CORROSION SCIENCE AND TECHNOLOGY, Vol.31, No.1(2002), pp.41~47

Damage Mechanisms and Metallic Materials Development in Multiphase Flow

Yugui Zheng, Wei Liu, Zhiming Yao, and Wei Ke

State Key Laboratory for Corrosion and Protection, Institute of Metal Research, Chinese Academy of Sciences
62 Wencui Road, 110016, Shenyang, P. R. China

The investigation on the synergistic effects among corrosion, slurry erosion and cavitation erosion has special significance for hydraulic turbines operated in Yangtze River and Yellow River where the high concentration solid particles exist in water. Two typical metallic materials i.e. Cr-Mn-N stainless steel and Ni-Ti shape-memory-alloy, and two typical materials used for hydraulic turbines 20SiMn and 0Cr13Ni5Mo as compared materials were selected in order to investigate the roles of work-hardening ability and martensitic transformation as well as pseudoelastics in damage mechanism in multiphase flow. Both modified rotating disk rig and ultrasonic vibration facility were used to simulate the possible damage mechanism of materials in multiphase flow. The effects of corrosion on cavitation erosion were investigated through adding 3wt% NaCl. The degradation mechanism was analyzed by electrochemical test, SEM observation, hardness and roughness measurement. The results showed that there was a strong synergistic interaction among electrochemical corrosion, slurry erosion and cavitation erosion for 20SiMn in liquid-solid two-phase medium. In contrast, corrosion played little role for 0Cr13Ni5Mo. Cr-Mn-N stainless steel with high Mn content showed better resistance to cavitation erosion and slurry erosion than 0Cr13Ni5Mo, which was mainly due to its good work-hardening ability as well as strain-induced martensite transformation. The cavitation micro-cracks for Cr-Mn-N stainless steel were parallel to the specimen surface in contrast with 0Cr13Ni5Mo whose micro-cracks were perpendicular to the surface. Ni-Ti alloy with pseudoelasticity showed excellent resistance to combined interaction of cavitation erosion and slurry erosion.

Keywords *: Cavitation erosion, Slurry erosion, Corrosion, Hydraulic turbine, Material development*

1. Introduction

Due to the severe soil erosion problems in China, many rivers such as the Yellow River and Yangtze River contain high concentration sand (up to 700kg/m^3 during the raining season). This causes a big problem for flow-handling components of hydraulic turbines and pumps, which suffer the combined damage of erosive wear, cavitation erosion and corrosion. Hydropower stations operated in these rivers have to be shut down frequently for damaged components to be repaired. Although there have been many efforts to combat against this long-term problem, the present techniques are far from satisfaction. These efforts can be classified into the following three categories: optimizing design of the flow-handling components to reduce cavitation erosion and/or erosive wear, establishing sand-block facilities to reduce erosive wear, screening and selecting better materials and coatings to resist the combined action.[1-8] The fundamental research on the damage mechanisms and metallic materials development in multiphase flow is very important for the construction of huge hydropower stations such as "Three-Gorge Project".

For materials development under above conditions, not only the single roles of erosive wear, cavitation erosion and corrosion, but also the possible synergistic effects among them must be understood. Erosive wear resulted from the slurry impingement causes the material removal in microcutting or deformation-induced-cracking and the material hardness is a dominant factor to be generally considered. Although it is not always true, the materials with high hardness (e.g. Ni-hard 4 and high chromium cast iron) often have better erosive wear resistance in non-aggressive medium. Therefore, various hardfacing techniques to intensify the materials have been used, such as nitriding, boronizing, weld overlay WC/Co, flame or plasma spraying NiCrBSi self-fluxing alloys with or without laser remelting. In addition, the stacking fault energy, work-hardening rate and martensitic transformation also play important roles for erosive wear resistance of materials. Cavitation erosion is caused by the growth and collapse of vapour cavities or bubbles due to local pressure fluctuation in a liquid.[9] This implosion may produce a pressure up to 1000MPa. So, how to absorb and dissipate the impact energy is key to the developing cavitation erosion resistant materials. Boronised martensitic chromium-nickel stainless steel (13Cr-4Ni) aiming at improving hardness was found to have poor resistance to cavitation erosion resistance because of its high brittleness and drastic reduction in elongation and strain-energy.[3] Recently, pseudoelastic Ni-Ti alloys with relative low hardness but high work-hardening rate, which deform primarily by the formation and reversion of stress-induced martensite, has been found to have very good resistance to slurry and water jet erosion, cavitation erosion and other kinds of wear.[10-14] Furthermore, a few attempts into practical application of Ni-Ti alloys by using explosive welding, cathodic arc plasma ion plating, laser plasma hybrid spraying and infrared brazing have been done.[15-18] In the literature, relative more researchers investigated the synergism between erosive wear and corrosion[19-20] or cavitation erosion and corrosion,[21] and the synergistic effects between erosive wear and corrosion was highlighted for developing erosion-corrosion resistant materials in aggressive medium.[22] Conversely, there is little reference on the synergism between erosive wear and cavitation erosion as well as the material development. It seems not so simple and reasonable to consider the combined weight loss (W_{C+A}) to be the simple sum of cavitation erosion (W_C) and erosive wear (W_A) modified by two coefficients (A and B) i.e. $W_{C+A} = AW_C + BW_A$ proposed by Zhao et al.[2] The above equation is only mathematical fitting result without physical significance. In this paper, the possible synergistic damage mechanisms among cavitation erosion, erosive wear and corrosion have been investigated by ultrasonic vibration facility and simulating apparatus - rotating disk rig. The aim is to find a new idea to develop materials for above application.

