Effect of Impact Energy on the Impact-Wear Properties of High Manganese Steels in Acidic Corrosive Conditions

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The impact abrasion behavior of high manganese steel is investigated under three kinds of impact energy in acid hematite ore slurry by using a modified MLD-10 impact abrasion tester. Through the SEM observation of the worn surface and the optical metallographic analysis of the cross-sectional samples, the corrosive impact abrasion mechanisms of the steel under different impact energies are studied. In acid-hematite slurry, the variations of impact energies would result in synchronous transformation of the impact abrasion properties and mechanisms of the high manganese steel in the corrosive condition, as led different corrosive impact abrasion mechanism under different impact energies.

Keywords *: impact energy; high manganese steel; corrosive impact abrasion; corrosive impact abrasion mechanism*

1. Introduction

High manganese steel, or hadfield steel, is a remarkable engineering alloy which has good ductility and is soft enough when it is fully austenitized. It has an enormous capacity for work-hardening upon impact, and is still commonly used for balling liner.[1)] However it can hardly be considered to be an advanced material, as high manganese steel applied in balling liner used in the wet-grinding machine at metallurgical mines works under severe conditions, it has to bear impact, corrosion and abrasion at the same time, and with insufficient work-hardening and resistance to corrosion, high manganese steel made the lining board have a short lifetime. In recent years, modified medium carbon alloy steel and high chromium cast iron have been researched in recent years in order to replace the high manganese steel.[2)-4)] But the service lives of balling liner made of these two steels have not yielded much improvement compared with high manganese steel. So it is important to figure out the corrosive impact abrasion mechanism of high manganese steel, as is useful to improve its property or develop new materials through this study. In this study, the impact corrosion and abrasion mechanisms of the high manganese steel were investigated under 0.7 J, 1.2 J and 1.7 J three low impact energies. This study is useful to develop better materials for balling liner in the wet-grinding machine at metallurgical mines.

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2. Experimental

2.1 Composition, heat treatment, microstructure and mechanical properties

Chemical composition and mechanical property of the high manganese steel used in this study is shown in Table. 1. It is water-quenched from 1050 ℃, and single-phase austenite is obtained. Impact-toughness (a_k, J×cm^{-2}, it is impact toughness of materials and defined as the sample absorbing impact energy divided by cross section area of the sample) is measured by JB-50 impact toughness tester according to Mesnager unnotched method (sample size is 10 mm × 10 mm × 55 mm). Hardness is determined from the corrosive impact abrasion samples.

2.2 Corrosive impact abrasion tests

Corrosive impact abrasion tester used in this study is rebuilt on the base of MLD-10 impact abrasion test machine (Fig. 1). The size of corrosive impact abrasion sample is 10 mm × 10 × mm × 10 mm, the samples are cleaned in the supersonic wave cleaning machine with acetone before test, and then the samples are fixed on the tester after dried and weighed. Test medium is made of hematite ore and sulfuric acid solution, whose ratio by volume is 3:5,

Table 1. Chemical composition and mechanical properties of high manganese steel

Material	Chemical Composition (wt%)					Mechanical Properties	
	C	Mn	Si	S	P	HB	a_k / J cm^{-2}
High Manganese Steel	1.1~1.3	12~14	0.3~0.8	<0.03	<0.07	220~230	>147

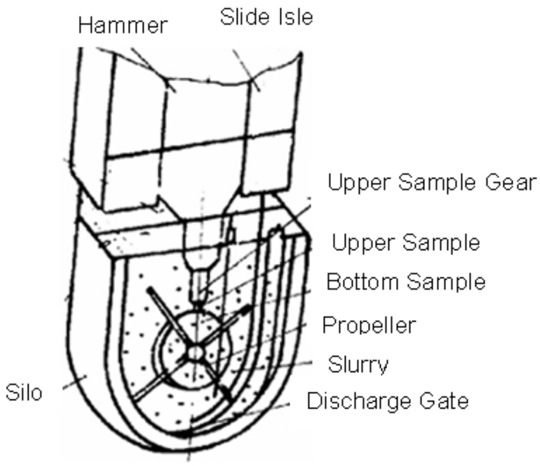


Fig. 1. Modified MLD-10 corrosive impact abrasion test machine.

