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Sliding friction properties of austenite- and martensite-based white cast iron containing 8.5% chromium

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Abstract In this paper, the wear resistance and track of austenite- and martensitic-based white cast iron (AWCI and MWCI) containing 8.5% chromium have been investigated with micro-fricative wear tester, optical microscopy (OM), scanning electron microscopy with EDS (SEM–EDS), and 3D digital microscope. The results show that significant differences exist in the hardness (AWCI: HRC41.2, MWCI: HRC55.8) and impact toughness (AWCI: 28.6 J cm^{-2}, MWCI: 20.3 J cm^{-2}) between as-forged AWCI and forged + heat-treated MWCI samples. At 20 N load, due to AWCIs' low resistance matrices (pearlite and austenite), the wear performance is poor. The depth of the wear track in AWCI sample was 45.479 μm, lower than 70.810 μm in MWCI sample, indicating that the wear performance of AWCI sample was better than that of MWCI at 120 N. Additionally, associating with oxide film and wear debris on the samples' surfaces, the sliding friction coefficient of AWCI increases with load increasing from 20 N to 60 N then decreases with load increasing from 60 N to 120 N, whereas the friction coefficient for MWCI decreases with load in the range of 20–60 N then increases with load increasing from 60 to 120 N.

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Introduction

Ordinary white cast iron (WCI) is well known as brittle metallic material, but it is the most widely used type among the cast iron family due to good castability, wear resistance, machinability, filling mold, high damping capacity, low melting point, and relatively low cost [1]. It has also been reported that alloying [2–5] is an effective way to further improve the performance of WCI. Addition of Cr [6–10] can significantly increase the hardness and toughness meanwhile improves the wear performance of WCI. The amount of Cr in medium Cr WCI is usually in the range from 5% to 10%, where the eutectic carbide [11] are mainly $(Cr, Fe)_7C_3$ and $(Fe, Cr)_3C$, resulting in high exceptional abrasive and erosive wear resistance [12]. Medium Cr WCI has become an important component in wear-resistant applications.

Both austenitic- (AWCI) and martensitic-white cast iron (MWCI) are superior to pearlitic WCI [13] on anti-abrasive wear resistance [14, 15]. There are several reports studying the effect of the matrix phase on the abrasive wear resistance of Cr-containing WCIs. It was thought that for hard abrasive application, a mostly austenitic matrix is preferable [15], while a mostly martensitic matrix containing a little retained austenite performs better under soft abrasive conditions [16]. On the lower impact load, it has a more logical reason for electing MWCI to resist wear resistance in scoring. While enduring the greater of the impact and the severe anamorphic load on wear resistance, and in order to resist erosion wear resistance, it can be more appropriate for the work-piece to use with high toughness and high fracture toughness of work-hardened AWCI [17, 18]. In order to cancel the heat treatment thus to economize energy and improve production, research [19] has been done to replace the heat-treated MWCI by the as-forged AWCI.

Presently, only a few researches and applications on medium chromium WCI were performed. The present work mainly aims at the wear resistance of the AWCI and MWCI of 8.5% Cr under different loads.

Experimental procedure

Pig iron, scrap steel, ferromanganese, ferrochrome, and ferrosilicon were used as raw materials. The nominal composition of the experimental alloy is listed in Table 1. The alloy was melted in a medium frequency induction furnace. And the weighted raw materials were put into the furnace then heated to 1450–1500 °C. When all materials were completely melted, pearlstone was used to cover the melt slag. After molten was pushed aside, and stewing, a special modifier was added into it using pressed bell. After about 10 min of heat preservation, the melt was cast into a 120 mm × 120 mm × 160 mm Ingot. Then, the ingot was cut into 75 mm × 50 mm × 50 mm blocks. Subsequently, the blocks were multi-directionally forged to a 10% reduction of each face at 1050 °C, and the forged blocks were cut into 25 mm × 25 mm × 15 mm testing samples. Then, part of the testing samples were heat treated to form MWCI according to the treatment process shown in Fig. 1

