	$R_{p0.2}$, MPa	R_m, MPa	A, %	a_K, J/cm^2
No. 1 cast steel (low Si)	51 ± 1	1480 ± 20	2020 ± 25	5 ± 1	111, 97, 118, 164
No. 2 cast steel (high Si)	53 ± 1	1490 ± 20	1780 ± 20	< 1	24, 61, 29, 32

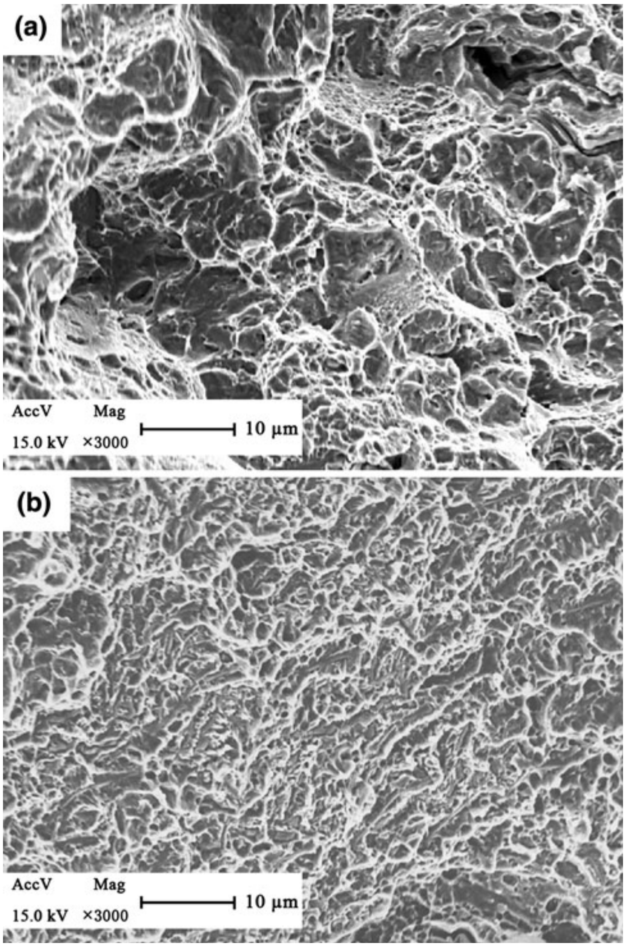

Fig. 7 SEM micrographs of fracture surfaces of broken non-notched impact samples of MnSiCrB cast steels after 850 °C air-cooling and 220 °C tempering, (a) cast steel with 0.5 wt.% Si, (b) cast steel with 1.5 wt.% Si

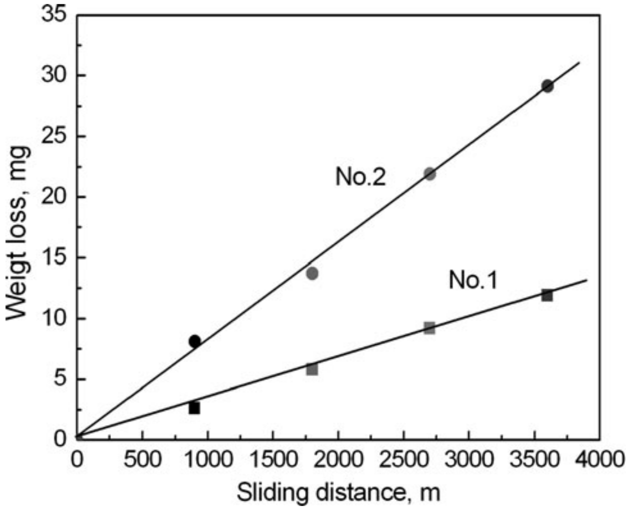

Fig. 8 Weight loss as a function of sliding distance in unlubricated sliding wear test: No. 1 cast steel containing 0.5 wt.% Si; No. 2 cast steel containing 1.5 wt.% Si

The mechanical properties of MnSiCrB cast steels depend upon their microstructures, whilst their microstructures greatly relate to their Si contents. As shown above, the MnSiCrB cast steel with 0.5 wt.% Si exhibits higher tensile strength, ductility and impact toughness than that with 1.5 wt.% Si. From the microstructure of the MnSiCrB cast steels, addition of Si to low-alloy steel retarded the formation of granular bainite and improved the formability of the carbide-free bainite/martensite multi-phase. Granular bainite is beneficial to the ductility and impact toughness (Ref 19). The solid solution of Si in the bainite ferrite and martensite may promote the occurrence of fracture (Ref 20). The medium carbon low-alloy steel containing Mn, Cr, and B can obtain high hardness where addition of Si does not significantly improve the hardness. Therefore, in the design of the high-performance and low-cost wear-resistant cast steel, low Si content was beneficial to the combination of strength and impact toughness.

