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Water erosion mechanism of mild carbon steels induced by micro-particles

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To clarify the water erosion mechanism of the mild carbon steels, the water erosion experiments were performed by using deionized water as steam source. The results showed that under the damage threshold velocity of liquid impact, the material surface would not be destroyed. However, when the micro-particles were added into the steam, the pits appeared on the surface soon. By comparison, it is found that the pits are quite different from those induced by micro-particles impact without steam, but similar to those induced by cavitation erosion. The results indicated that the water erosion mechanism was similar to that of cavitation erosion under the damage threshold velocity. The micro-particles carry the micro-bubbles to approach the surface of the material, and the micro-bubbles collapse and generate micro-jet to impinge vertically on the surface, which lead to the produce of pits.

water erosion, micro-particle, mild carbon steel

The low-pressure blades of the steam turbine are vulnerable to water erosion because of the wet steam impact[1]. Water erosion of blades brings a series of problems, such as reduction of the anti-fatigue strength, change of the vibration characteristic and breaking of structures[2]. Therefore, further understanding of water erosion mechanism is necessary.

The water erosion mechanisms have been investigated by using simulation experiments[3–5]. With the water-drop speed of 500 m/s to 1200 m/s or even much higher, the water erosion experiments were performed by spraying the millimeter-size water-drops to vertically impinge on the surface of blades. The results indicated that the stress wave and the high-speed lateral jet were generated when the water-drops directly impacted on the rotor blades. Suffering these actions, the initiation and expansion of crack occurs. Once the subsequent water-drops impinge on the crack, the internal pressure of water-drop would aggravate the crack ulteriorly. Finally, the material is separated from the blade surface[6,7].

However, the linear velocity of the top of the blade ranges from 300 m/s to 700 m/s in actual status. The included angle between the vapor impact direction and the surface of the blade ranges from 15° to 25°. The velocity of water-drop is 20%—40% of that of the steam[8,9]. Therefore, being much lower than the water-drop velocity of the previous experimental study, the normal impact velocity of the water-drop just ranges from 100 m/s to 400 m/s. Under such a low velocity, the blade is hard to be damaged regardless of the impact number[10]. In addition, some impurities and the ferric oxides can be peeled from the inside of the superheated tube [11], thus the micro-particles inevitably exist in the steam. Many reports indicated that the micro-particles had significant impacts on the erosion of the material[12,13].

In this paper water erosion experiments have been performed under various experimental conditions. The experimental results are analyzed and discussed and the water erosion mechanism is proposed.

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1 Experimental setup

1.1 Water erosion test-bed

The water erosion is related to some factors, such as temperature, water-drops, micro-particles, and surface topography[14,15]. Taking into account these effect factors, a test-bed for the water erosion experiment was designed as shown in Figure 1. The high-temperature high-pressure steam is generated by the steam generator (A). The velocity of the steam is controlled by valve (B), ranging from 50 m/s to 200 m/s. The micro-particles are dispersed by the supersonic vibration implements (K), which are supplied by plunger cylinder, stepmotor and controller (J). The steam carrying the micro-particles impinges towards the surface of specimen (Q) after passing the mixer (L), steam flowmeter (M), pressure transmitter (N), temperature and humidity sensors (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 experimental completion, the pipeline is cleaned by using deionized water.

The thruster was designed to push micro-particles into the pipeline. The specimen is fixed in the working chamber. The distance and angle between nozzle and specimen can be adjusted. Meanwhile, the parameters, such as pressure and flow rate, can be adjusted and measured during the experimental process. Compared with the experimental equipments mentioned in the literature[16,17], this experimental equipment has two characteristics: First, the impact medium is heated wet steam containing many water-drops[18]. Second, the effect of micro-particle containing in the steam can be investigated in this equipment.

1.2 Experimental condition

The 45# steel is used as experimental material, and the size of specimen is 50 mm×30 mm×2.5 mm. The chemical composition of this material is listed in Table 1. After being polished, the surface topography images of the specimen are recorded in Figure 2. The results showed that the surface of the specimen was very smooth with a RMS roughness of 17.2 nm. The water sources for steam are the deionized water and the tap water.

