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Investigation of Erosion Damages Induced by Wet Steam Containing Micro-Particles

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Abstract Based on the self-developed experimental apparatus, the wet steam erosion experiments were performed on polished steel specimens. Scanning Electronic Microscope (SEM) and Atomic Force Microscope (AFM) were used to identify the pit characteristics. The experimental results showed that there was little damage on the surface after being impacted by wet steam erosion. However, when the micro-particles were added into the wet steam, not only indentations and scratches but also craters appeared on the eroded surface. Some characteristics of crater, such as the circular shape and intergranular fractures, make the damages distinguish from those of the water-drop or micro-particle impact to solid wall, and they are considered as the results of cavitation erosion.

Keywords Erosive wear · Impact wear · Micro-particles

1 Introduction

Erosion of steam turbine blades, especially the last low pressure ones, has been one of the important problems in power generation systems [1]. It is known that the erosion has brought about severe problems in steam turbine blades, including high cost of maintenance and repair, safety problem as well as low efficiency of power generation [2].

Much work has been conducted to investigate the erosion mechanisms. Obara et al. [3] and Mann et al. [4] performed the experiments of water jet impingement on solid surfaces, and reported that the initiation and expansion of crack occur on the surface due to the stress wave and the high-speed lateral jet generated by water-drops impact. Hutchings et al. [5, 6] and Alfonso et al. [7] introduced the theoretical analysis and experimental study for predicting erosion damage caused by solid particle impact. They proposed an idea that erosion damage is the gradual removal of materials suffered from repeated deformation and cutting actions. However, little work has been carried out on the influence of micro-particles on wet steam erosion, although extensive researches have been conducted in each field, respectively [8]. Actually, the ferric oxides will be peeled from the inside of the superheated tube [9], thus the particles will inevitably exist in the steam. Many reports indicated that the particles have significant impact on the erosion of materials. In the abrasive water jet erosion, the particles cut the material surface [10]. In the erosion of hydro-machinery, the particles with proper size play an important role in the generation of cavitation erosion [11].

In this ongoing study, the characteristics of the surface damages induced by erosion of wet steam containing micro-particles are different from those induced by micro-particles or water-drop impact to solid wall. Such investigation may help us understand the mechanism of the wet steam erosion more completely.

2 Experimental

2.1 Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig. 1. The wet steam is generated by steam generator (A). The velocity changes along with the variation of flow rate of wet steam by valve (B). The

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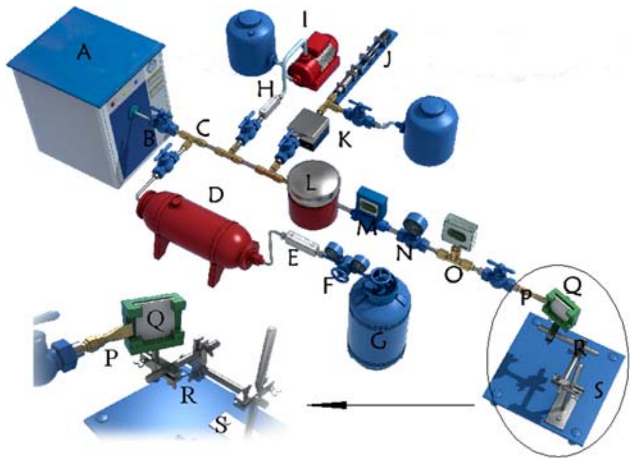

Fig. 1 Schematic diagram of experimental apparatus

Table 1 Chemical composition of AISI 1045 steel (%)

C	Cr	Si	Mn	P	Ni	Cu	S	Fe
0.37–0.44	0.80–1.10	0.17–0.37	0.50–0.80	0.021	0.126	0.15	0.001	Others

micro-particles can be pushed into pipeline by the designed thruster (J) after being dispersed by supersonic vibration implements (K). The feed rate of micro-particles can be controlled by rotary speed of stepper motor. Then, wet steam carrying micro-particles impinges toward the sample surface (Q) after passing through the mixer (L), steam flowmeter (M), pressure transmitter (N), temperature sensor (O) and nozzle (P). The other components are pipe tee T (C), nitrogen heater (D), nitrogen flowmeter (E), reducing valve (F), nitrogen gas storage holder (G), fluid flowmeter (H), water pump (I), kickstand (R), and jig and temperature sensor (S). After the erosion, the pipeline can be cleaned by using de-ionized water.