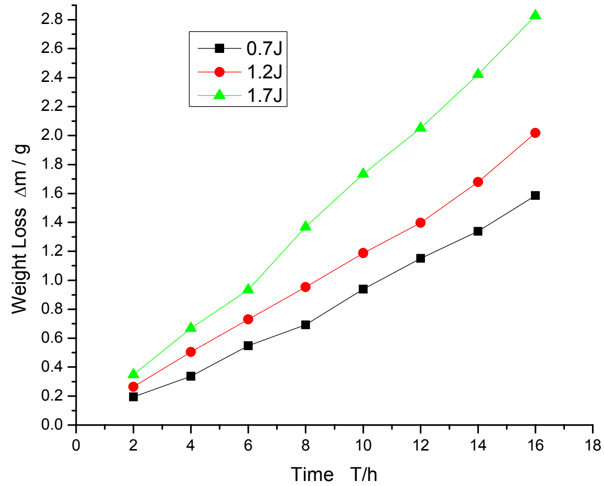


Fig. 2. Weight loss curve at three different impact energies.

and the pH value of the slurry medium is 2.0~2.5. The particle size of the hematite ore is 1 mm ~ 5 mm, and its microhardness is 766 ~ 1097 Hv. In this study, the testing sample were fixed to the impact hammer by the upper sample gear, and the testing high manganese sample moves up and down reiteratively with the impact hammer along the isle onto the rotating bottom standard sample (which is a disk made of GCr15 steel (C 1%, Cr 1.5%)), the ironstone abrasive materials enters between the friction surface under the function of the agitating service. Test impact energy is 0.7J, 1.2J and 1.7J. The high manganese steel sample bears impact corrosion and abrasion continuously and is cleaned every two hours in ultrasonic wave cleaning machine with acetone and then dried and weighed. The weight loss of the sample is measured and then the average value of three different samples is calculated. The worn surfaces were observed through Sirion-200 FEG SEM (Scanning Electron Microscope), and the subsurface cross-sectional microstructures of the samples were analyzed by Olympus optical metallographic microscope, and then the corrosive impact abrasion mechanisms of the steel were discussed as below.

3. Results and discussion

3.1 The corrosive impact abrasion resistance of high manganese steel

The relationship between the weight loss and the wear time of the steel in acid-hematite slurry at three kinds of impact energy is shown as Fig. 2. From the relationship, it can be figured out that for the same test duration, the weight loss of the steel increases along with the increasing of the impact energy, thus it tells us that the impact energy has great effect on the corrosive impact abrasion resistance of the steel. The weight loss curve of the steel is approximately linear under the impact energy of 0.7J, 1.2J and 1.7J. Thus, it should be possible to postulate an abrasion mechanism by more detailed investigation of the microscopic structure. The work-hardening layer is generated in the abrasive surface under the synergistic role of the impact and the abrasive particles (hardness is up to HV_{200}500~600, and the matrix hardness is HV_{200}225 as shown in Fig. 3), as the impact energy increases, the work-hardening also get a synchronous increase. The microstructure of high manganese steel is single-phase austenite whose hardness is lower than that of the ironstone, previous research has proved that the wear lies on the hardness when the ratio of the materials' hardness to the abrasive materials' is less than 0.85,[5] so the wear loss of high manganese steel depends on the micro-plough when the work-hardening is not obvious, with the increasing test time and impact energies, work-hardening will create in the surface of the high manganese steel, which will aggravate the wear. In a brief word, for the poor hardness and relatively good resistance to the corrosion of sin-