The weight loss as a function of sliding distance in unlubricated sliding wear test is shown in Fig. 8. It can be seen that there is a linear relationship between the wear weight loss and sliding distance for the studied cast steels, and that the weight loss of the cast steel with 0.5 wt.% Si is less than that of the cast steel with 1.5 wt.% Si in identical sliding distance. It is indicated that the cast steel with low Si content is more wear resistant than the cast steel with high Si content in the unlubricated sliding wear test. The observed difference in wear resistance does not reflect in the corresponding difference in the hardness values as the cast steel pins with 1.5 wt.% Si are ca. 2 (HRC) harder than ones with 0.5 wt.% Si. Therefore, the wear resistance of the cast steels at the similar hardness levels depends on not only hardness but also ductility and toughness which can influence the wear mechanisms.

In sliding contact, wear can occur due to adhesion, surface fatigue, tribo-chemical reaction, and/or abrasion (Ref 21). Many factors (such as contact load, contact area, environment, and counter-body) influence the wear mechanisms. In this study, the sliding wear test was carried out in the same condition so that the study can focus on the effect of microstructure and mechanical properties on the wear behavior for the cast steels containing different Si contents.

The variation of friction coefficient as a function of the sliding distance for the cast steels is shown in Fig. 9. It can be seen that the friction coefficient curve exhibits more obvious saw-tooth patterns for the cast steel containing 0.5 wt.% Si than for the cast steel containing 1.5 wt.% Si in the unlubricated sliding wear process. The macrographs of the worn surfaces of the cast steels are shown Fig. 10 and the micrographs of selected areas, as shown in Fig. 11 and 12, were taken from corresponding positions in Fig. 10. It can be seen that there was abrasion for both the cast steels, as shown in Fig. 11(a) and 12(a). Abrasion, removal of material due to scratching, occurs in the relatively moving surfaces of pin and disk. This kind of displaces of material is caused by grooving in the form of micro-cutting and/or micro-ploughing as the counter-face, the disk made of hardened high carbon high Chromium steel, is harder than the tested MnSiCrB cast steels. In addition to the abrasive wear mechanism existing both in the cast steels, there are other different wear mechanisms for the cast steels. In Fig. 11(a), on the worn surface of the cast steel with 0.5 wt.% Si, it can be seen that there was plastic deformation flow on the worn surface and debris formed by flaking after plastic deformation flow in the sliding wear process. When the plastic deformation flow plays a predominant role in the unlubricated sliding wear process, the friction coefficient can be very high