Table 1 Chemical constitution

C	Cr	Si	Mn	S	P	Ti
2.37	8.5	0.55	0.7	0.011	0.032	0.06

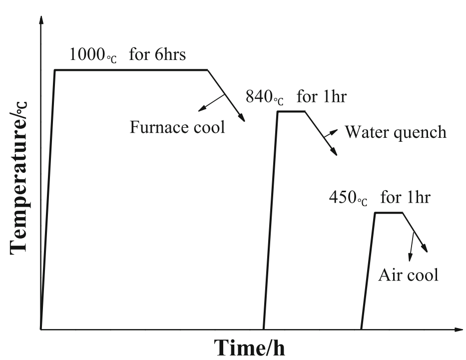

Fig. 1 Heat treatment cycle curves of MWCI samples

A multi-functional micro-fricative wear tester (CETR UMT-3) was adopted to perform reciprocating sliding test. The subjacent samples were as-forged AWCI and heat-treated MWCI, whose sizes were 25 mm × 25 mm × 15 mm. The upper sample is chromium steel ball (HRC62) of ∅9.5, and its reciprocating frequency was 2 Hz and the distance of running was 20 mm per second, then, respectively, loading with 20, 40, 60, 80, and 120 N. After such testing, the wear track volume in each test sample was measured and the surface topography was observed with a 3D digital microscope (KH-7700). NEOPHOT-21 OM and QUANTA 200 SEM (EDS) were adopted to observe the morphology of the wear track and the oxide layer's.

Results and discussion

Microstructure and mechanical property

Metallographic microstructure of AWCI and MWCI samples after hot deformation are, respectively, shown in Fig. 2. Particulate-type of carbides were distributed dispersedly in the matrix, and such microstructure characteristic has been reported [20–22]. In Fig. 2a, the AWCI sample was composed of austenite, $(Fe,Cr)_7C_3$ (like chrysanthemum and spotted state) and a small quantity of pearlite. Figure 2b shows that MWCI sample consists martensite, $(Fe,Cr)_7C_3$ carbide (like chrysanthemum and spotted state) and quite small quantity of retained austenite.

Table 2 lists the mechanical properties of hot forged AWCI and MWCI. The average hardness of AWCI sample was HRC41.2 with its average impact toughness 28.6 J cm^{-2}, in comparison with the corresponding values of MWCI, HRC55.8 and 20.3 J cm^{-2}. According to

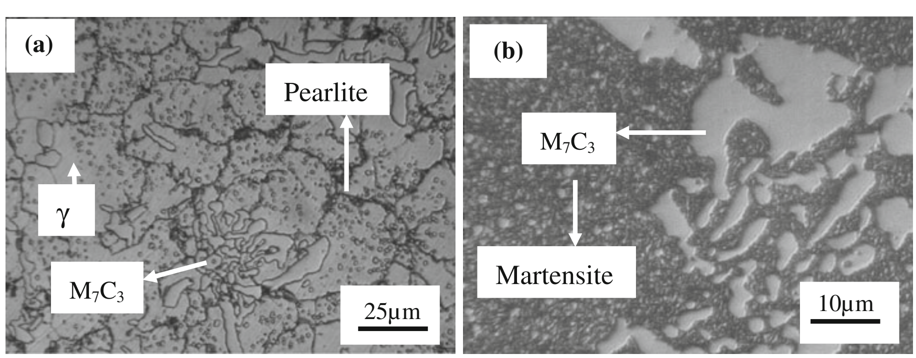

Fig. 2 As-forged microstructure 8.5% chromium white cast iron (**a** AWCI, **b** heat-treated MWCI)

Table 2 Hardness and impact toughness properties of AWCI- and MWCI samples

Sample name	Average hardness (HRC)	Average impact toughness (J cm^{-2})
As-forged: 8.5% Cr AWCI	41.2	28.6
After heat treatment: 8.5% Cr MWCI	55.8	20.3

literature [20–22], hot deformation might increase the impact toughness of WCI.