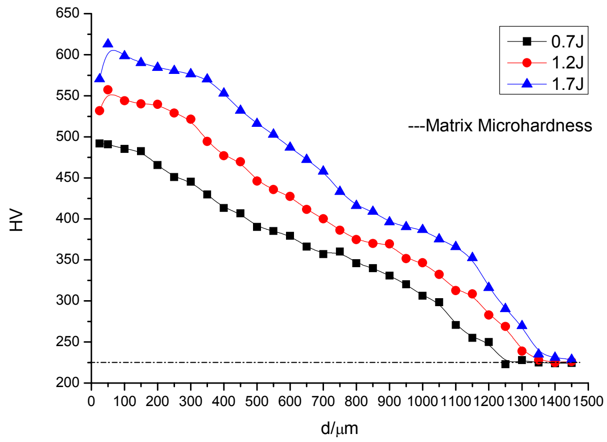


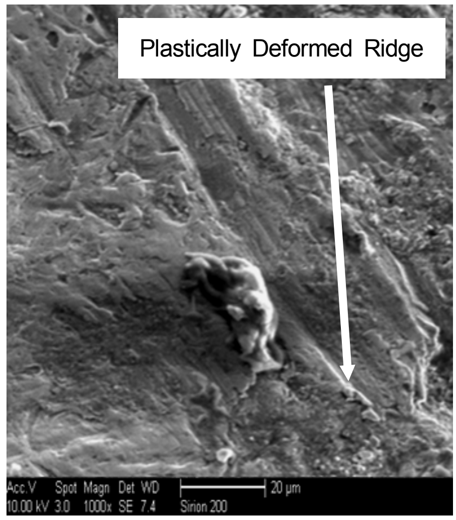
Fig. 3. Microhardness curves at three impact energies after 16h impact abrasion and corrosion.

gle-phase austenite, the resistance to impact corrosion and abrasion of the manganese steel is not good enough for applying in balling mining liner.

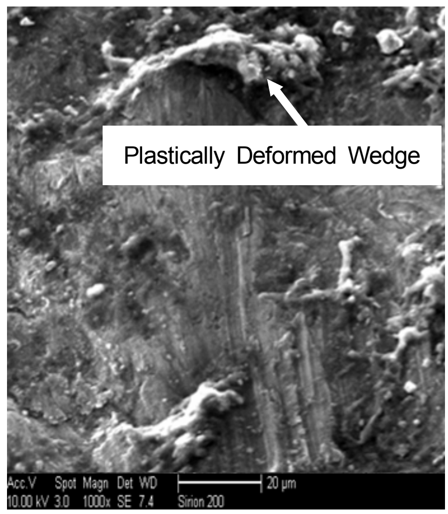
3.2 The corrosive impact abrasion mechanism of high manganese steel at the impact energy of 0.7J

Fig. 4 shows the worn surface of the steel at 0.7J impact energy for 8 hours and 16 hours in acid-hematite slurry. Through Fig. 4 (a), after impact for 8 hours, a deformed furrow could be found on the sample wear surface, and besides there are many salient accumulations beside the furrow. Doubling the impact time to 16 hours, the scale of number and depth of the furrows are larger than that of the 8 hours. Of course, these deformed furrows in the abrasive surface of the high manganese steel also accelerate the process of the corrosion and abrasion. In the 500X surface image of Fig. 4 (c), contribute to the single-phase austenite which enhances the electrode potential of the high manganese steel, only small mounts of etching pits could be found on the surface, which shows the relatively good erosion resistance of high manganese steel in the corrosive environment.