2. Experimental

In order to investigate the roles of work-hardening ability and martensitic transformation as well as pseudoelastics in damage mechanism in multiphase flow, two typical materials i.e. Cr-Mn-N steel and near-equiatomic Ni-Ti alloy ($Ni_{50.6}Ti$) were selected. Two kinds of materials commonly used for hydroturbines in China i.e. martensitic stainless steel 0Cr13Ni5Mo and ferritic and pearlitic low alloy steel 20SiMn, were also chosen for comparison. Table 1 shows the chemical compositions and hardness of three test steels. Table 2 lists the phase transformation temperatures of $Ni_{50.6}Ti$ alloy measured by differential scanning calorimetry (DSC). At room temperature the matrix of $Ni_{50.6}Ti$ was austenitic β phase with good pseudoelasticity. Both modified rotating disk rig and ultrasonic vibration facility (frequency:20kHz, peak-to-peak vibratory amplitude:60μm) were used to simulate the possible damage mechanism of materials in multiphase flow. The test media for ultrasonic vibration facility and rotating disk rig were distilled water with or without silica sand (3 kg/m^3, 200~300 mesh) and tap water with or without silica sand (0.25 kg/m^3, 200~300 mesh) respectively. The volume of the container for ultrasonic vibration tests was 20 ml in order to make solid particles suspend uniformly. The effects of corrosion on cavitation erosion were investigated through adding 3wt% NaCl. The tests for erosive wear and combined action of cavitation erosion and erosive wear were conducted with rotating disk rig without or with cavitation inducer (cylindrical rod 10mm in diameter and 5mm in height) posited ahead of specimens. The linear rotating speed of specimens was 18m/s.

Table 1. Chemical compositions and hardness of three test

steels	Chemical compositions (wt%)										Hardness (HB)
	C	Cr	Ni	Mo	Mn	Si	P	S	N	Fe	
20SiMn	0.22	-	-	-	1.10	0.64	0.021	0.013	-	Bal.	144
0Cr13Ni5Mo	0.045	12.6	5.6	0.72	0.58	0.31	0.031	0.014	-	Bal.	298
Cr-Mn-N	0.25	17	1.9	1.5	13	1.0	-	-	0.33	Bal.	211

Table 2. Phase transformation temperatures of $Ni_{50.6}Ti$ alloy measured by differential scanning calorimetry (DSC).

Alloy	Heat treatment	M_f (℃)	M_s (℃)	A_s (℃)	A_f (℃)
$Ni_{50.6}Ti$	750℃/30min+400℃/60min	−20	7	10	37