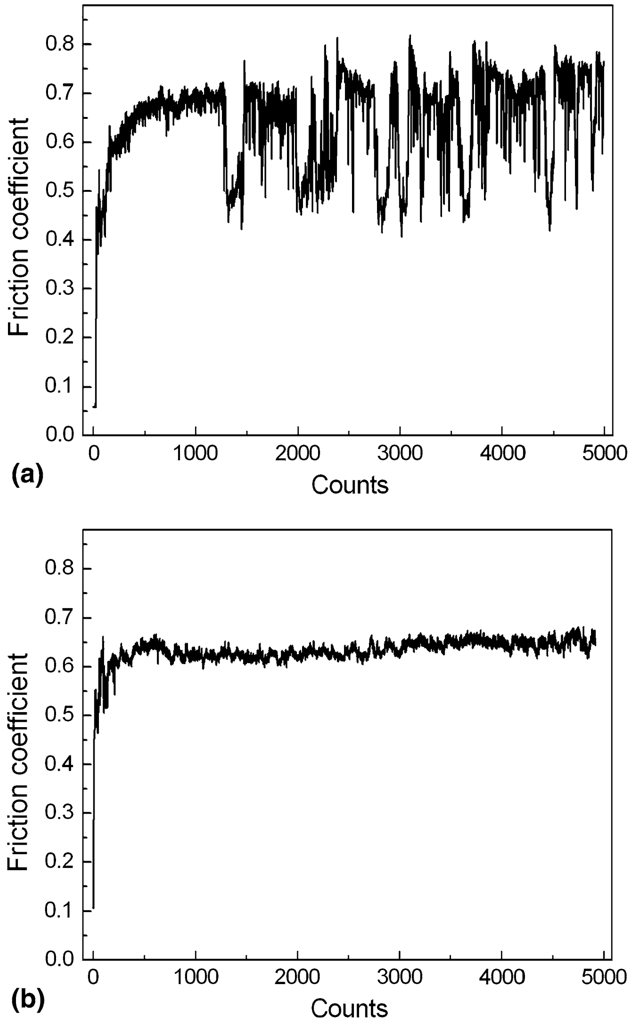

Fig. 9 Variation of friction coefficient with sliding distance for the MnSiCrB cast steels: (a) cast steel with 0.5 wt.% Si, (b) cast steel with 1.5 wt.% Si

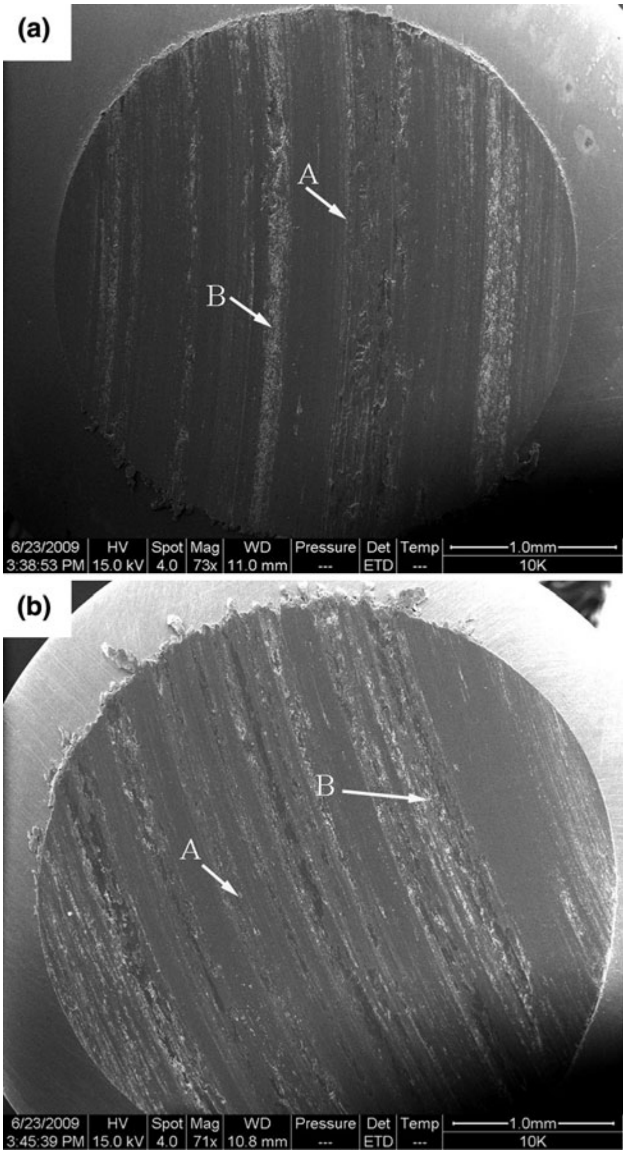

Fig. 10 Macrographs of the worn surface of MnSiCrB cast steels: (a) the cast steel with 0.5 wt.% Si, (b) the cast steel with 1.5 wt.% Si

because more energy was consumed for the accumulation of plastic deformation flow. Under the driving of contact stress, when the plastic deformation flow formed in the surface layer of the worn material accumulated to a certain extent, cracks formed and propagated and then abrasive debris formed. The debris seems to act as lubricant between pin and disk, as shown in Fig. 11(b). When the debris played an important role as lubricant between pin and disk at some stage in the unlubricated sliding wear process, the friction coefficient deceased. When the debris escaped from the contact surfaces of the pin and disk, new wear occurred on the fresh surface, plastic deformation flow took place and the friction coefficient increased again. Therefore, the variation of friction coefficient as a function of the sliding distance exhibits more obvious saw-tooth pattern, as shown in Fig. 9(a). In comparison, on the worn surface of the cast steel with 1.5 wt.% Si, it can be seen that the mechanism was crack formation and propagation in surface fatigue in addition to the abrasion, as shown in Fig. 12(a). The debris was caused by flaking and brittle fracture. In the unlubricated sliding wear test, in connection with adhesion or abrasion, the repeated sliding of counter-face (disk) across the pin can result in cyclic surface stressing. Localized surface fatigue may occur on a microscopic scale by crack formation and crack propagation at or below the stressed surface and wear occurs by flaking, as shown in Fig. 12(b). Obvious plastic deformation flow was not observed. Therefore, the friction coefficient was more stable than that of the cast steel containing 0.5 wt.% Si as shown in Fig. 9 and the wear behaviors of the cast steels reflected its plastic deformation ability (characterized by ductility and toughness).