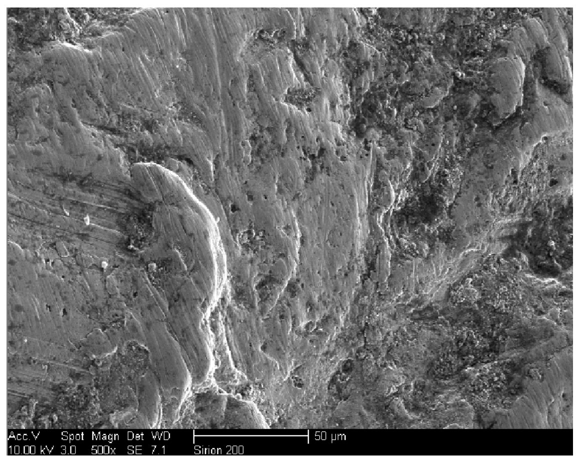
As the high manganese steel is soft enough, the abrasions can be pressed into the surface of the steel through the normal stress, by which the pits formed. At the same time, the abrasions glided along the surface of the steel by the role of the shear stress, and then the furrows formed. Because the toughness of the steel comparatively is high, but the impact energy is low, it didn't form chips while only the micro-plough occurred. When the micro-plough occurred, the materials which were pushed into the sides of the furrows are called plastically deformed ridge, and the materials that were pushed to the frontage of the furrows are called plastically deformed wedge. The ridges



(a) 8h

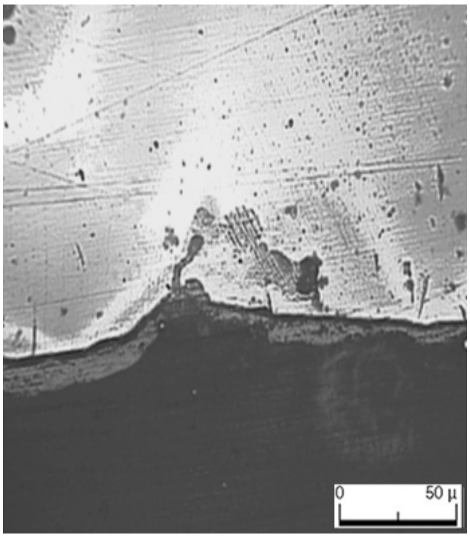


(b) 16h

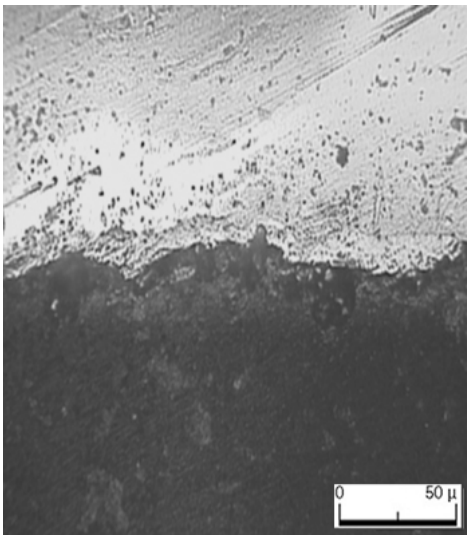


(c) 16h

Fig. 4. The worn surface of high manganese steel after 8h and 16h impact wear at an impact energy of 0.7 J in simulated slurry.



(a) 8h



(b) 16h

Fig. 5. Subsurface microstructures of high manganese steel after 8h and 16h impact wear at an impact energy of 0.7 J in simulated slurry.

and wedges will become salient accumulations when they get repeatedly impact. During subsequent abrasion cycles, these ridges and wedges got repeatedly impacted, or re-shaped again, which led to the work-hardening and other invigoration effect on the worn surfaces. Successive abrasion (grinding away) of the ridges and wedges off the sample is what causes the weight loss.[6] The phenomenon above happened can be considered as the micro-plough mechanism under impact condition.

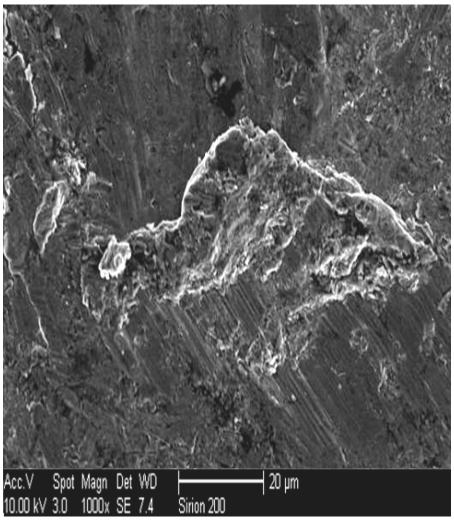
In addition, from the cross-sectional view of the worn subsurface (Fig. 5), the number of etching pits found in 8 hours was so small, which coincided with the surface morphology, as reflects that the high manganese steel have relatively good anti-erosion performance. From Fig. 5, the worn surface looks like flat with some extruded wedge as the low impact energy. In this condition, the worn surface didn't get severe damaged, and the high manganese steel had the best performance under the role of the low 0.7J impact energy.

