Wear 266 (2009) 345–348

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Short communication

Cavitation damages on solid surfaces in suspensions containing spherical and irregular microparticles

Chen Haosheng*, Wang Jiadao, Chen Darong

State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 6 October 2007
Received in revised form 26 April 2008
Accepted 27 May 2008
Available online 7 July 2008

Keywords:
Cavitation erosion
Cavitation
Cavity
Abrasion
Microparticle

ABSTRACT

Spherical and irregular microparticles both in the size of 5 μm were put into the de-ionized water respectively to form different suspensions, and vibrating cavitation experiments were performed in the two kinds of suspensions. After the experiment, the damages on the specimen surfaces were measured and free radicals in suspensions were detected. It was found that suspensions with particles cause more severe cavitation erosion than those without particles. Compared with a spherical particle, the shape of the irregular particle has little effect on the number of the cavities, but it causes abrasion on the solid surface besides the cavitation erosion.

1. Introduction

The cavities formed on solid particle surface are proved to play an important role in the cavitation erosion, and this work continues the previous study on the effect of the microparticle in cavitation erosion [1]. Besides the size, the shape and the surface profile of the microparticle would also affect the cavity formation according to Harvey's theory [2]. Many experiments reviewed by Jones [3] have proved that the cavity formation would like to occur on the surface with crevices and concaves. However, most of the experiments were performed on large plane surfaces. Recently, cavity was found to grow both on spherical microparticles with smooth surfaces [4] and on almost spherical microparticles with concaves on the surfaces [5]. It seems that the cavity formation on the microparticle surface is a little different from that on the plane surface, and the effect of the microparticle's shape on the nucleation is still obscure.

On the other hand, abrasion by microparticles couples cavitation erosion on the damages on solid surface, which has been investigated by the experiments including artificial particles [6,7], and the experiments in sandy water [8,9]. In Li's recent study [10], the cavitation on microparticle's surface was found to even enhance the silt erosion directly. In those experiments, the size and the shape of the particles are proved to be important to the abrasion on the specimen surface. The specimen surface was damaged not only by the cavitation erosion from the collapse impingement, but also by the abrasion from the particle's collision, and the irregular shape of the micro sands was proved to play an important role in the abrasion.

In our ongoing study, vibration cavitation erosion experiment was performed in suspensions containing microparticles with the same size and different shapes. According to the measurement on damaged surface and free radicals detection in the suspension, the effects of the microparticle's shape on the cavitation erosion and abrasion are investigated.

2. Experimental

2.1. Particles and suspensions

Fig. 1(a) shows the vibration cavitation apparatus used in the experiment, which was described in detail in the previous work [1]. The vibration horn performs an axial vibration with the frequency of 20 kHz and the amplitude of 6 μm. The sample piece is installed at the tip of the vibration horn. The specimen used here was made of 40 Cr stainless steel, and its testing surface is polished. The surface roughness is tested by an Atomic Force Microscope (AFM, CSPM 4000), and the root mean square (Rq) value of four testing regions is 28.5 ± 1.5 nm. The experiment is performed in a beaker filled with de-ionized water at the room temperature.

Two kinds of particles were put into de-ionized water to form suspensions. One is spherical SiO_2 particle and the other is irregular SiO_2 particle. The mean diameter of spherical particles is 5.0 ± 0.5 μm, and the sphericity is 0.1% of the diameter. The size

* Corresponding author. Tel.: +86 10 62797646; fax: +86 10 62781379.
E-mail address: chenhs@mail.tsinghua.edu.cn (C. Haosheng).