Table 1 Chemical ingredient of 45 steel

Steel grade	Chemical ingredient (%)				
	C	Mn	Si	S	P
45	0.48	0.60	0.31	0.026	0.023

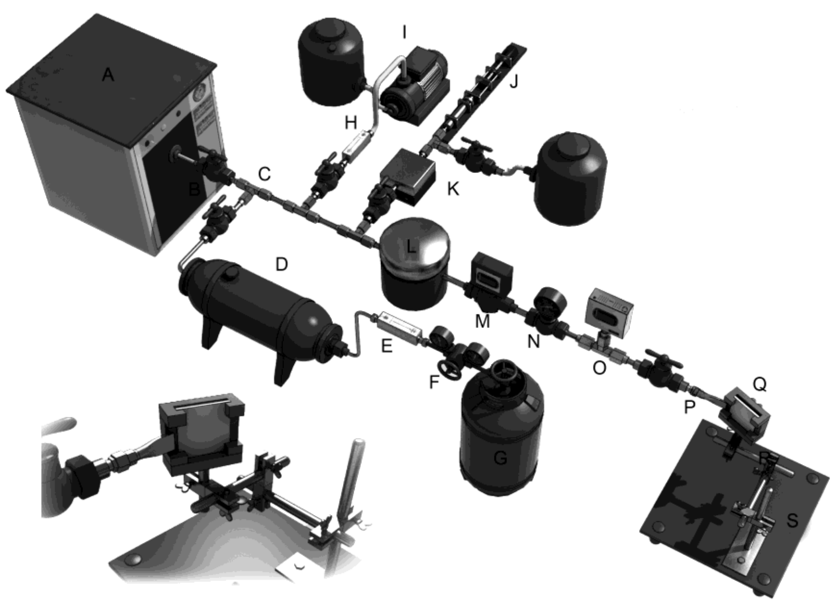

Figure 1 Sketch for the water erosion test-bed.

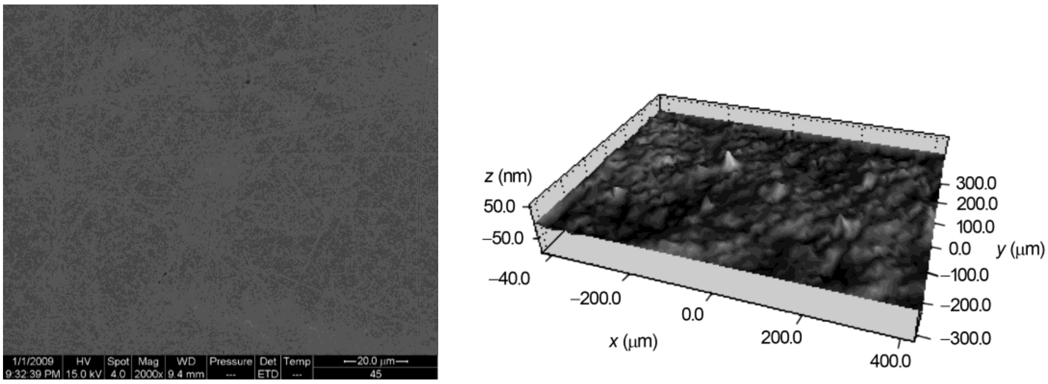

Figure 2 Original surface of 45# steel.

Before the experiment, the test specimen is fixed in the chucking appliance. The included angle between the steam impact and the specimen is 20°, and the distance from the nozzle to the test specimen is 5 mm. The cross section of nozzle is rectangle, with the size of 0.4 mm×1.5 mm. Figure 3 shows grain-size distribution and geometry of micro-particle in tap water (Figure 3(a)) and SiC (Figure 3(b)). It shows that the tap water includes irregular particles, with the diameter of 0.5—3 μm. And the SiC is irregular, with the diameter of 1.5 μm. The particles disperse well after the ultrasonic vibration.

For 45# steel the damage threshold velocity of liquid impact is 120 m/s[6]. In order to avoid material destruction because of water-drop impact, the velocity of steam is 80 m/s during the water erosion. The other working conditions are as follows: the pressure of steam is 0.15 MPa, the temperature of steam is 125℃, the ambient temperature of test specimen is 99℃, and the experimental time lasts 10 min.

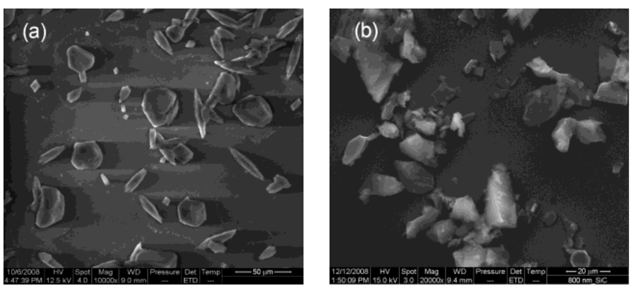

Figure 3 Distribution and geometry of micro-particles. (a) Micro-particles containing in tap water; (b) micro-particles of SiC, nominal diameter 1.5 μm.