3.3 The corrosive impact abrasion mechanism of high manganese steel at the impact energy of 1.2J

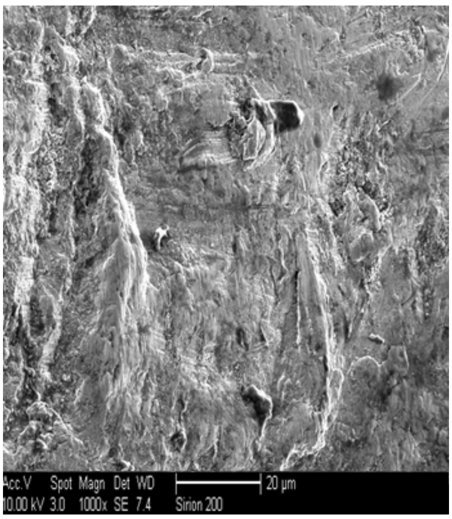
The worn surfaces of the steel after impact wear for 8 and 16 hours at the impact energy of 1.2J in simulated slurry are shown in Fig. 6. Extruded wedges can still be found in both images. As the impact energy increased, the resisting force that the particles glided along with the worn surface of the high manganese also increased, as a result, micro-plough morphology got much heavier. In Fig. 6b, there are some massive accumulations left on the surface, which might be the reason why the wear weight loss increased.

The small wedges were easily pushed forward by the function of micro-plough at higher impact energy. As it is a periodic impact, once the impact halt, the pushing also halt. After long times of repeated impact and pushing, the small wedges gradually accumulated as the large wedges. In Fig. 6a, a small wedge is just about to accumulate to the large wedge could be found. The process is consisting of the formation, prolongation and accumulation of the small wedges. And finally the whole large wedge spalling off the surface will cause the increasing of wear loss. Also in Fig. 7a, a coronal is observed which might be the cross section of the large wedge.

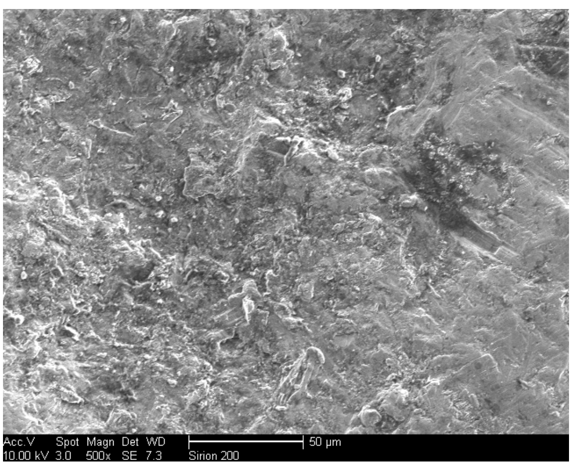
As the function of cyclic normal stress, it inevitably led to the deformation of the crystal lattice and the increased density of the dislocation, the micro cracks were easily to be generated at the interface between the hardened area and the unhardened area, and namely the low-cycle fatigue break occurred.[7] Compared with the cross section microhardness test (Fig. 3), the highest microhardness point of 1.2J appeared at about 50 μm from the surface, which accord with the banding spalling width. From Fig. 7b the superficial cracks occurs, which are parallel to the surface of the high manganese steel. The micro cracks initiated at the defects (normally the voids, dislocations) of the high manganese steel by the impact effect, and then prolonged along the hardened area and the unhardened area which has the lowest resistance pressures, and finally accumulated as obvious cracks, and the hardened materials up the cracks would easily spall off the impact worn surfaces. After the material spalled away from the worn surfaces, the new materials would be exposed in the acid