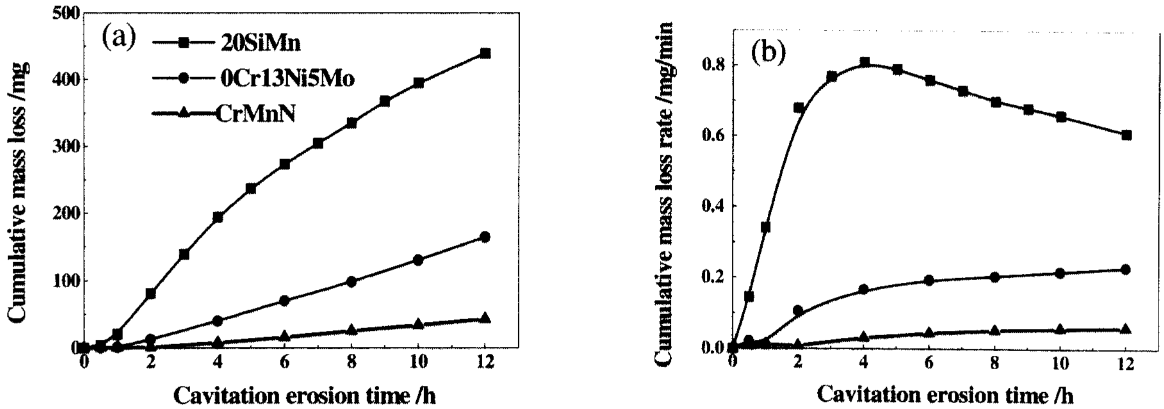

Fig. 1. Cavitation erosion behaviors of 20SiMn, 0Cr13Ni5Mo and Cr-Mn-N in distilled water.

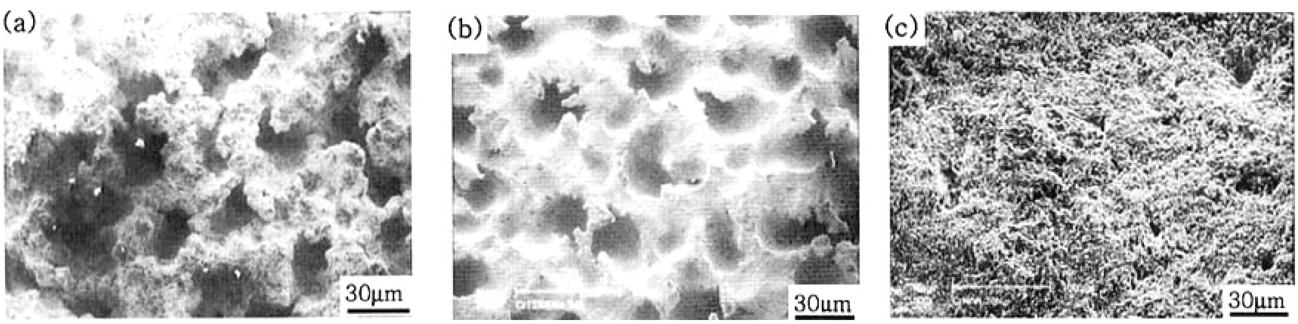

Fig. 2. Cavitation erosion morphologies of20SiMn, 0Cr13- Ni5Mo and Cr-Mn-N in distilled water. (a) 20SiMn (12h) (b) 0Cr13Ni5Mo (34h) (c) Cr-Mn-N (20h)

The degradation mechanism was analyzed by electrochemical test, SEM observation, hardness and roughness measurement.

3. Results And Discussions

3.1 Cavitation Erosion Behaviors in Distilled Water by Ultrasonic Vibration Facility

Figure 1 shows the comparison of cavitation erosion resis- tance of three steels in distilled water. 20SiMn had the worst cavitation erosion resistance and went into the steady state of cavitation erosion after 12-hour test following the incubation period, accumulation or transition period and attenuation period. In contrast, Cr-Mn-N and 0Cr13Ni5Mo steels had much better cavitation erosion resistance and were just in the accumulation or transition period (figure 1 b). The incubation period of Cr-Mn-N stainless steel was longer than that of 0Cr13Ni5Mo. The excellent cavitation erosion resistance of Cr-Mn-N steel could be explained by morphology observation, roughness measurement, cavitation crack propagation, and work-hardening ability. After relative short test time, deep cavities appeared on the specimen surfaces of 20SiMn, and 0Cr13Ni5Mo showed the similar morphologies after long test time. Conversely, there were almost no any deep cavities, and only very smooth appearance on Cr-Mn-N specimen surface (figure 2). This was in accordance with the roughness measurements, which showed that the surface roughness after 3-hour cavitation erosion test was 7.90μm, 2.95μm and 2.28μm for 20SiMn, 0Cr13Ni5Mo and Cr-Mn-N respectively. The cross-section views (figure 3) showed that the cavitation cracks propagated perpendicular to the specimen surface of 0Cr13Ni5Mo which caused more damage, but parallel to the specimen surface of Cr-Mn-N. Although the hardness of Cr-Mn-N was lower than that of 0Cr13Ni5Mo, the good work-hardening ability (figure 4) with relative soft matrix and strain-induced martensitic transformation[5,23] attributed its better ability to absorb and dissipate the impact energy. The favorite crack propagation along the surface was the additional reason for its good cavitation erosion resistance.