0043-1648/$ – see front matter
doi:10.1016/j.wear.2008.05.010

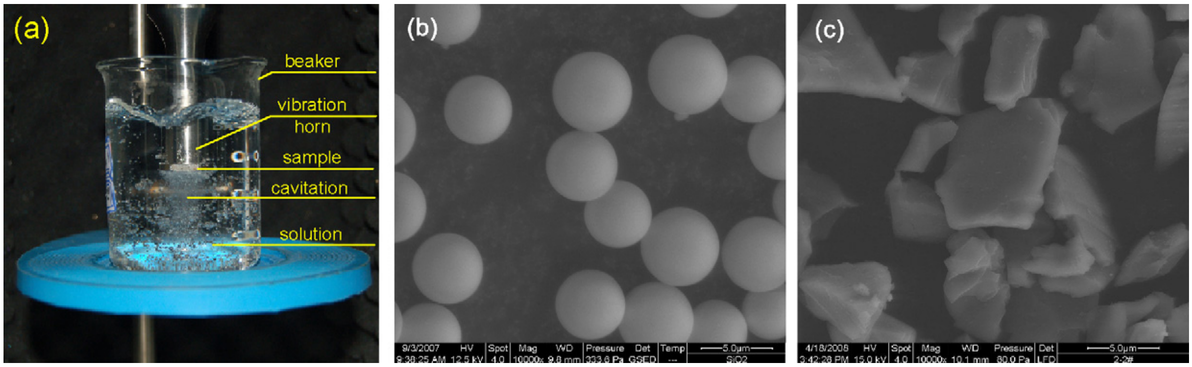

Fig. 1. (a) Vibration cavitation apparatus, (b) SEM picture of spherical particles, and (c) irregular particles.

Table 1
Suspensions and specimen for the experiments

Suspension no.	Suspension description	Specimen no.
0	200 ml TA suspension, not used in the experiment	/
I	200 ml TA suspension + 0.2 wt% spherical particle	1#
II	200 ml TA suspension + 0.2 wt% irregular particle	2#
III	200 ml TA suspension	3#

of irregular particles is 5.0 ± 1.0 μm. Fig. 1 shows the particles observed by Scanning Electrical Microscope (SEM, FEI Quanta 200). The surface of the spherical SiO_2 particle is smooth, while crevices and concaves are found on the irregular particle surface.

Terephthalic acid (TA) in the suspension was used as a cavitation detector according to a fluorescence testing theory [11]: the thermal and mechanical energy released by bubble collapse is sufficient to cause the sonolysis of water and lead to free radical formation, mainly the hydroxyl ($OH^\bullet$) and hydrogen ($H^\bullet$) radicals. Terephthalic acid is a scavenger of $OH^\bullet$ and a well-known dosimeter for ionizing radiation [12]. It rapidly reacts with the resulting $OH^\bullet$ to produce intensely fluorescent hydroxyterephthalate (HTA) [13]. TA suspension was prepared by dissolving the TA in about 800 ml de-ionized water into which 5 ml 1 M NaOH was added. The suspension was stirred for about 1 h and water was added to adjust the volume to 1 l. Then, 200 ml suspension was picked up and put into a beaker where 0.2 wt% particles were added. In this experiment, spherical particles and irregular particles were added into TA solutions respectively to form different kinds of suspensions. The composition of each kind of suspensions and the corresponding specimen used in it are listed in Table 1.

2.2. Cavitation damages on surfaces

The duration of each vibration cavitation experiment was set to 1 min based on Karimi's study [14]. Fig. 2 shows the damaged surface of each specimen after the experiment. Plastic deformations and erosion pits appeared on the original smooth surface, and the surface roughness increased. It is a typical damaged surface at the incubation stage of the cavitation erosion under the collapse impingements. The mean surface roughness and the number of erosion pits are marked in Fig. 2 and Table 2, respectively. It was found that the surface roughness of specimen and the number of erosion pits in different suspensions were different. The surface testing results indicate that the suspensions containing particles cause more severe erosion than suspension without particles, and suspension containing irregular particles causes more severe erosion than the suspension containing spherical particles.

There is another difference between the damaged surface in suspension II and the surfaces in the other two suspensions. As shown in Fig. 3(a) and (c), the pit has a round shape with rim around it. It is a typical erosion pit by the collapse impingement [15]. However, as shown in Fig. 3(b), some indentations and scratches appear on the specimen surface besides the typical erosion pits. Such indentations are smaller than the erosion pits, and they have sharp triangle shapes. Such marks are not found on the other two surfaces, and they are assumed to be the result from the collision of the irregular particles to the polished solid surface.