It is well accepted that the martensitic matrix in MWCI gives higher hardness and lower toughness compared with austenite in AWCI sample. In addition, dispersed carbide can result in higher hardness. So, it is reasonably estimated [23] that both AWCI and MWCI sample should show better abrasion wear resistance than its casting state. This will be further analyzed in "Wear response" and "Wear resistance performance" sections.

Wear response

Figure 3 illustrates the friction coefficients for AWCI and MWCI samples under different loads. Clearly, when under the load of 20 N, the friction coefficient of AWCI fluctuated relatively large in the whole process and the similar case also happens to MWCI sample during the fore 300 s. Under higher load (>20 N), friction coefficient increases to a steady value after about 100 s sliding.

Relationship between the friction and load for the two kinds of samples is described in Fig. 4. For AWCI, friction coefficient generally increases with load increasing from 20 N to 60 N, then decreases with load increasing further to 120 N. On the contrary, friction for MWCI generally decreases first with load increasing from 20 N to 60 N and then increases with load increasing to 120 N.

Generally to say, although flat surfaces of solid blocks contact each other, a large number of junctions may be formed between the surfaces [24]. In light of this, the

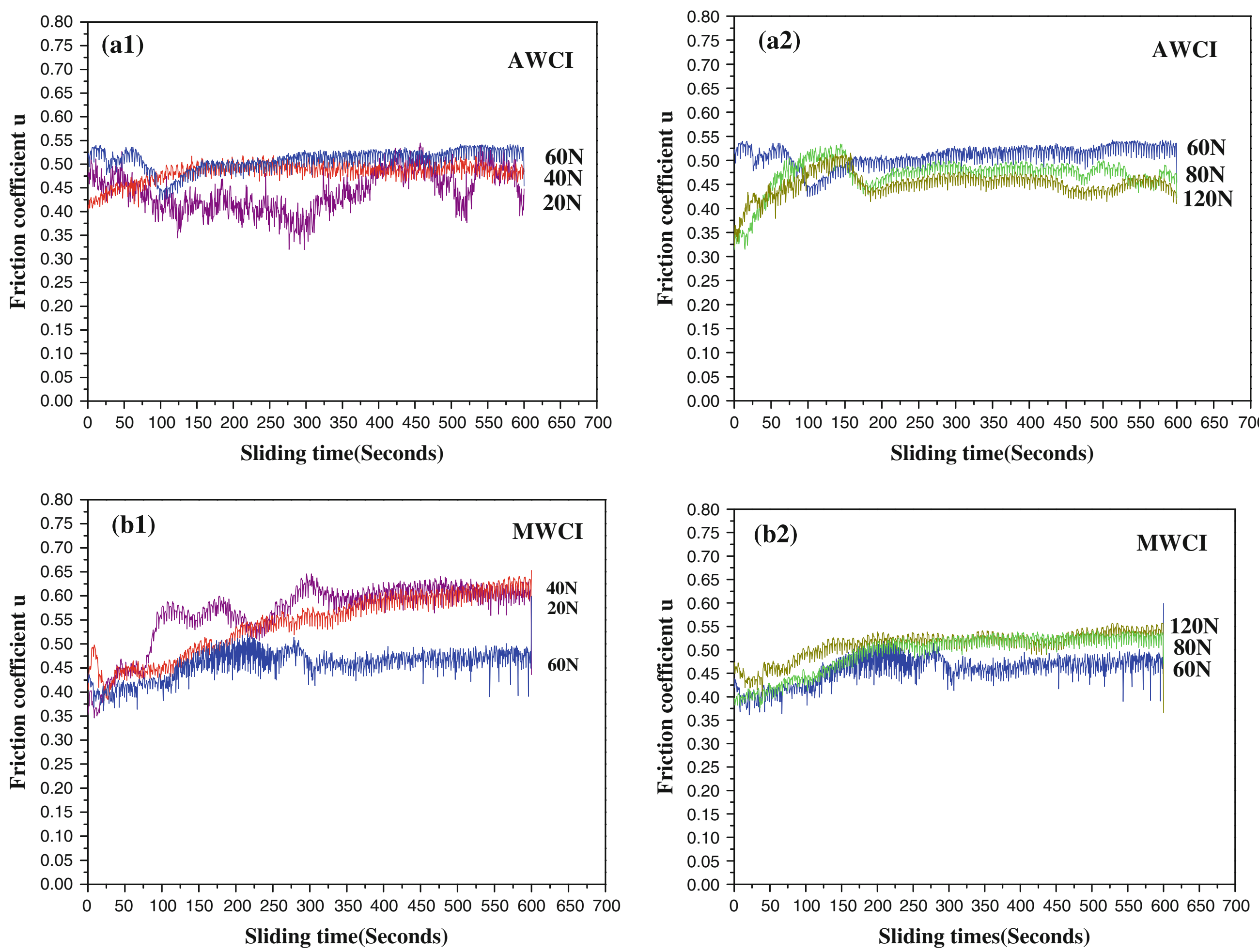

Fig. 3 Friction coefficient curves under different loads changing with time of AWCI (**a1**, **a2**) and MWCI (**b1**, **b2**) samples (**a1** from 20 to 60 N, **a2** from 60 to 120 N; **b1** from 20 to 60 N, **b2** from 60 to 120 N)