3.2 Effects of Solid Particles and Corrosion on Cavitation Erosion by Ultrasonic Vibration Facility

figure 5 shows the effects of solid particles and corrosion on the cavitation erosion of 20SiMn and 0Cr13Ni5Mo.

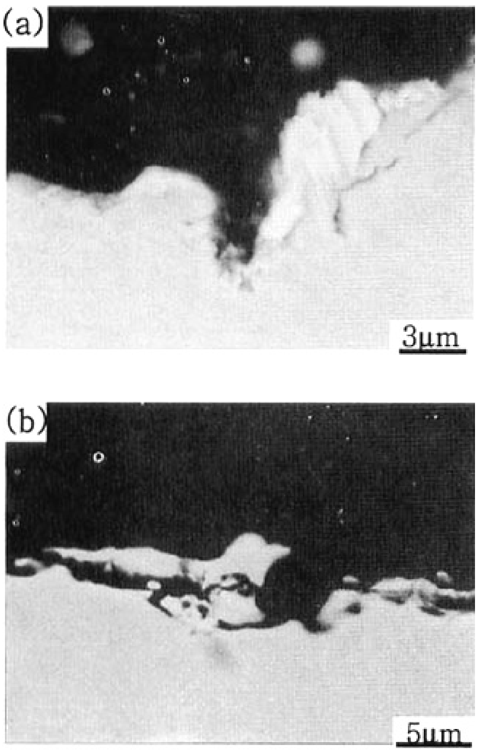

Fig. 3. Cross-section view of cavitation erosion specimen of 0Cr13Ni5Mo and Cr-Mn-N in distilled water. (a) 0Cr13Ni5Mo (3h) (b) Cr-Mn-N (9h)

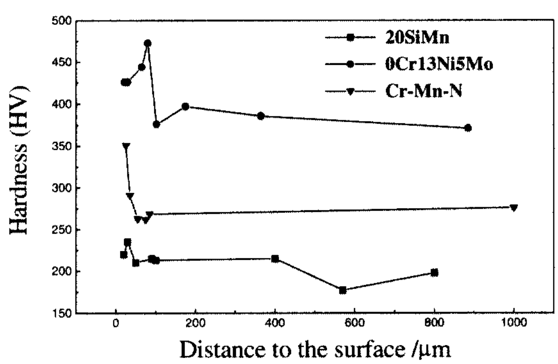

Fig. 4. Hardness of 20SiMn, 0Cr13Ni5Mo and Cr-Mn-N after 3-hour cavitation erosion test in distilled water.

When there were solid particles in water, the two steels were damaged more seriously i.e. solid particles erosion accelerated the cavitation erosion. The possible reason for this is that solid particles act as cavitation nuclei and increasing the formation of bubbles. In liquid-solid medium, the microjets produced by collapsing bubbles will propel erosive particles onto the contacting area with a high angle and cause additional damage. The surfaces of materials roughened by this kind of solid particle erosion are prone to the later cavitation erosion. In another aspect, this kind of erosion produces more intense damage on the

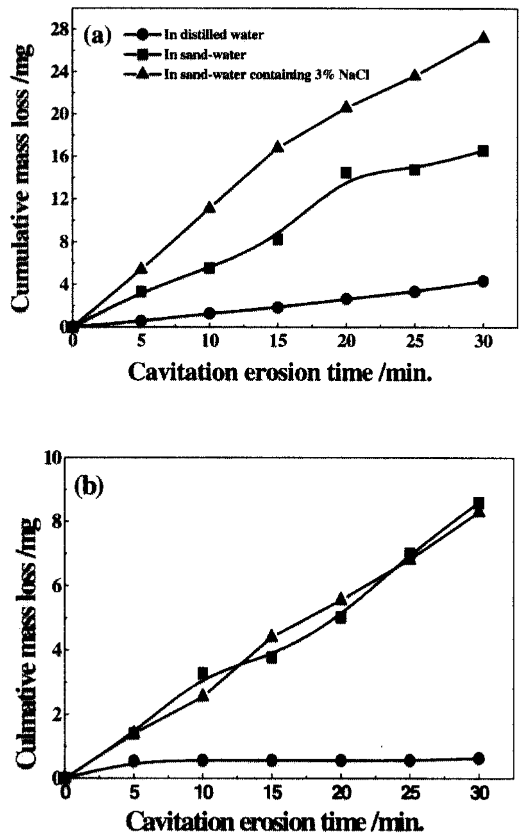

Fig. 5. Effects of solid particles and corrosion on cavitation erosion behaviors of 20SiMn and 0Cr13Ni5Mo. (a) 20SiMn (b) 0Cr13Ni5Mo

cavitated surface of the specimens produced by cavitation.