(a) 8h

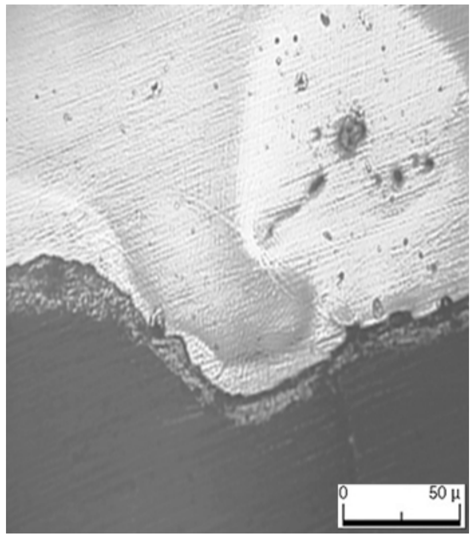


(b) 16h

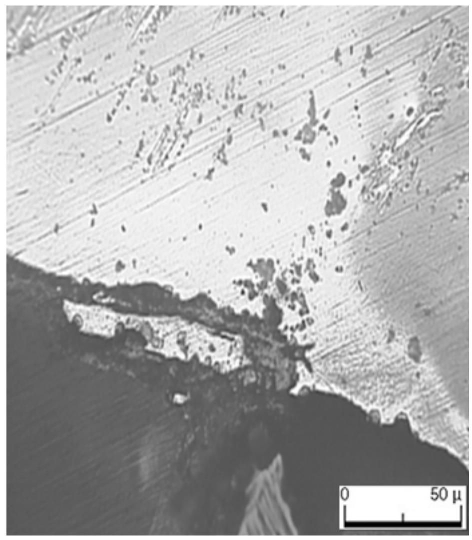


(c) 16h

Fig. 6. The worn surface of high manganese steel after 8h and 16h impact wear at an impact energy of 1.2 J in simulated slurry.



(a) 8h



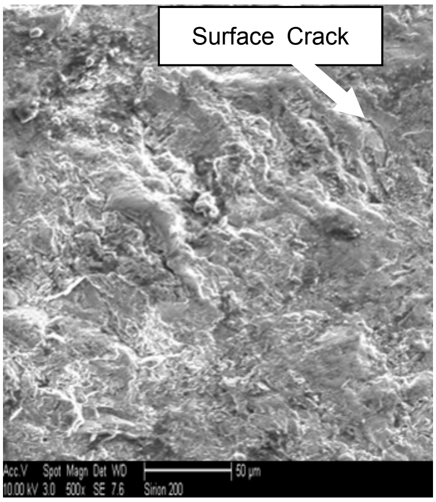
(b) 16h

Fig. 7. Subsurface microstructures of high manganese steel after 8h and 16h impact wear at an impact energy of 1.2 J in simulated slurry.

slurry, which got server corrosion, and the new cracks and spalling would form again. Under the role of impact stress, the work-hardening layer can be formed in the surface of the high manganese steel again and slowly spall after a time of impact corrosion and abrasion. This cycle process of the work-hardening layer's formation and spalling is the impact corrosion and abrasion fail process under the impact energy of 1.2 J.

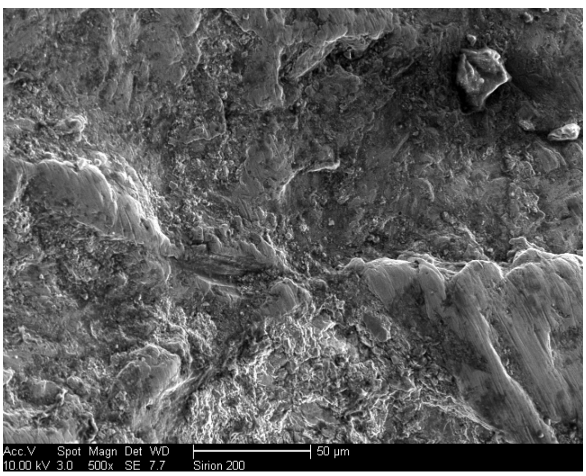
3.4 The corrosive impact abrasion mechanism of high manganese steel at the impact energy of 1.7J