2.2 Experimental Condition

The specimen is made of medium carbon steel (AISI 1045 steel), whose yield stress σ_s is 385 MPa and ultimate tensile stress σ_b is 670 MPa. Its chemical composition is shown in Table 1. The specimen surface is polished, and the root mean square (R_q) value is 50 ± 5.6 nm, which is measured by an Atomic Force Microscope (AFM) CSPM 4000.

There are three different kinds of fluid media for each experimental group, and the ingredients of fluid media for each group are listed in Table 2. The de-ionized water, which was obtained by filtering the tap water by multi-layer reverse osmosis membrane, contains few micro-particles. Figure 2a shows the micro-particles that originally existed in the tap water, and Fig. 2b shows the SiC micro-particles to be added in the wet steam. It can be seen from Fig. 2 that they are both irregular particles with the diameter of 1–5 μm. In order to avoid material destruction caused by water-drop impact, the velocity of steam is 60 m/s considering that the estimated damage threshold velocity of liquid impact is 100 m/s [12]. The detailed experimental conditions are listed in Table 3.

Table 2 Ingredients of fluid for each group

Groups	I	II	III
Fluid media	De-ionized water steam	De-ionized water steam + SiC	Tap water steam
Specimen no.	#1	#2	#3

3 Experimental Results

The eroded surfaces were observed by Scanning Electronic Microscope (SEM) after erosion experiments. Figure 3 shows scanning electron micrographs of the eroded surfaces.

From Fig. 3a, there was little damage on the sample a after being impacted by de-ionized steam. However, when the micro-particles were added into the wet steam, not only indentations but also craters appeared on the sample b, as shown in Fig. 3b. In the figure, the craters are distinctly different from the indentations. The indentations usually have triangle shape and they are smaller than the micro-particles. But for the craters, the shapes are circular and their brims are smooth. The diameters are 3–6 μm, which are bigger than those of micro-particles. Brittle features such as the fractures and the transgranular cracks are found around and inside the craters. Similar craters and indentations appeared on the sample c surface under the erosion of tap water steam, as shown in Fig. 3c. It is attributed to micro-particles contained in tap water.

4 Discussion

4.1 Effect of Micro-Particles

According to the damage threshold velocity of liquid impact, the material cannot be destroyed when the impact speed is lower than the threshold velocity [12]. The experimental result also proved this theory when the surface was impacted by de-ionized water wet steam. However, when the micro-particles were added into the wet steam, indentations and craters appeared on the surface after the experiment. In addition, this damage style is also

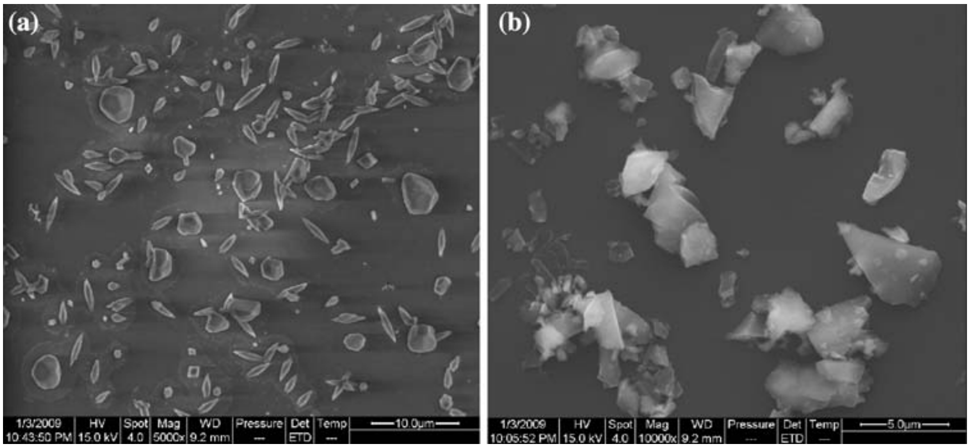

Fig. 2 Geometry and size distribution of micro-particles (SEM). **a** Micro-particles contained in tap water, **b** SiC micro-particles

Table 3 Erosion test parameters

Water	Particle	Impingement angle (°)	Impingement velocity (m/s)	Particle feed rate (g/m^3)	Test temperature (K)	Pressure of steam (MPa)	Distance from sample to nozzle (mm)	Experimental time (min)
De-ionized water	SiC	20	60	0.6	383	0.1	10	10