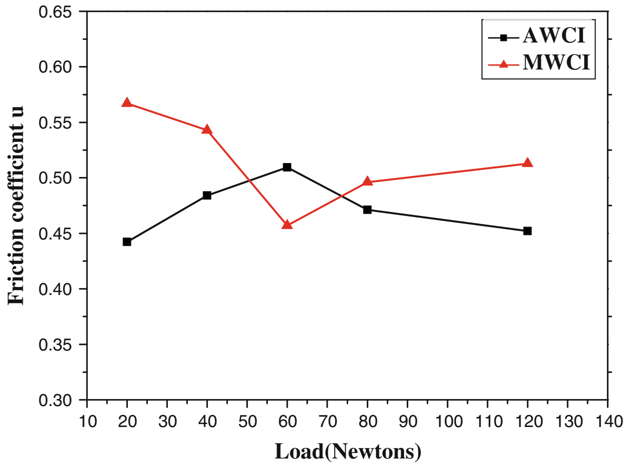

Fig. 4 Relationship between the average friction coefficient and the different loads (from 20 N to 120 N) of AWCI- and MWCI samples

relationship between the wear and friction coefficient for the contact surface in a sliding test can be classified into several cases [25]. Due to a large number of junctions in the samples' surfaces, even if the sliding surface has broken the junctions, new junctions will form immediately. Most of the wear products will move to opposite surface without falling off. And, the friction coefficient increases because the debris from worn surface becomes more and more that works as a hindrance, where the increased friction coefficient is shown in Fig. 3a1, b2. However, the temperature of the surfaces will ascend when lots of junctions slide on the other junctions, so the wear products will be oxidized quickly. And the quantity of oxide became more and more in the samples' surfaces. Then, the friction coefficient decreases by the high lubricity of the oxide, where the decreased friction coefficient is shown in Fig. 3a2, b1. So, the influence of oxides and debris is a dominant factor about the wear micromechanism in this sliding test. When AWCI and MWCI samples were, respectively, sliding with chrome steel ball, microploughing occurs where the chrome steel ball particle impacts the carbides. Then, the debris accumulated in the sample's surface. Not only the debris but also their surfaces became smoother and the oxide coverage became thicker to 2–3 µm, avoiding metal/metal contact. So, the additional proportion of milder oxidative wear replaces metallic wear.