The assumption was validated by the elemental composition detection on the surface. The energy spectrums of two damaged surfaces of specimens 1# and 2# were shown in Fig. 4. Because there is little Si on the original stainless steel surface before the experiment, the Si peak appearing in the curves represents the direct contact of the particles to the specimen surfaces. Compared with the few concentration of Si on the surface of specimen 1#, irreg-

Table 2
Pits on the specimen surface

Specimen no.	Number of pits	Average depth of pits (μm)	Average diameter of pits (μm)
1#	41.0 ± 7.5	0.60 ± 0.06	1.33 ± 0.22
2#	51.0 ± 5.0	0.50 ± 0.05	0.85 ± 0.50
3#	21.5 ± 5.0	0.58 ± 0.08	1.75 ± 0.50

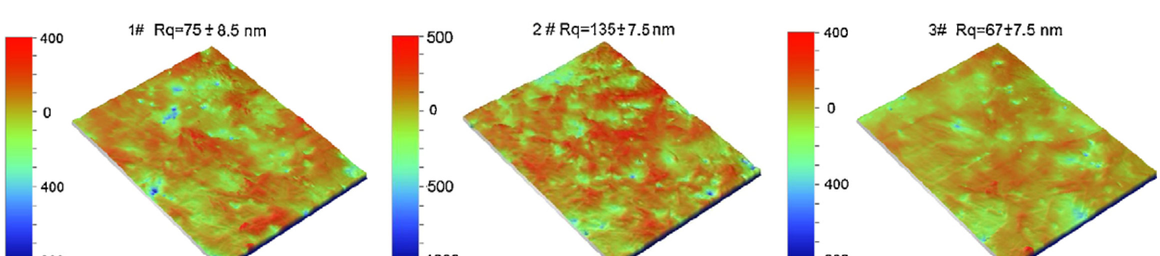

Fig. 2. Damaged surfaces of specimen under Wyko MHT-III interferometer with measured surface roughness.

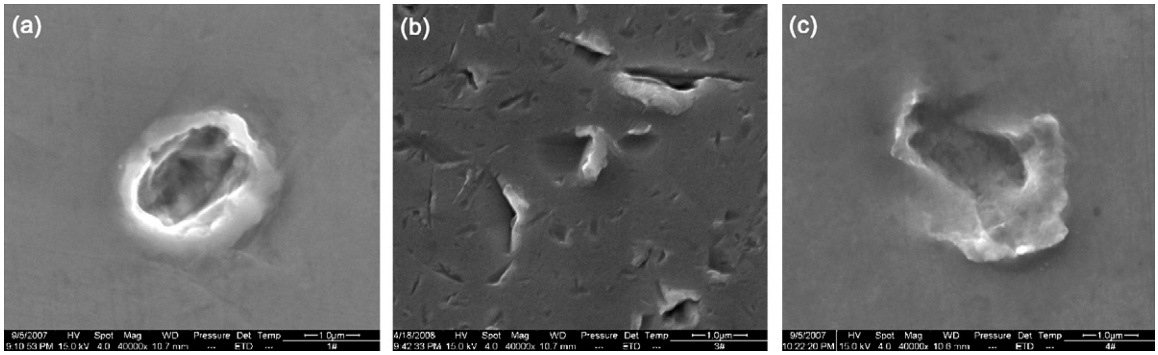

Fig. 3. Pits on specimen surfaces in different suspensions. (a) specimen 1#, (b) 2# specimen, and (c) 3# specimen.

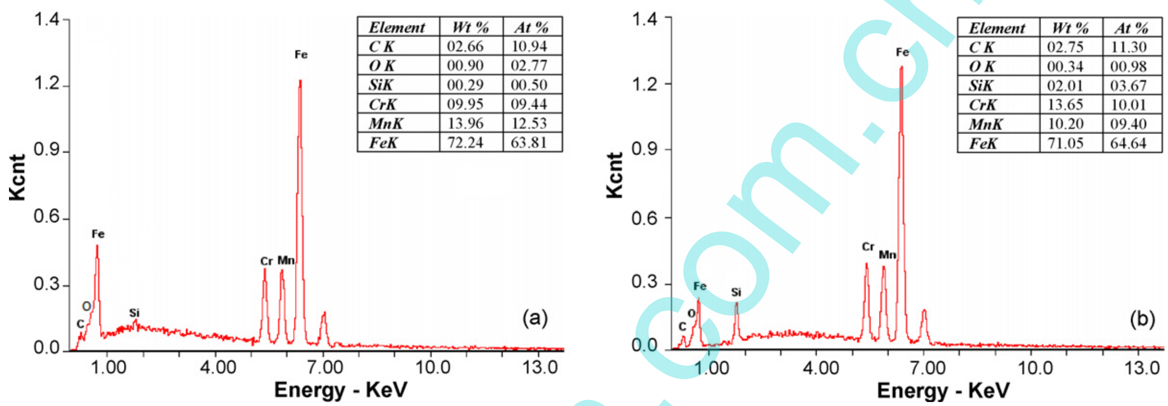

Fig. 4. Energy spectrum done by EDS in Quanta 200 SEM. (a) Elements on 1# specimen surface and (b) elements on 2# specimen surface.