The worn surface of the steel impacted for 8 and 16



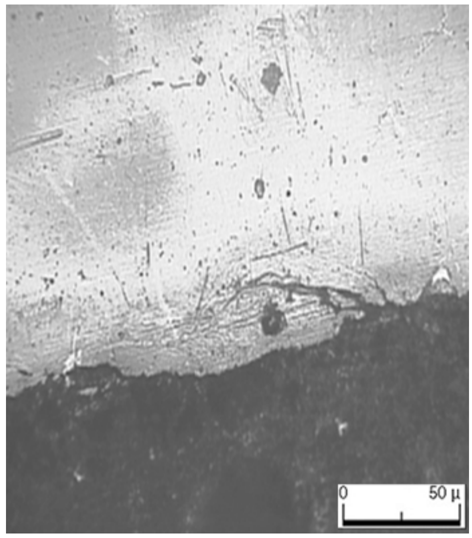
(a) 8h

(b) 16h

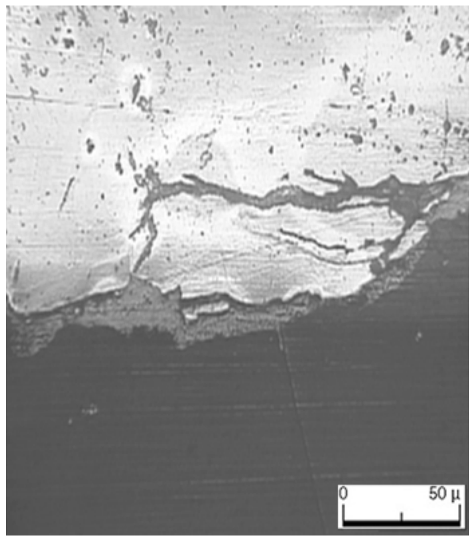


(c) 16h

Fig. 8. The worn surface of high manganese steel after 8h and 16h impact wear at an impact energy of 1.7 J in simulated slurry.



(a) 8h



(b) 16h

Fig. 9. Subsurface microstructures of high manganese steel after 8h and 16h impact wear at an impact energy of 1.7 J in simulated slurry.

hours at 1.7J impact energy are shown in Fig. 8. Extruded wedges and cracks can still be observed on the worn surface in Fig. 8a. These extruded wedges are still the same result of micro-plough mechanism. Although the surface got work hardened, the micro-plough mechanism is still working effectively.

Cracks along the surface can be observed in Fig. 9. According to the delamination theory[8)] and fretting fatigue mechanism,[9)] the wear loss is the process of nucleation and propagation of the microcracks. From Fig. 9a to 9b, it can be seen that the microcracks initiated at the worn surface and then propagated into the subsurface. As the high impact energy of 1.7J, the hardened layer becomes thicker and harder than those of lower impact energy (Fig. 3), which enhance the brittleness of impact surface materials. These brittle areas impacted onto the hard iron stone particles, the microcracks would easily initiate. Due to the exit of the 1.7J high impact load and shearing stress of the iron stone particles, those surface microcracks then extended to the subsurface with the angle about 30~45° until the interface between the hardened area and unhardened area. As the highly tough single-austenite substrate, the expansion of the cracks were stopped, thus they had to change the directions under the effects of impact wear onto the worn surface. When the microcracks reached the surface, the materials between the microcracks and surfaces would form the massive spalling and then spalled away. And the width of work hardened layer is about 60 μm (Fig. 3), which accord with the width of the massive spalling in Fig. 9b. So under this impact energy, it is sure that the fretting fatigue crack mechanism is working. And at the same time, the corrosion medium infiltrated into these cracks, which also accelerated the corrosion and spalling of the materials.[10)-11)] Besides, some micro-crush microstructure could be observed in Fig. 9(b), which should be the residuals of layer delamination.