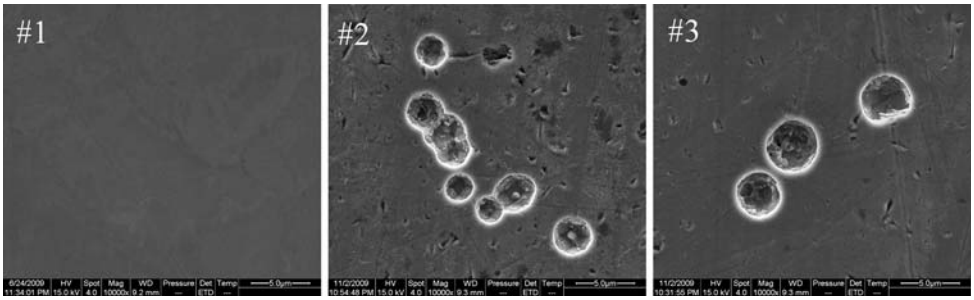

Fig. 3 Scanning electron micrographs of the eroded surfaces

different from those obtained by Lee et al. [13]. Their results showed that under the water-drop impact, the surface exhibits a ductile behavior featured with continuous surface undulation without loss of material, and the behavior then changes into a brittle one in that cracks and local fracture are extended over the surface by liquid impact. Therefore, micro-particles play a very important role in the generation of craters.

Compared with Fig. 3b, c the quantity of craters and the erosion damage degree of surface are different. This phenomenon may be related to micro-particle. As the micro-particle size is one of the characteristic parameters, the erosion experiments were performed by adding SiC micro-particles of the same mass but different sizes into the wet steam so as to clarify the influence of micro-particle size. The de-ionized water was used as steam source, and the other experimental conditions were identical to the experiment in Sect. 2. The experimental results were shown in Fig. 4.

The erosion damage degree was evaluated so as to analyze the effect of micro-particle size. There are many methods to evaluate the erosion damage degree, such as mass loss and pit number [14]. In our experiment, the plastic deformation appeared on the surface, and the shape and size of pits were different, as shown in Fig. 4b. In contrast, area loss is more suitable to evaluate the erosion damage degree. Herein, area loss is defined as the areas of indentations, scratches and craters. Figure 5 shows the relation curves of area loss with micro-particle size.

The curve “a” represents the area loss caused by indentations and scratches. It can be seen that the area loss increases with the increment of micro-particle size, which is also agree with Rickard et al [15]. The curve “b” shows the area loss caused by indentations, scratches and craters. The total area loss can be divided into three parts: (i) An accelerated loss part, in which the area loss increases rapidly. In this part, besides the indentations, the craters also appeared on the surface. The area of crater is usually

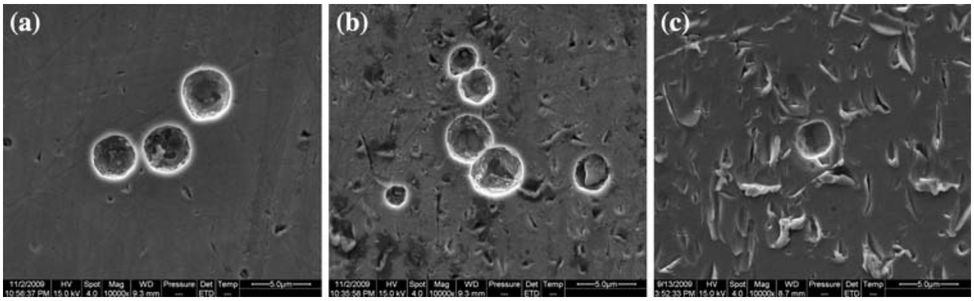

Fig. 4 Scanning electron micrographs of surfaces eroded by adding micro-particles of different sizes into the wet steam. **a** For 0.8 μm, **b** for 3.5 μm, and **c** for 6.5 μm

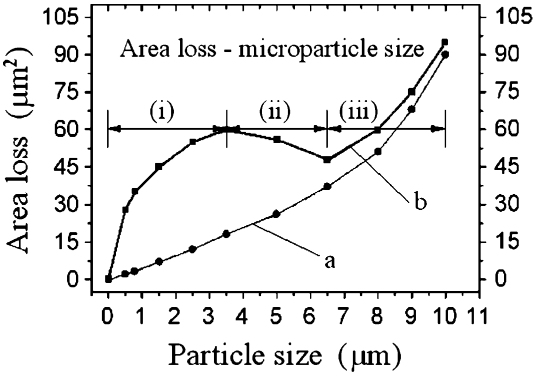

Fig. 5 Area loss as a function of micro-particle size

bigger than that of indentation, and the area loss is mainly caused by the generation of craters, as shown in Fig. 4a and b; (ii) A damped loss part, in which the area loss decreases. The reduction in the damage degree is associated with reduction in the proportion of craters, since the indentations and scratches intensify the damage to area loss; (iii) An accelerated loss part, during which the crater decreases and particle abrasion is the main damage style with further increment in micro-particle size, as shown in Fig. 4c. Therefore, the micro-particle size has a significant effect on the crater generation and erosion damage degree.