From figure 5, the corrosion effects on the cavitation erosion behaviors of two steels were much different from each other. For 20SiMn steel with lower corrosion resistance, the adding of 3wt%NaCl enhanced the cavitation damage in liquid-solid two-phase medium. In contrast, it seemed no any corrosion effects on cavitation erosion behaviors of 0Cr13Ni5Mo stainless steel with relative higher corrosion resistance in liquid-solid two-phase medium. A few researchers also reported the similar results on stainless steels.[18,21] In order to understand the above phenomenon, more electrochemical tests were done. figure 6 shows the effect of 3wt%NaCl on polarization behaviors of 20SiMn and 0Cr13Ni5Mo under quiescent conditions. The adding of 3wt%NaCl obviously deteriorated the corrosion behaviors of both steels. But, based on the Tafel extrapolation the corrosion current density of 20SiMn changed a lot in contrast with that of 0Cr13Ni5Mo. More electrochemical tests under cavitation conditions need to be done to explain the above phenomenon in detail. Kwok et al proposed that good repassivation ability of stainless steel (304, 316L), which

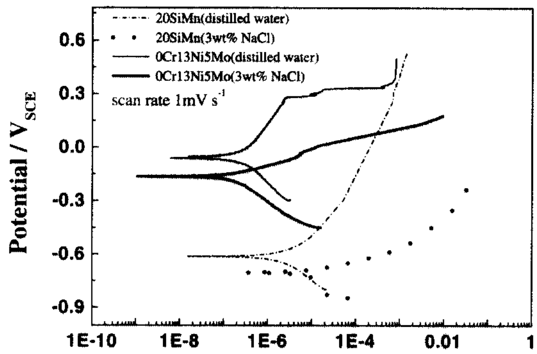

Fig. 6. Potentiodynamic polarization curves for 20SiMn and 0Cr13Ni5Mo in distilled water and 3wt%NaCl solution under quiescent condition at 27°C.

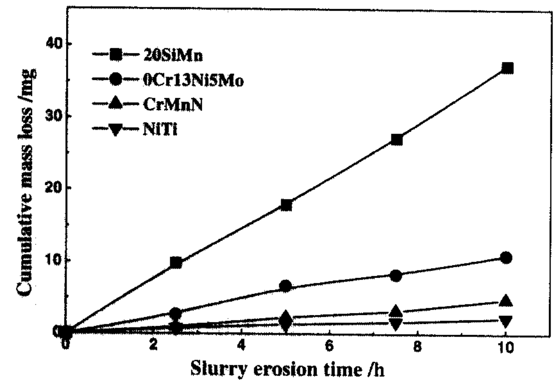

Fig. 7. The comparison of slurry erosion behaviors of four materials in tap water containing 0.25 kg/m^3 silica sand (200-300mesh) at 18m/s obtained by rotating disk rig.

could immediately repair the damaged passive film by cavitation erosion, was responsible for the different behaviors of stainless steel from that of low alloy steel.[21] But, 0Cr13Ni5Mo almost lost its good passivation and repassivation ability in 3wt%NaCl (figure 6). Therefore, Kwok's explanation was not reasonable for 0Cr13Ni5Mo. Ogino et al investigated the effect of amplitude on cavitation erosion and found that there was upper threshold amplitude above which the corrosion factor became ineffective.[24] The upper threshold amplitude for 20SiMn and 0Cr13Ni5Mo might be different, and this was another possible reason for the phenomenon. More tests for 0Cr13Ni5Mo with vibration amplitude lower than 60μm need to be done to verify the above possibility. It seems that the ratio between cavitation erosion rate and corrosion rate is a key factor to cause the different effects of corrosion on cavitation behaviors of low alloy steel and stainless steel. It also implies that relative higher corrosion resistance is a prerequisite for materials with higher cavitation erosion resistance in aggressive medium.