From the results and analyses of the wear behaviors above, it can be seen that the observed difference in wear resistance is related to the wear mechanisms which are influenced by the mechanical properties of the cast steels. The cast steel with high Si has higher hardness than the cast steel with low Si but has lower tensile strength, ductility, and toughness than the latter. In the sliding wear, more weight loss was caused by flaking due to the brittle fracture in surface fatigue. Therefore, in the design of the high-performance and low-cost wear-resistant cast steel, low Si content was not only beneficial to the combination of

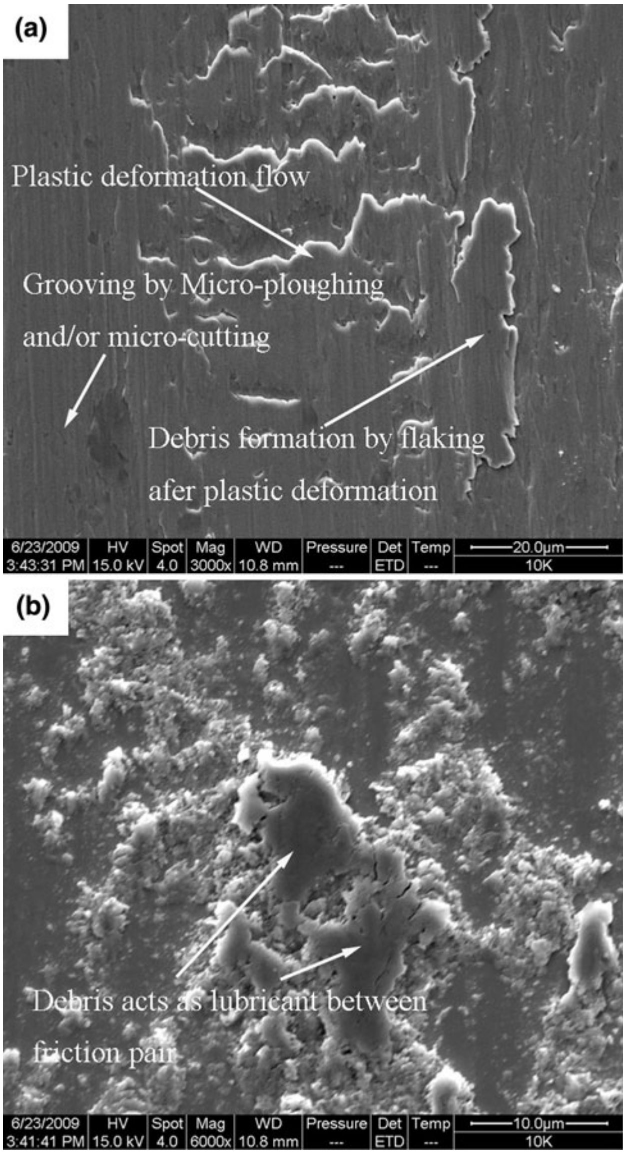

Fig. 11 Scanning electron micrographs of the worn surface of the cast steel with 0.5 wt.% Si: (a) corresponding to position A in Fig. 10(a), (b) corresponding to position B in Fig. 10(a)