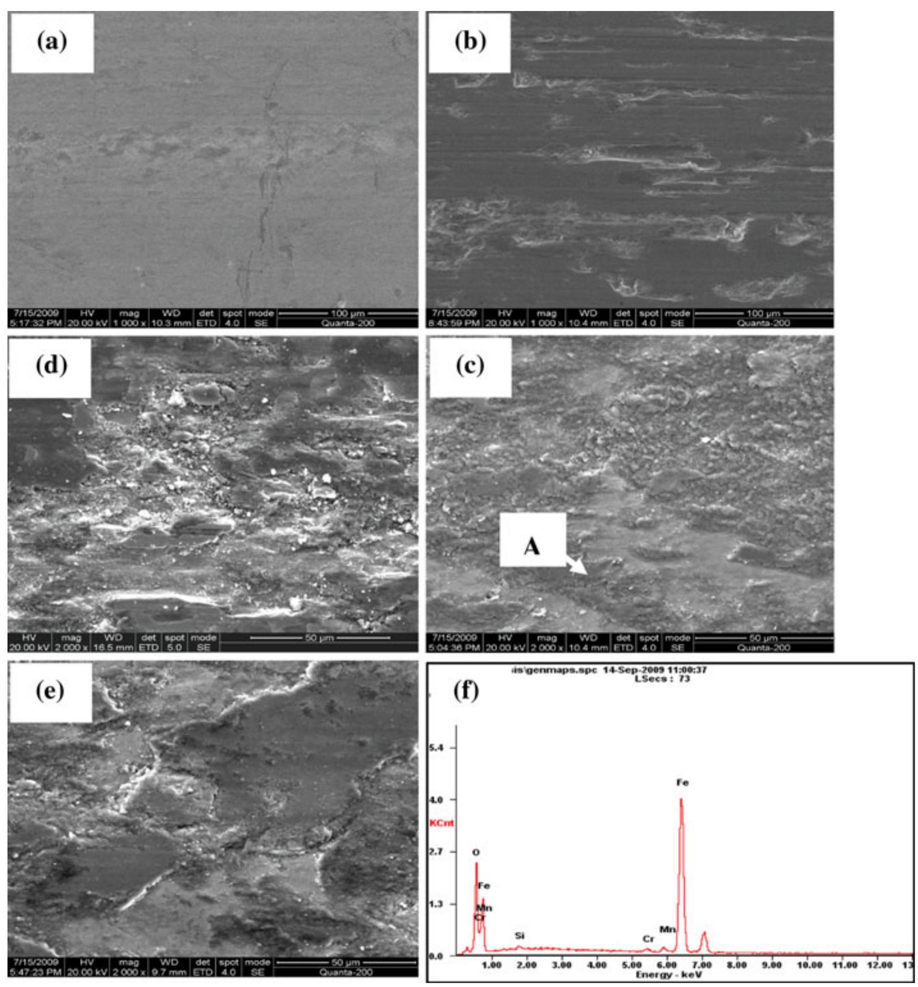

Fig. 5 Worn surfaces of the AWCI samples tested in: **a** 20 N, **b** 40 N, **c** 60 N, **d** 80 N, **e** 120 N, **f** energy spectrum of the dot-shaped A in **c**, indicating the oxides in the surface