3.3 Slurry Erosion and Combined Action of Slurry Erosion and Cavitation Erosion by Rotating Disk Rig

Rotating disk rig was commonly used to simulate the damage of hydraulic turbine in liquid-solid two-phase flow.[1-4,6] figure 7 shows the comparison of slurry erosion rate of four materials obtained by rotating disk rig. The ranking of the slurry erosion resistance was Ni-Ti alloy > Cr-Mn-N > 0Cr13Ni5Mo > 20SiMn. After 10-hour test, the normalized slurry erosion resistance with respect to 20SiMn was 16.9, 7.8 and 3.4 for Ni-Ti alloy, Cr-Mn-N and 0Cr13Ni5Mo steel respectively. Much improvement in slurry erosion resistance could be found for Ni-Ti alloy, and this could be explained by the morphology observation (figure 8). There were only a few shallow scratching scars on the specimen surface of Ni-Ti alloy in contrast with the severe plastic deformation of other three steels. But, for all of the tested materials, the surface morphologies were almost along the flow directions.

Figure 9 shows that the combined action of slurry erosion and cavitation erosion did not change the ranking order of the materials, but much increased the cumulative mass loss. After 10-hour test, the normalized resistance to the combined action of slurry erosion and cavitation erosion with respect to 20SiMn was 8.7, 3.5 and 1.2 for Ni-Ti alloy, Cr-Mn-N and 0Cr13Ni5Mo steel respectively. Comparing with the slurry erosion resistance, the relative improvement of Ni-Ti alloy, Cr-Mn-N and 0Cr13Ni5Mo over 20SiMn under condition of combined action was much decreased. And, 0Cr13Ni5Mo almost lost its advantage over 20SiMn low alloy steel i.e. cheaper 20SiMn low alloy steel rather than relative expensive 0Cr13Ni5Mo stainless steel should be used under the combined action of slurry erosion and cavitation erosion. figure 10 shows the damage morphologies by the combined action. Comparing with the single action of slurry erosion, the directional morphologies almost disappeared for all of the materials, and more damage with a few micro-cracks presented on the surface of Ni-Ti alloy. 0Cr13Ni5Mo with higher hardness showed little plastic deformation comparing with 20SiMn and Cr-Mn-N. The above test results indicated that it was not enough to resist the high-energy impact from cavitation only relying on the improvement of material hardness. The better resistance of Cr-Mn-N to the combined action was came from its high work-hardening ability (figure 4) and strain-induced martensitic transformation.[5,21] The best resistance of NiTi alloy was not only related with its high work-hardening ability, but also related with its pseudoelasticity.[14] The high impact energy could be absorbed and dissipated through deforming by the formation and reversion of stress-induced

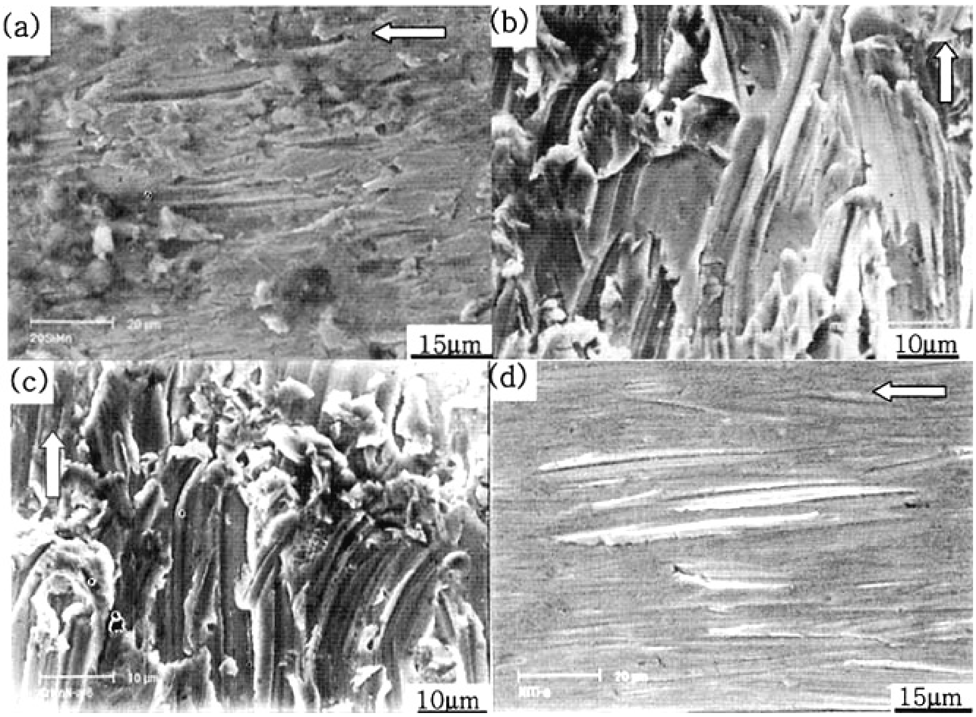

Fig. 8. Surface morphologies of four materials after 10-hour slurry erosion in tap water containing 0.25 kg/m^3 silica sand (200-300mesh) at 18m/s obtained by rotating disk rig. (Arrows represent flow direction) (a) 20SiMn (b) 0Cr13Ni5Mo (c) Cr-Mn-N (d) $Ni_{50.6}Ti$ alloy