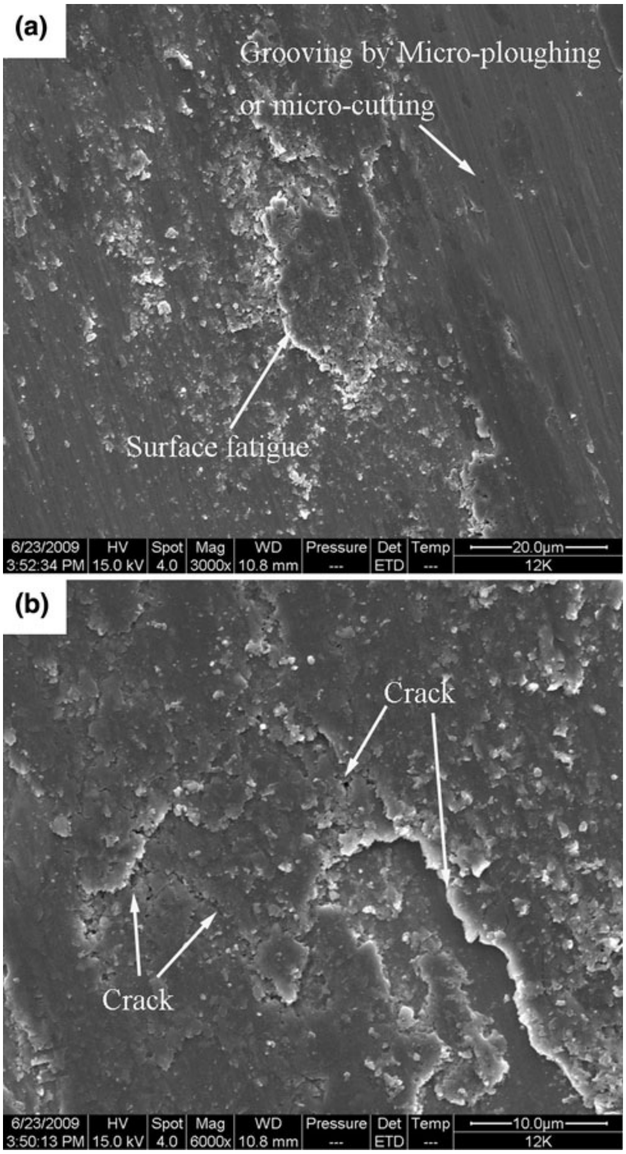

Fig. 12 Scanning electron micrographs of the worn surface of the cast steel with 1.5 wt.% Si: (a) corresponding to position A in Fig. 10(b), (b) corresponding to position B in Fig. 10(b)

strength and impact toughness, but also to the wear-resistance in unlubricated siding wear.

4. Conclusions

Two medium carbon low-alloy MnSiCrB cast steels containing different Si contents (0.5 and 1.5 wt.%) were designed, and the effect of Si contents on the microstructure, mechanical properties, and unlubricated sliding wear behavior of the cast steels after 850 °C air-cooling and 220 °C tempering was studied. The following results can be concluded:

(1) The microstructure of the MnSiCrB cast steels was influenced by the content of Si. At lower Si content, the microstructure of air-cooled MnSiCrB cast steel consists of granular bainite and lower bainite/martensite multiphase. In the cast steel containing 1.5 wt.% Si, granular bainite was not observed. The microstructure consists of carbide-free bainite/martensite multi-phase. Excellent hardenability can be obtained at both low and high Si levels.

(2) The rare-earth elements can effectively globularize the sulfide inclusions in the cast steels.

(3) The MnSiCrB cast steel with 0.5 wt.% Si can obtain better combination of strength and impact toughness than that with 1.5 wt.% Si. The MnSiCrB cast steel samples with 0.5 wt.% Si have higher tensile strength (R_m = 2020 MPa on average) with good ductility (A = 5% on average). By contrast, the MnSiCrB cast steel samples with 1.5 wt.% Si have low tensile strength (R_m = 1780 MPa on average) with low ductility (A < 1%). Especially, the impact toughness can reach

97-164 J/cm^2 for the cast steel with 0.5 wt.% Si but 24-61 J/cm^2 for that with 1.5 wt.% Si at the similar hardness levels 51-53 (HRC).

(4) The wear resistance of MnSiCrB cast steel containing 0.5 wt.% Si level is better than that of MnSiCrB cast steel containing 1.5 wt.% Si level in the unlubricated sliding wear condition. The abrasive wear, plastic deformation, and fracture mechanism play a dominant role for the MnSiCrB cast steel with low Si, while abrasion and surface fatigue play a dominant role for the MnSiCrB cast steel with 1.5 wt.% Si. At similar hardness level, more weight loss was caused by flaking due to the brittle fracture in surface fatigue because the tensile strength, ductility, and toughness of the cast steel with high Si are lower than those of the cast steel with low Si.

(5) The MnSiCrB cast steel with low content of Si (0.5 wt.%) by air-cooling and low temperature tempering can obtain excellent combination of hardness, tensile strength, ductility, impact toughness, and wear-resistance. It promises to be a potential, advanced, wear-resistant cast steel for unlubricated sliding wear condition.

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