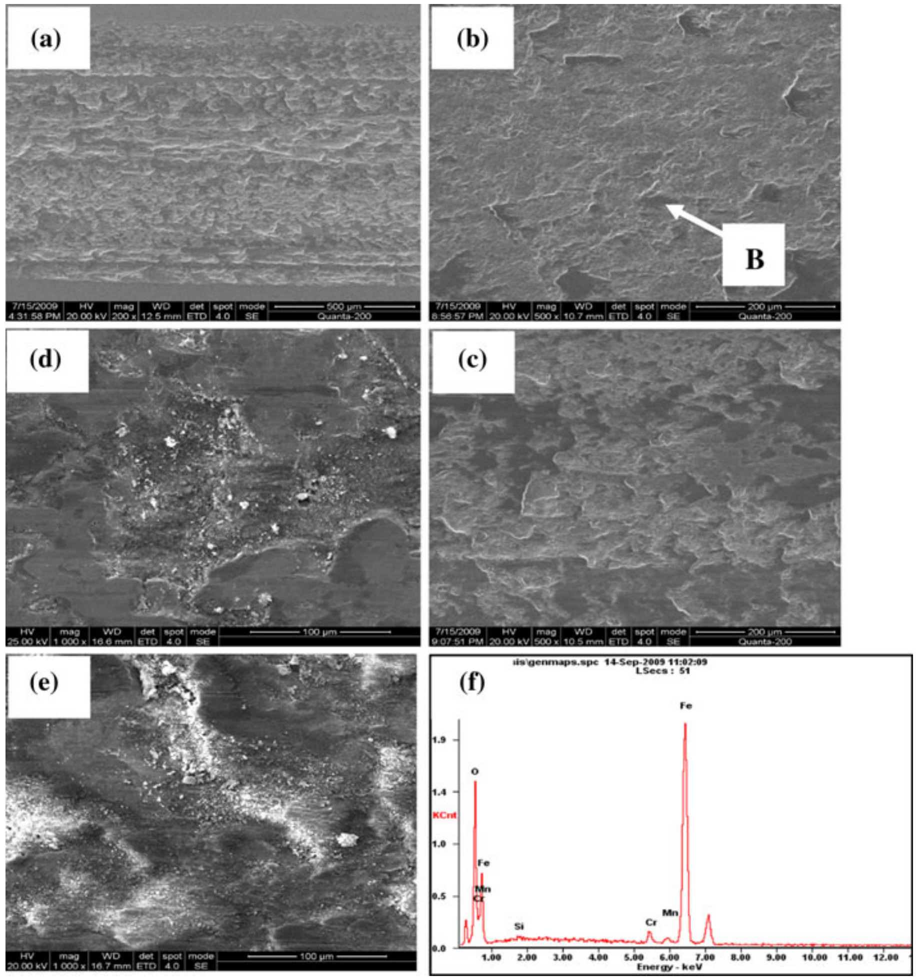

Fig. 6 Worn surfaces of the MWCI samples tested in: **a** 20 N, **b** 40 N, **c** 60 N, **d** 80 N, **e** 120 N, **f** energy spectrum of dot-shaped B in **c**, indicating oxides in the surface

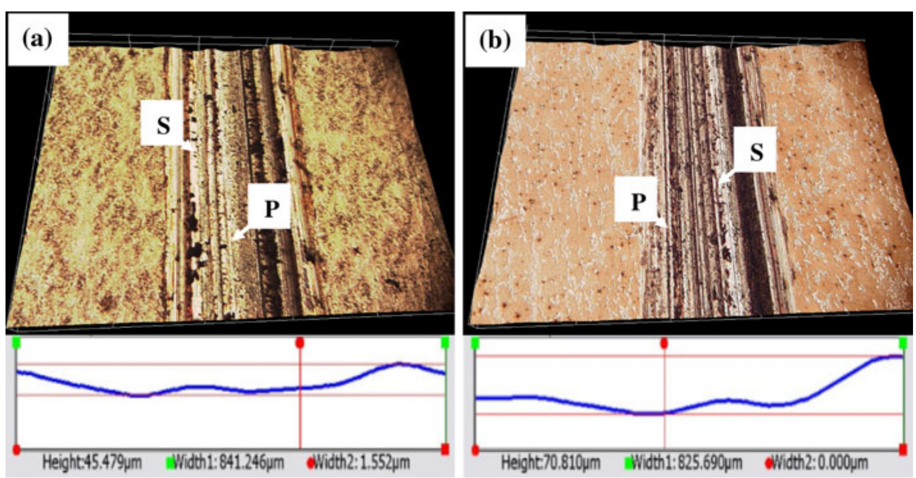

Fig. 7 3D images showing the surface topography of a portion of wear tracks at 120 N load: **a** AWCI, **b** MWCI. For both pictures it can be observed that the major micromechanisms of wear are: microploughing (P) and squeeze (S)

Therefore, the friction coefficient would be decreased attributing to a thicker oxide film and increased resulting in the debris.