2 Results and discussion

2.1 Water erosion experiment by using tap water as steam source

The tap water, which contains the micro-particles and dissolves tiny gas, is used as a water source to generate steam in the water erosion experiment. The experimental results are shown in Figure 4. Compared with the original surface, the material surface is destroyed severely with many erosion pits appearing on the surface in Figure 4(a). The surface has not only the single pit, but also many pits distributing like chain. The sizes of the pits on the surface are 2—8 μm in diameter, which is bigger than that of micro-particles containing in tap water. Figure 4(b) represents that their brims are relatively smooth and the profile is nearly circular. Figure 4(c) shows that clastics and cracks appear in the pit.

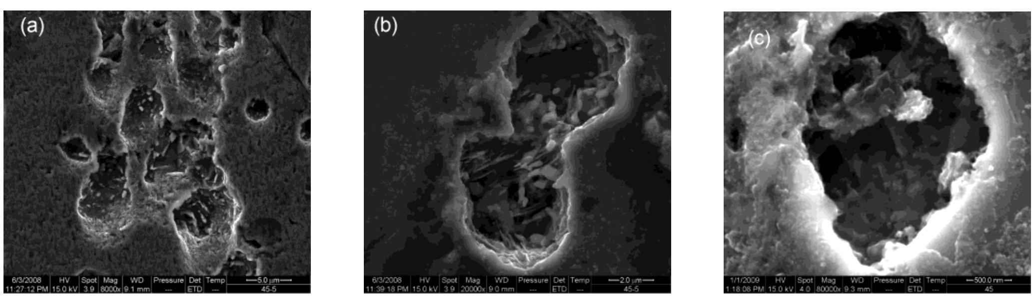

Figure 4 The pits after water erosion experiment by using tap water as steam source.

According to the damage threshold velocity of liquid impact[10], the material cannot be destroyed when the impact speed is lower than the threshold speed. However, in our study, the material surface is destroyed after the experiment. In addition, our results are also different from those obtained by Lee et al.[7]. Their results showed that the impacted surface exhibited a ductile behavior featured with continuous surface undulation without loss of material. The behavior then changes into a brittle one in that cracks and local fracture are extended over the surface by liquid impact induced work hardening. Our experimental results can be attributed to the micro-particles and gas containing in tap water.

2.2 Water erosion experiment by using deionized water as steam source

To avoid the effect of micro-particles containing in tap water, the deionized water was used as steam source, and the other experimental conditions were identical to the experiment in section 2.1.

After experiment the surface topography images of the specimen are shown in Figure 5. Compared with the original surface, the test specimen seems intact and no pits appear on it. Therefore, during the impact of steam, only the water droplet impact cannot destroy the material surface, which further verifies the effects of the micro-particles.

2.3 Water erosion experiment by using deionized water as steam source and adding SiC particle

In this section, the 1.5 μm SiC micro-particles are added into deionized water steam so as to further investigate the effect of micro-particle. During the experiment, 1 g micro-particles are equably added into the steam pipe in the 10 minutes experimental time. Figure 6(a) represents that the pits appear on the surface of 45# steel after water erosion. The diameters of pits are 2－6 μm, which are much bigger than those of SiC micro-particles. The brims of the pits are relatively smooth, and the profile is nearly circular. The collapse of surface material and the cracks in the pit are shown in Figure 6(b) and (c) respectively. Compared with the results shown in Figure 4, the shapes of pits are similar. These results verify the great contributions of the micro-particle to water erosion.

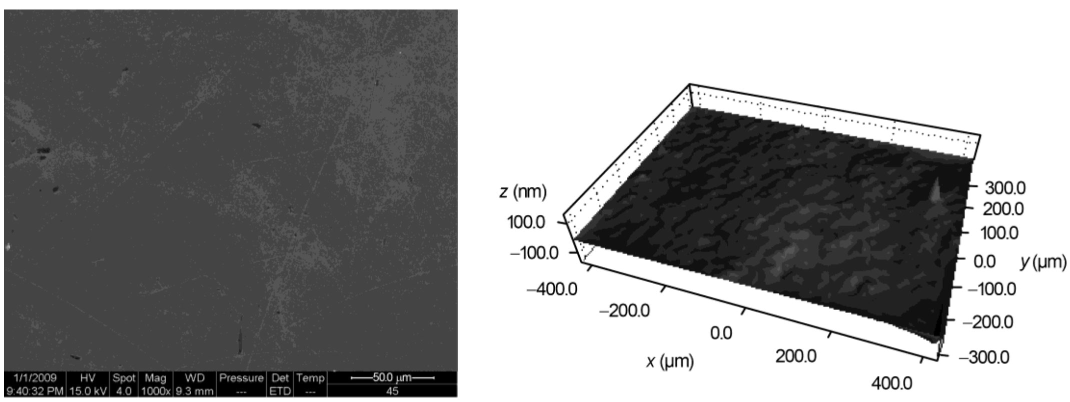

Figure 5 The surface after water erosion experiment by using deionized water as steam source.