4.2 Mechanism Analysis of Generation Crater

Atomic Force Microscope (AFM) was used so as to further analyze the crater. Figure 6a shows the micrograph, and Fig. 6b shows the profile of the crater at the cross-section A–A. The lip appeared around the crater, which shows a plastic flow of material. According to the viewpoint [16], the lip corresponds to the plastic deformations under the effect of force. Meanwhile, brittle features such as the fractures and the transgranular cracks are found around and inside the craters, as shown in Fig. 3b. Therefore, mechanical behaviors are the main causes to generate crater.

When the liquid impact on the material surface, the liquid behaves compressibly in the early stage and so-called ‘‘water hammer’’ pressures can be generated. This high pressure is responsible for most of the damage resulting from liquid impact, and the high pressure is maintained while the edge of the contact area between the impacting liquid and the solid moves supersonically with respect to the shock speed in the liquid [17]. The water hammer pressure P_c on the central axis is given by

$$P_c = \frac{V\rho_1 C_1 \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2} \tag{1}$$

where V is the impact velocity and ρ_1, ρ_2 and C_1, C_2 are the densities and shock velocities of the liquid and the solid, respectively. For impact on a rigid target, the pressure is

$$P_c = \rho_1 C_1 V. \tag{2}$$

The pressure at the contact periphery is somewhat higher and reaches approximately $3\rho_1 C_1 V$ at the instant the shock envelope overtakes the contact periphery and starts to move up the free surface of the drop [18]. Shock wave velocity C is related to the acoustic velocity, C_0 (ca. 1,500 m/s for water) by

$$C = C_0 + KV \tag{3}$$

where K is a constant which has a value close to 2 for water.

It is known that the impact angle α is 20° and the impact velocity V is 80 m/s. According to the Eqs. 2 and 3, the pressure P_c on the central axis is 42.54 MPa and the pressure at the contact periphery is 127.26 MPa. Since yield stress σ_s of AISI 1045 steel is 385 MPa, the material surface cannot be damaged by liquid impact. Therefore, the generation of crater is not caused by liquid impact, which was also verified by experimental result, as shown in Fig. 3a.

In order to analyze the damage morphology caused by micro-particles, the erosion was investigated with the micro-particles accelerated by high-pressured nitrogen without wet steam. Figure 7a shows that many scratches and indentations appeared on the surface, and the scratches are usually strips. Figure 7b shows that the indentations are usually triangle shape, and the interior walls are smooth. Along with the impact direction, material stack appears on the indentations. This kind of damage style is similar to experimental results obtained by Chang et al. [19]. These

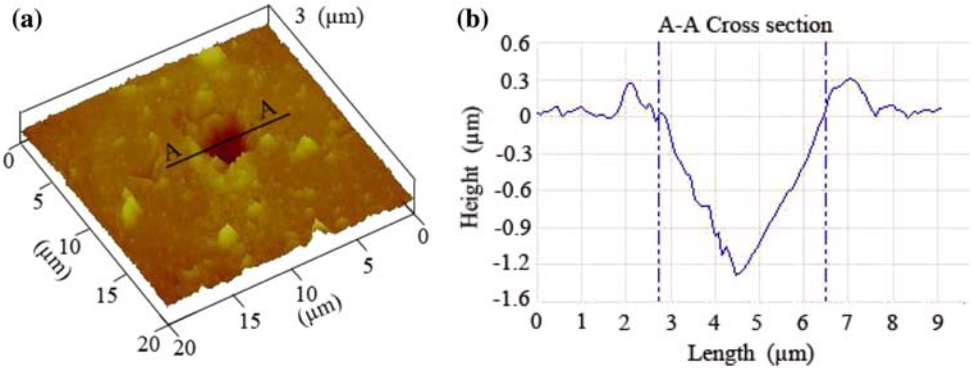

Fig. 6 **a** Crater observed by atomic force microscope, **b** Profile of the crater at the cross-section A–A