Comparing Fig. 4 (c), Fig. 6 (c) and Fig. 8(c), as the impact energy increases from 0.7 J to 1.2 J and 1.7 J, the surface morphology become more and more corrugated. Thus the impact wear mechanism also changes under different impact energies. When it is at 0.7 J, the impact energy is low enough not to create spallings, only micro-plough could the energy generate. While the impact energy increase to 1.2 J, the large wedges produced by higher energy micro-plough would then spall off the surfaces under the impact of the hammer and the wear of the hematite particles, thus the impact wear mechanism alters to low cycle fatigue spalling. Finally when the impact energy reaches 1.7 J, it is easy to create microcracks on worn surface of work-hardening layers, and then the nucleation and prolongation of these microcracks under high impact energy would result in fretting fatigue delamination.

As shown above, the micro-plough mechanism is at work under all of the all three impact wear conditions. Single-austenite phase has given the high toughness and low hardness to the high manganese steel, without observing any brittle microstructures in the test conditions. Besides the work-hardening effect of the high manganese steel is not enough, it could not overpass the hardness of the hematite particles. So the hematite particles were easily scratched through the worn surfaces by the rotating of bottom disk, to form the micro-plough morphology. These two conditions assist each other, and both are necessities. As the micro-plough mechanism is not the worst weight loss mechanism among those impact wear mechanisms, the high manganese steel still has adequate impact corrosion and abrasion properties, so this kind of steel is still widely used in the balling wet-grinding machines. However there is an increasingly strong cry calling for the new material to replace the high manganese steel in the factory productions. According to the composite-structure-performance rule and this research, the new materials should provide with properties of high hardness and work-hardening effect, good erosion resistance and ductility, in order to work better in this severe impact wear acidic slurry condition.

4. Conclusions

1) Under different impact energies, the wear loss of the high manganese steel increases along with the increasing of the impact energies, and the impact energy has significant effect on the corrosive impact abrasion properties of the steel.

2) In the condition of impact corrosion and abrasion, the performance of the high manganese alloy steel has a corresponding relationship with its single-austenite phase of high toughness and suitable resistance to corrosion, but lack of work-hardening is the default of this steel.

3) In acid-hematite slurry, under all three test impact energies, the corrosive impact abrasion mechanism of the steel is always accompanied with the micro-plough, which is the dominate wear mechanism while under 0.7J impact energy; when the impact energy is up to 1.2J, the impact wear mechanism expands to the low cycle fatigue fracture; while the impact energy reaches 1.7J, the mechanism alternates to the fretting fatigue delamination mechanism.

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References

1. R. W. Smith, A. DeMonte, and W. B. F. Mackay, *J. Mater. Proc. Tech.*, **153**, 589 (2004).
2. C. H. Pan, *Mater. Mech. Eng.*, **25**, 32 (2001).
3. Y. T. Chen, B. Z. Bai, and H. S. Fang, *J. Iron Steel Res.*, **13**, 40 (2001).
4. Z. L. Lv, Y. S. Deng, and Q. C. Rao, *Mater. Mech. Eng.*, **25**, 32 (2001).

5. J. L. Basse and B. Premaratne, *Proc. Int. Conf. on Wear of Materials*, Ed, by Ludema KC, **161-6**, ASME, 1983
6. H. Meyer, *J. Wear*, **66**, 379 (1981).
7. Y. X. Zhao, Q. Gao, and J. N. Wang, *Fat. Frac. Eng. Mater. Struc*., **22**, 469 (1999).
8. P. S. Nam, *Wear*, **44**, 1 (1977).
9. M. P. Szolwinski and T. N. Farris, *Wear*, **198**, 93 (1996).
10. X. X. Jiang, S. Z. Li, and S. Li. Corr. Wear Met. p. 220, *Chem. Ind*,. Press, Beijing (2003).
11. T. W. Chenje, D. J. Simbi, and E. Navara. *Min. Eng*., **16**, 619 (2003).