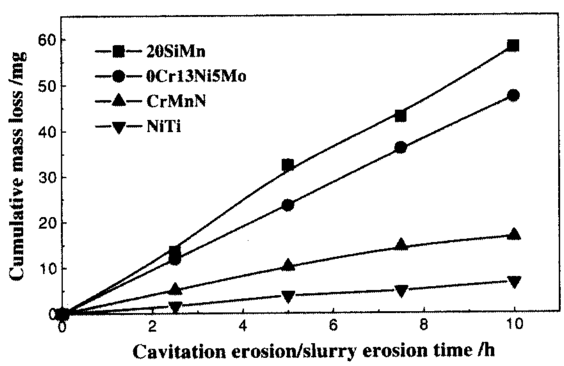

Fig. 9. The comparison of the combined action of slurry erosion and cavitation erosion of four materials in tap water containing 0.25 kg/m^3 silica sand (200-300mesh) at 18m/s obtained by rotating disk rig.

martensite as well as the interchange between martensitic variants.[14,23] Therefore, it is an important new way for developing and selecting materials used for flow-handling components of hydroturbines to make use of work-hardening, phase transformation and pseudoelasticity. Using various techniques such as explosive welding, infrared brazing to make Ni-Ti alloy coating on normal steels or using other low-cost Cu-based or Fe-based pseudoelastic alloys as hydroturbine materials are underway in our lab.

4. Conclusions

1. Solid particles exist in single liquid accelerated the cavitation erosion of both 20SiMn low alloy steel and 0Cr13Ni5Mo stainless steel. There was a strong synergistic interaction among electrochemical corrosion, slurry erosion and cavitation erosion for 20SiMn low alloy steel in liquid-solid two-phase medium. In contrast, corrosion played little role for 0Cr13Ni5Mo stainless steel.

2. Cr-Mn-N stainless steel with high Mn content showed better resistance to cavitation erosion and slurry erosion than 0Cr13Ni5Mo, which was mainly due to its good work-hardening ability as well as strain-induced martensite transformation. The cavitation micro-cracks for Cr-Mn-N stainless steel were parallel to the specimen surface in contrast with 0Cr13Ni5Mo whose micro-cracks were perpendicular to the surface.

3. Ni-Ti alloy with pseudoelasticity showed excellent resistance to combined interaction of cavitation erosion and slurry erosion.

4. Work-hardening ability, phase transformation and pseudoelasticity are very important factors to be considered for developing and selecting materials used for flow-handling components of hydroturbines.