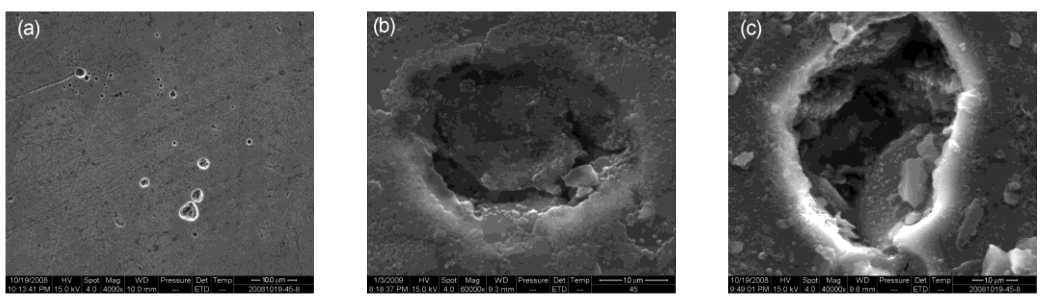

Figure 6 The pits after water erosion experiment by using deionized water as steam source and adding SiC micro-particles.

2.4 Erosion experiment of SiC micro-particle accelerated by high-pressure nitrogen

The above analysis showed that the micro-particles were necessary to the water erosion in water steam. Here, the erosion is to be investigated with the micro-particles accelerated by gas without water steam. The nitrogen, as an inert gas, is selected to avoid oxidation. The nitrogen was heated to 125℃ and the pressure of nitrogen in pipeline was 0.15 MPa. The results, as shown in Figure 7, show that many indentations and scratches appear on the erosion surface. The indentations are polygon with the side length of 0.2—2 μm. And, the scratches are strip with the length of 1—3 μm and the width of 0.1—1 μm. However, such marks are not found on the surface of Figure 6. Therefore, it can be deduced that the micro-particles are necessary, but not enough to the water erosion. The water steam is also needed.

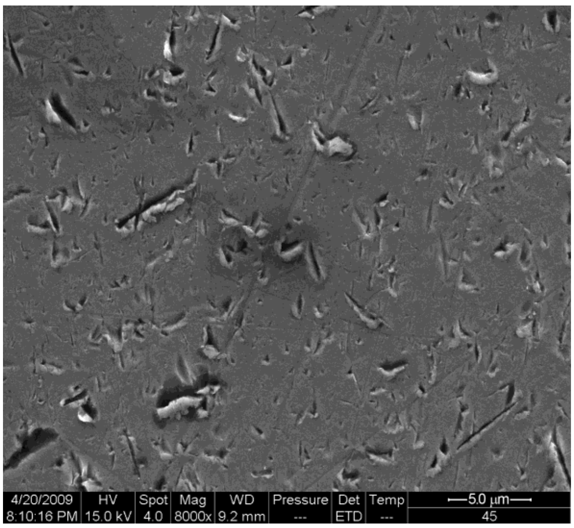

Figure 7 Indentations and scratches after being impacted by SiC micro-particles.

To elucidate the water erosion mechanism, the cavitation erosion experiment of the 45$^{\#}$ steel is performed on rotating disk experimental equipment. The water source is tap water. The experimental results show that many pits appear on the surface with the diameter of 2—6 μm. The surface has not only the single pit, but also many pits distributing like chain. The border of the pit is comparatively smooth, and the profile is nearly circular. These phenomena are similar to the results of water erosion. Wang et al.[19] researched the effect of micro-particles for cavitation erosion in hydraulic machinery, and proved that micro-particles played an important role in the cavitation erosion. The micro-particles are also of great importance to water erosion. If there are no micro-particles, the surface is not damaged obviously. But when the micro-particles are added, the pits appear on the surface. Therefore the pits produced in the water erosion have many similarities to those produced in cavitation erosion.