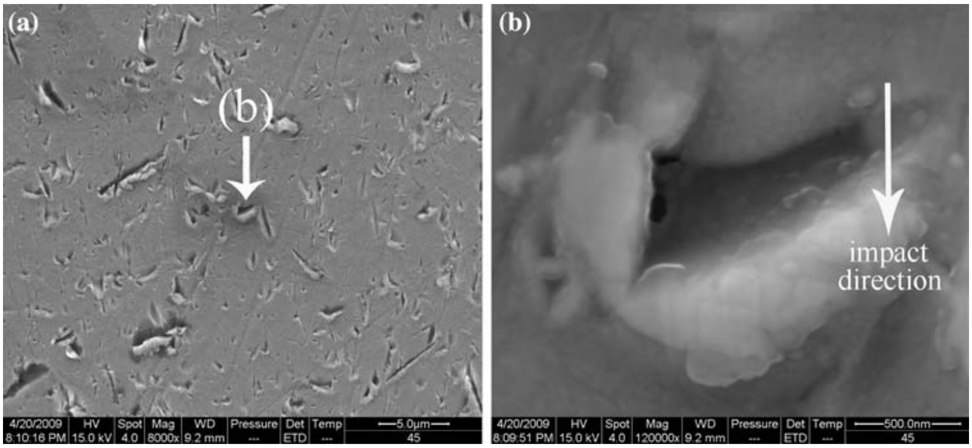

Fig. 7 Indentations and scratches after being impacted by SiC micro-particles

characteristics of indentations and scratches are different from those of craters. Thus, the generation of craters is not caused by micro-particle impact.

The water-drops containing micro-particles may have gas nuclei, and the reduction of pressure provides the condition to make the gas nuclei grow micro-bubble after the wet steam was spouted from the nozzle [20]. Cavitation erosion means the attack of metal surfaces caused by the collapse of cavitation bubbles on the surface of the liquid [21]. Therefore, to analyze the damage style caused by micro-bubble collapse, the cavitation erosion experiment of the AISI 1045 steel was performed on rotating disk experimental apparatus. Figure 8a shows the crater induced by cavitation erosion. The border of the crater is comparatively smooth, and the profile is nearly circular. Brittle features are found around and inside the crater. Figure 8b shows the crater induced by erosion of wet steam containing micro-particle. Compared with Fig. 8a and b, the characteristics of both craters have many similarities.

The above analysis indicated that mechanical behaviors are the main factor to generate crater, but they are not caused by the water-drops or micro-particles impact to solid wall. The generation of crater is the combined effect of water-drop and micro-particle. Compared with the crater induced by cavitation erosion, the characteristics of both craters indicate that cavitation erosion occurs during the erosion of wet steam containing micro-particles.

5 Conclusion

From the experimental results and discussions presented above, the following conclusions can be drawn.

(1) Indentations and scratches caused by micro-particles impact and cracks caused by water-drop impact are not the only damage styles when the steel surface was eroded by wet steam containing micro-particles. Craters also appear on the surface. Micro-particles play a key role in the generation of craters, and their sizes have significant effects on the crater generation and erosion damage degree.

(2) Mechanical behaviors are the main causes to generate crater, which is validated by the special damages such as fractures and transgranular cracks around and inside the craters, but the craters are not caused by liquid or micro-particles impact to the solid wall. Compared with the craters induced by cavitation erosion, the craters are considered as the results of cavitation erosion.

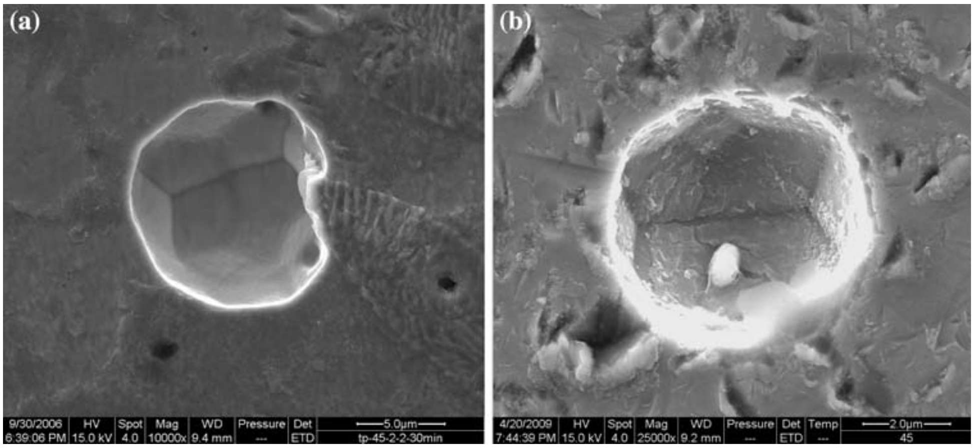

Fig. 8 **a** Crater induced by cavitation erosion, **b** Crater induced by erosion of wet steam containing micro-particle