The worn surfaces of AWCI samples tested after 600 s under various loads were further observed in Fig. 5. At the load of 20 N, there are some scratches and a little debris on the smooth surface (Fig. 5a). And when the load increases to 40 N, more scratches and debris are covered on the surface (Fig. 5b). Then, the surface was dotted with several oxides at 60 N (like point A) in Fig. 5c. Figure 5d shows the worn surface at 80 N that corresponds to the bottom of the wear loss and plenty of oxides on the wear curve. At the load of 120 N, the whole worn surface seemed to be covered by oxide layer (Fig. 5e).

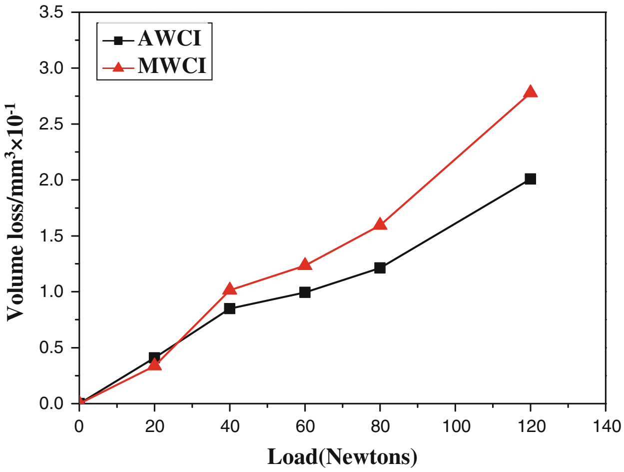

Fig. 8 Wear track volume under different loads of AWCI- and MWCI samples

Wear surfaces of the MWCI samples tested in 600 s under different loads are demonstrated in Fig. 6. As shown in Fig. 6a, plastic deformation appears on the surface tested against the dual of the conventionally chrome steel ball (HRC62.5) at 20 N load. A few oxides were noticed on the wear surfaces (Fig. 6b) when the load was at 40 N and plenty of oxides like B also appeared in the wear surfaces which load of 60 N (Fig. 6c). However, at load of 80 N and 120 N, the worn surface seemed to be covered by debris and oxide layer (Fig. 6d, e).

Wear resistance performance

The 3D surface topographies of the wear track in the AWCI and MWCI samples at 120 N load is further taken as illustrated in Fig. 7. An intense wear in both samples indicated similar wear micromechanisms, namely microploughing and squeeze. Nevertheless, the MWCI sample showed more intense wear. The height of wear track in AWCI sample was 45.479 μm, lower than 70.810 μm in MWCI sample. Obviously, at the load of 120 N, the wear resistance of AWCI sample was better than that of MWCI sample.

By using the 3D digital microscope (e.g. Fig. 7), wear track volumes as a function of different loads for AWCI and MWCI samples under similar test conditions was shown in Fig. 8. At the lower load of 20 N, the wear track volume of MWCI sample was lower than that of AWCI sample. Due to hard abrasive condition [15] of dual chrome steel ball (HRC62.5), the wear track volume obtained with the AWCI sample at a 120 N load was lower than that of the MWCI sample. This means that the wear resistance of AWCI sample is better than that of MWCI sample on a higher load condition. Such view further confirms that the work-hardened AWCI is more appropriate to endure the greater of the impact and the severe anamorphic load on wear resistance.

Figure 9 shows surrounding wear track microstructure of tested MWCI and AWCI samples at 20 N load. In the case of MWCI (Fig. 9a), carbides in the surface did not crack. Recalling to Fig. 8, it is clear that a hard but not too brittle matrix like in MWCI provides the better abrasion resistance under a low load (20 N) abrasion condition, which is in accordance with literature [16]. The matrix greatly affects the wear resistance. This is also closely related to the carbides. The carbides are very hard, but the interactions between chrome steel ball grains and carbides are severe enough to promote the breaking of carbide patterns in the prevailing conditions during sliding wear test. Because the abrasive hardness of chrome steel ball is also much superior to that of samples' matrices, this effect is made possible by the fact that the grains of the steel ball cut away the samples' martensitic matrix easily. Once the matrix is removed, various patterns of carbides are exposed and subsequently broken by interactions with grains or any other element of the samples'. Apparently, in spite of their fragile behavior in usual conditions, the carbides near the surface could be plastically deformed and bent, with the martensitic matrix acting as an anvil for the carbides to support the load. So, the matrix and the carbide were removed all together, and the carbide played a protective role in the matrix [26]. Hence, at the load of 20 N, the wear track volume of MWCI sample was lower than AWCI