ular particles must have much more chances to collide with the specimen surface.

2.3. Free radicals detection

The fact that irregular particles collide with the specimen surface makes it hard to determine the effect of the microparticles on cavitation erosion. Whether the more severe damages on the surface are caused by the more collapse impingement due to the particle's irregular shape, or by the additional abrasion from the collision? This problem can hardly be clarified according to the surface damages, because the plastic deformations from the two reasons may be superposed. Here, free radicals detection is adopted to determine the number of collapse in different suspensions. Each kind of suspension was centrifuged at the speed of 15,000 round/min for 10 min after the cavitation experiment. The particles were separated from the suspension, and the clarified suspensions were picked up for the fluorescence test. The exciting wavelength is 310 nm and the emission wavelength is 423 nm. Fig. 5 shows the fluorescence intensities of different suspensions.

3. Explanation and discussion

According to the experimental results, microparticles show great effects on the cavitation erosion on solid surfaces. Firstly, based on the fluorescence intensity of suspension, the particles, either spherical or irregular, increase the number of cavities collapsed in the liquid, and the solid surface has more chances to be damaged by the impingement. This result copes with the higher surface roughness and more erosion pits on specimen 1# and 2#. It indicates that the solid particles help to increase the cavitation erosion on solid surfaces through increasing the number of the cavities. Furthermore, the fluorescence intensity of suspension containing spherical balls is almost the same as that of suspension containing irregular particles, which indicates that the shape of the particles has little effect on the number of the collapsed cavities. This result seems to conflict with Harvey's theory to some extent, because the crevices and concaves on the solid surfaces are usually thought to help the growth of the cavities. Herein, the micro size of the particle is considered as the main reason. In the experiment done by Arora et al., large vapor cavities were directly seen to grow from small regions on spherical particle surface through high speed photographs [4]. The relationship between the particle radius and the

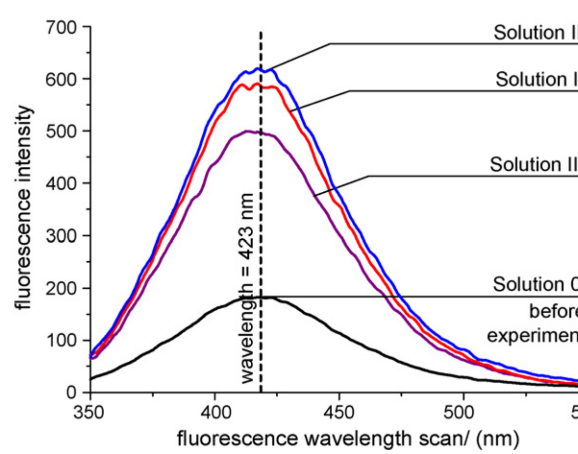

Fig. 5. Experimental data of fluorescence intensity for different suspensions using PerkinElmer LS-55.

cavity radius before separation was also provided in his work. Thus, for microparticles, cavities can grow from their surfaces, and the number of such cavities is almost independent of the particles' shape, or, at least the shape is not so important as the particle's other properties, such as the size [1].

Secondly, it can be deduced from the indentations and the existence of Si on the sample surface that the irregular particles directly collide the surface. Thus, the irregular particles not only increase the cavitation erosion but also cause the particle abrasion on the surface. On the other hand, few abrasive damages were found on the surface in suspension containing spherical particles. Since both of the two kinds of particles have the same size and same hardness, the shape of the particle is a key factor to cause that difference. The microparticle is like an indenter when it collides the steel surface, because the 40 Cr steel is softer than SiO_2 particle (the hardness of SiO_2 is HV750-1200, 40 Cr steel is HV600). Since an indentation is much easier to be formed by a sharp triangle indenter than by a spherical indenter, it is easy for irregular particles to cause indentation, while it is not easy for spherical particles to do so. This postulation was validated by the sharp edge of the indentations on the sample surface shown in Fig. 3(b). Therefore, for irregular particles, additional abrasive effect needs to be considered in the cavitation erosion when calculating the mass loss rate or analyzing the fatigue process.