(3) The analysis of damage style may help us understand the mechanism of the wet steam erosion more completely, which provides the theoretical foundation for finding out alternative materials and alloys or improving measures to enhance the erosion resistance of steam turbine's blades. In subsequent work, the related researches, such as the effect of particle's characteristic parameter, the interaction between particles and bubbles, etc., will be carried out from experimental investigations and theoretical analyses.

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References

1. Mukhopadhyay, N.K., Ghosh, S., Das, G., Chattoraj, I., Das, S.K., Bhattacharya, D.K.: An investigation of the failure of low pressure steam turbine blades. Eng. Fail. Anal. **15**, 191–193 (1998)
2. Stanisa, B., Ivusic, V.: Erosion behaviour and mechanisms for steam turbine rotor blades. Wear **186–187**, 395–400 (1995)
3. Obara, T., Bourne, N.K., Field, J.E.: Liquid-jet impact on liquid and solid surfaces. Wear **186–187**, 388–394 (1995)
4. Mann, B.S., Vivek, A.: An experimental study to correlate water jet impingement erosion resistance and properties of metallic materials and coatings. Wear **253**, 650–661 (2002)
5. Hutchings I.M., Winter R.E., Field J.E.: Solid particle erosion of metals: the removal of surface material by spherical projectiles. Proc. R. Soc. Lond. Ser. A **348**, 379 (1976)
6. Hutchings, I.M., Macmillan, N.H., Rickerby, D.R.: Further studies of the oblique impact of a hard sphere against a ductile solid. Int. J. Mech. Sci. **23**, 639–646 (1981)
7. Alfonso, C.A., Armando, G.M., Romero, C.A., Zdzislaw, M.C., Rafael, C.A.: Numerical investigation of the solid particle erosion rate in a steam turbine nozzle. Appl. Therm. Eng. **27**, 2394–2403 (2007)
8. Ahmad, M., Casey, M., Suken, N.: Experimental assessment of droplet impact erosion resistance of steam turbine blade materials. Wear **267**, 1605–1618 (2009)
9. Mann, B.S.: Solid-particle erosion and protective layers for steam turbine blading. Wear **224**, 8–12 (1999)
10. Momber, A.W., Kwak, H., Kovacevic, R.: Investigations in abrasive water jet erosion based on wear particle analysis. J. Tribol. **118**, 759–766 (1996)
11. Wang, J.D., Chen, H.S., Qin, L., Li, Y.J., Chen, D.R.: Key roles of micro-particles in water on occurrence of cavitation-erosion of hydro-machinery. Chin. Sci. Bull. **50**, 1603–1607 (2008)
12. Kenndey, C.F., Field, J.E.: Damage threshold velocity for liquid impact. J. Mater. Sci. **35**, 5331–5339 (2000)
13. Min, K.L., Whung, W.K., Chang, K.R.: Investigation of liquid impact erosion for 12Cr steel and stellite 6B. J. Nucl. Mater. **257**, 134–144 (1998)
14. Li, Y.J.: Study on mechanism of surface topograhpy effects on generation of cavitation erosion. Doctoral Dissertation of Tsinghua University, Beijing (2008)
15. Rickard, G., Staffan, J.: The particle size effect in abrasion studied by controlled abrasive surfaces. Wear **224**, 118–225 (1999)
16. Karimi, A., Avella, F.: Ripple formation in solid-liquid erosion. Wear **156**, 33–47 (1992)
17. Lesser, M., Field, J.: The impact of compressible liquids. Annu. Rev. Fluid Mech. **15**, 97–122 (1983)
18. Lesser M.B.: Analytic solutions of liquid-drop impact problems. Proc. R. Soc. Lond. Ser. A **377**, 289–308 (1981)
19. Chang, L.C., Hsui, I.C., Chen, L.H., Lui, T.S.: A study on particle erosion behavior of ductile irons. Scripta Mater. **52**, 609–613 (2005)
20. Huan, J.T.: The principle and application of cavitation and cavitation erosion. Tsinghua University publishing house, Beijing (1991)
21. Buravova, S.N.: Surface damage as a result of cavitation erosion. Tech. Phys. **43**, 1107–1110 (1998)