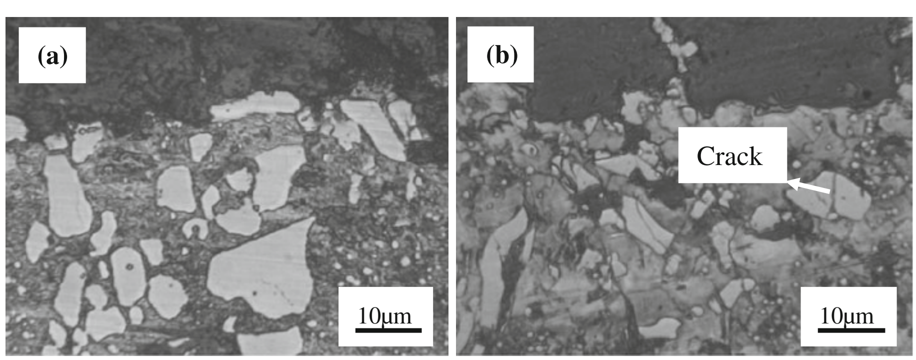

Fig. 9 Surrounding wear track microstructure of tested MWCI- and AWCI samples at 20 N load: **a** martensitic matrix: deformed carbides, without cracking, **b** austenitic matrix: subsurface carbide cracking

sample and the wear resistance of MWCI sample was better than that of AWCI sample.

But in AWCI, cracked carbides were observed in the worn surface, as shown in Fig. 9b. The wear process continually exposed these carbides at the surface, where they were rapidly removed when the load is at 20 N. And it can be explained that the mechanical effort acting on the chrome steel ball can cause the cracking of carbides that are not supported by austenitic matrix (seen in Fig. 2a). And the same behavior was observed in laboratory jaw-crusher tests by Sare and Arnold [27] in literature. Besides the above explanation, the carbide cracking could have been produced by the sample's pearlite microstructure, which could also be explained that pearlitic matrix is less effective in supporting the carbides [14], and there is a little pearlite in AWCI's matrix, yet reducing its wear resistance. Different from the case at 20 N load, the austenitic matrix of AWCI gave the better performance than that of MWCI in the wear tests when the load is at 120 N (Fig. 8). It is further concluded that work-hardened AWCI samples endure the greater impact and severe anamorphic load on wear resistance sliding with hard dual chrome steel ball.

Conclusions

1. There were significant differences in the hardness and impact toughness between AWCI (as-forged) and MWCI (forged + heat-treated). AWCI has lower hardness and higher impact toughness (HRC41.2, $\alpha_K = 28.6\ \mathrm{J\ cm^{-2}}$) when compared with MWCI (HRC55.8, $\alpha_K = 20.3\ \mathrm{J\ cm^{-2}}$).
2. The amount of the wear debris increased with an increase in load in respective range 20–60 N (for AWCI) and 60–120 N (for MWCI) resulted in increased wear coefficient. Otherwise, the wear coefficient decreased with load from 60 N to 120 N (for AWCI) and 20 N to 60 N (for MWCI) associating with a reduction in the metal/metal contact and also a thicker surface oxide film.
3. At 20 N load, AWCI samples showed higher wear track volume than that of MWCI. When a load was greater than 40 N, the wear track volume of AWCI sample was lower than that of MWCI. Especially at 120 N, the wear track depth of AWCI samples was 45.479 μm lower than 70.810 μm of MWCI samples. Finally, the wear performance of AWCI is better than that of MWCI at 120 N load condition.

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