It should be notified that all the results and explanations provided here are based on the fact that the particles are in the size of 5 μm, and they may be not proper for larger or smaller particles.

4. Conclusions

Under the condition that the particles are in the size of 5 μm, some conclusions can be drawn as follows based on the experiment results discussed above.

(1) Microparticles, either spherical or irregular, increase the cavitation erosion through increasing the number of cavities in the suspension, and the particle's shape has little effect on the cavitation erosion.
(2) Detection on specimen surface proves that the irregular particles directly collide the specimen surface while spherical particles may not. This result indicates that the particle abrasive effect needs to be considered in cavitation erosion when the suspension contains irregular particles.

Acknowledgments

Project (No. 50505020) supported by *NSFC*, and *Project* (2007CB707702) supported by National Basic Research Program of China are thanked. The authors would also like to thank *Yang Wenyan and Tao Shenyang* (Tsinghua University) for their help in SEM picture preparation and free radicals detection.

References

[1] H.S. Chen, S.H. Liu, D.R. Chen, J.D. Wang, Study on effect of microparticle's size on cavitation erosion in solid-liquid system, J. Appl. Phys. 101 (2007) 103510-1–103510-5.
[2] E.N. Harvey, W.D. McElroy, A.H. Whiteley, On cavity formation in water, J. Appl. Phys. 18 (1947) 162–172.
[3] S.F. Jones, G.M. Evans, K.P. Galvin, Bubble nucleation from gas cavities—a review, Adv. Colloid Interface Sci. 80 (1999) 27–50.
[4] M. Arora, C.D. Ohl, K.A. Morch, Cavitation inception on microparticles: a self-propelled particle accelerator, Phys. Rev. Lett. 92 (2004) 174501-1–174501-4.
[5] H.B. Marschall, K.A. Morch, A.P. Keller, M. Kjeldsen, Cavitation inception by almost spherical solid particles in water, Phys. Fluids 15 (2003) 545–553.
[6] J. Sato, K. Usami, T. Okamura, S. Tanaba, Basic studies of coupled damaged caused by silt abrasion and cavitation erosion, ASME Fluids Eng. Div. 136 (1992) 65–70.
[7] J. Sato, K. Usami, T. Okamura, S. Tanaba, Basic study of coupled damage caused by silt abrasion and cavitation erosion (experiments with submerged water jets), JSME Int. J., Ser. 2: Fluids Eng., Heat Transfer, Power, Combust., Thermophys. Prop. 34 (1991) 292–297.
[8] K. Zhao, C.Q. Gu, F.S. Shen, B.Z. Lou, Study on mechanism of combined action of abrasion and cavitation erosion on some engineering steels, Wear 162–164 (1993) 811–819.
[9] S. Huang, A. Ihara, Effects of solid particle properties on cavitation erosion in solid–water mixture, J. Fluids Eng. 118 (1996) 749–755.
[10] S.C. Li, Cavitation enhancement of silt erosion—an envisaged micro model, Wear 260 (2006) 1145–1150.
[11] H.G. Flynn, Generation of transient cavities in liquids by microsecond pulses of ultrasound, J. Acoust. Soc. Am. 72 (1982) 926–927.
[12] R.W. Matthews, N.T. Barker, D.F. Sangster, A comparison of some aqueous chemical dosimeters for absorbed doses of less than 1000 rads, Int. J. Appl. Radiat. Isot. 29 (1978) 1–8.
[13] R.W. Matthews, The radiation chemistry of the terephthalate dosimeter, Radiat. Res. 83 (1980) 27–41.
[14] A. Karimi, F. Avellan, Comparison of erosion mechanisms in different types of cavitation, Wear 113 (1986) 305–322.
[15] A. Karimi, R.K. Schmid, Ripple formation in solid-liquid erosion, Wear 156 (1992) 33–47.