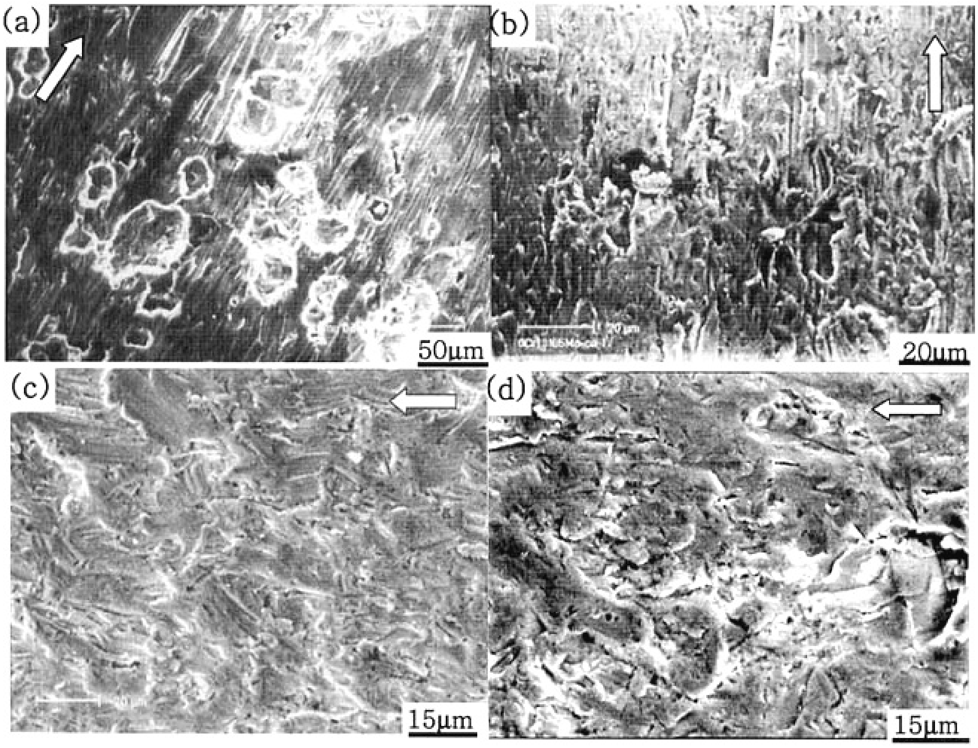

Fig. 10. Surface morphologies of four materials after 10-hour test under the combined action of slurry erosion and cavitation erosion in tap water containing 0.25 kg/m^3 silica sand (200- 300mesh) at 18m/s obtained by rotating disk rig. (Arrows represent flow direction) (a) 20SiMn (b) 0Cr13Ni5Mo (c) Cr-Mn-N (d) $Ni_{50.6}Ti$ alloy

Acknowledgement

The authors are grateful for financial support from National Science Foundation of China (No. 59831030) and the Special Funds for the Major State Basic Research Projects (No. G19990650). The authors also express their appreciation to Dr.Suzhen Luo for her kind assistance in electrochemical tests.

References

1. J. Zhang, M. O. W. Richardson, G. D. Wilcox, J. Min and X. Wang, *Wear*, **194**, 149 (1996).
2. K. Zhao, C. Q. Gu, F. S. Shen and B. Z. Lou, *Wear*, **162-164**, 811 (1993).
3. B. S. Man, Wear, **208**, 125 (1997).
4. B. S. Man, *Wear*, **237**, 140 (2000).
5. W. T. Fu, Y. Z. Zheng, T. F. Jing and M. Yao, *Wear*, **205**, 28 (1997).
6. Y. Zhang, Z. C. Wang and C. Yan, *Wear*, **240**, 231 (2000).
7. K. Z. Sang and Y. G. Li, *Wear*, **189**, 20 (1995).
8. C. T. Kwok, H. C. Man and F. T. Cheng, *Materials Science and Engineering*, **A303**, 250 (2001).
9. A. Karimi and J. L. Martin, *International Metals Reviews*, **31**, 1 (1986).
10. Y. Suzuki and T. Kuroyanggi, *Titanium Zirconium*, **27**, 67 (1979).
11. Y. Shida and Y. Sugimoto, *Wear*, **146**, 219 (1991).
12. R. H. Richman, A. S. Rao and D. E. Hodgson, *Wear*, **157**, 401 (1992).
13. Y. N. Liang, S. Z. Li, Y. B. Jin, W. Jin and S. Li, *Wear*, **198**, 236 (1996).
14. R. Liu and D. Y. Li, *Materials Science and Technology*, **16**, 328 (2000).
15. R. H. Richman, A. S. Rao and D. Kung, *Wear*, **181-183**, 80 (1995).
16. H. Hiraga, T. Tnoue, H. Shimura and A. Matsunawa, *Wear*, **231**, 272 (1999).
17. J. L. He, K. W. Won, C. T. Chang, K. C. Chen and H. C. Lin, *Wear*, **233-235**, 104 (1999).
18. S. K. Wu, H. C. Lin and C. H. Yeh, *Wear*, **244**, 85 (2000).
19. S. Zhou, M. M. Stack and R. C. Newman, *Corrosion*, **52**, 934 (1996).
20. Y. G. Zheng, Z. M. Yao, X. Y. Wei and W. Ke, *Wear*, **186-187**, 555 (1995).
21. C. T. Kwok, F. T. Cheng and H. C. Man, *Materials Science and Engineering*, **A290**, 145 (2000).
22. Y. G. Zheng, Z. M. Yao, W. Ke, *Materials Letters*, **46**, 362 (2000).
23. W. Liu, Y. G. Zheng, Z. M. Yao, W. Ke, *Chinese Journal of Materials Research*, **15**, (2001) in press(in Chinese).
24. K. Ogino, A. Hida and S. Kishima, *Corrosion*, **44**, 97 (1988).