The above experiments indicated that the surface was not damaged after being eroded by using deionized water as steam source. But when the SiC micro-particles are added into the wet steam, the surface is destroyed with many pits appearing on the surface. Therefore, the micro-particle is of great importance during the water erosion. Compared with the pits of cavitation erosion, the characteristics of pits showed that the cavitation erosion would be encountered during the water erosion. With the temperature reduction, part of the high-temperature steam will condense into water droplets. The water droplet containing micro-particle has the vapor core, and the pressure reduction provides the condition to make the vapor core grow bubbles[20]. The destruction of material surface is due to the particles, which carry the micro-bubble of liquid-drop, approach the surface of the material, and form high-pressure microdmain with the asperities. The micro-bubbles collapse in the high-pressure microdmain and micro-jets pointing to the surface are generated[21]. When the micro-jets vertically impinge on the surface at the speed from several hundreds to several thousands meters per second[22], the surface is finally destroyed.

3 Summary and conclusions

(1) Under the damage threshold velocity of liquid impact the pits produced during the water erosion are similar to those induced in cavitation erosion, but quite different from those produced by micro-particles impact without steam. The cavitation erosion behavior would occur during the water erosion.

(2) The micro-particles play important roles in the generation of pit, and the damage threshold velocity of liquid impact would decrease due to the effect of micro-particles containing in wet steam.

1 Pollard D, Lord M J, Stockton E C. An evaluation of low pressure steam turbine blade erosion. GECJ Sci Technol, 1983, 1: 29－34
2 Xing X L, Wang C Z. Analysis to satety of typt - C50 - 8. 83/ 0. 118 steam turbine with humid steam to several end class leafs silce. Coal Technology, 2006, 25: 131－133
3 Staniša B, Schauperl Z, Grilec K. Erosion behaviour of turbine rotor blades installed in the Krsko nuclear power plant. Wear, 2003, 254: 735－741[doi]
4 RAO J S. Application of fracture mechanics in the failure analysis of a last stage steam turbine blade. Mech Mach Theory, 1998, 33: 599－602[doi]
5 Dehouve J, Nardin P, Zeghmati M. Erosion study of final stage blading of low pressure steam turbines. Appl Surf Sci, 1999, 144－145: 238－243[doi]
6 Yan Y P, Sun B, Cai Y N. The research of water erosion for steam turbine's rotor blades. Turbin Technol, 1994, 36: 305－317
7 Lee M K, Kim W W, Chang K R, et al. Investigation of liquid impact erosion for 12Cr steel and Stellite 6B. J Nuclear Mater, 1998, 257: 134－144[doi]
8 Stanisa B, Ivusic V. Erosion behaviour and mechanisms for steam turbine roto blades. Wear, 1992, 186－187: 395－400
9 Yang B, Ding H, Hu J M. The application of high pressure pulse water jet in simulating liquid impact erosion of materials. PTCA (PART:Physical testing), 2003, 39: 341－345
10 Kennedy C F, FIELD J E. Damage threshold velocities for liquid impact. J Mater Sci, 2000, 35: 5331－5339[doi]
11 Zhu B T. The effect of solid particle for the water erosion in steam turbine flow passage component and prevention countermeasure. Chin Electric Power, 2003, 36: 150－154
12 Huang S. The effect of solid particle properties on cavitation erosion in solid-water mixtures. J Fluids Engin, 1996, 118: 749－755[doi]
13 Chi M P. Investigations of bubble-particle interactions. Int J Miner Process, 2003, 72: 239－254[doi]
14 Li Y J. Study on mechanism of surface topograhpy effects on generation of cavitation erosion. Dissertation for the Doctoral Degree. Beijing: Tsinghua University, 2008.
15 Marschall H B, Mørch K A, Keller A P, et al. Cavitation inception by almost spherical solid particles in water. Phys Fluids, 2003, 15: 545－553[doi]
16 Mann B S, Vivek A. Coating and surface treatment for enhancing droplet erosion resistance of steam turbine blades. Wear, 2003, 254: 652－667[doi]
17 Tabak W. High-temperature erosion resistance of coatings for use in turbomachinery. Wear, 1995, 186－187: 224－229[doi]
18 Wang L L, Cai X S. progress in research on water droplet size in two phase wet steam flow in steam turbine. J Univer Shanghai Sci Tech, 2003, 25: 307－312
19 Wang J D, Chen H S, Qin L, et al. The crucial effect of micro-particles in hydraulic machinery cavitation corrosion. Chinese Sci Bull, 2007, 52: 2683－2687
20 Huan J T. The Principle and Application of Cavitation and Cavitation Erosion. Beijing: Tsinghua University Press, 1991
21 Klastrup K J, Hansson I, Morch K A. A simple model for cavitation erosion of metals. J Phys D: Appl Phys, 1978, 11: 899－912[doi]
22 Benjamin T B, Ellis A T. The collapse of cavitation bubbles and the pressure thereby produced against solid boundaries. Philos Trans R Soc London Ser A, 1966, 260: 221－240[doi]