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Short communication

A ring area formed around the erosion pit on 1Cr18Ni9Ti stainless steel surface in incipient cavitation erosion

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ABSTRACT

After a 1 min cavitation experiment performed in an ultrasonic vibration system, needle-like erosion pits appeared on a polished stainless steel surface, and a special ring area was formed around each pit. The shape of the pit and the plastic deformation of the ring area indicate that the mechanical impaction on the surface is the main reason for the cavitation erosion. On the other hand, the iridescent color, the decreased surface hardness and the appearance of the precipitated carbon ring prove that the ring area has experienced a tempering process with the temperature higher than 300 °C. Also, the lack of oxygen in the ring area proves that it is not a chemical oxygen result.

It has been acknowledged that a mechanical damage process of the cavitation erosion is often accompanied by a thermal effect [1]. Numerical results acquired by Plesset [2] and experimental phenomenon observed by Nowotny [3] and Gavranek et al. [4] show that a high temperature is reached in the cavity at the end stage of bubble collapse. The temperature is so high that the metal strength is reduced and sometimes the metal surface even melts. Numerical results given by Wu and Robert [5] and Ying and An [6] recently show that the temperature in the cavity reaches 10,000 °C at the moment of collapsing. However, the thermal effect is not considered as the main reason for the cavitation erosion. Knapp et al. [7] have pointed out that the heat is hard to be transferred to the surface effectively, and the surface of some materials with good heat conductivity cannot reach a high temperature. Additionally, the color changed on the metal surface is considered as a chemical oxygenized result under a lower temperature. In the undergoing study, characteristics of the erosion pit at the incipient stage of the cavitation erosion are observed to investigate how the erosion pit forms and whether the thermal effect takes part in the formation of the pit. A sample made of stainless steel (1Cr18Ni9Ti) is installed on a static platform and the bubbles generated by an ultrasonic vibration system rush forward to the sample surface. After the experiment, surface profile, surface hardness and elemental composition of the erosion pit are tested.

Fig. 1 shows an ultrasonic vibration cavitation system. The vibration horn performs an axial vibration with the frequency of 20 kHz and the amplitude of 6 μm. A sample piece is installed on the support arm of a two dimensional table. The testing surface of the sample faces the tip of the vibration stick, and the interval between them is adjusted by the translation stage, while the pitch angle of the sample surface is adjusted by the rotation stage. The experiment is performed in a beaker filled with de-ionized water. The sample is designed according to Chinese standard (GB6383-86) on vibration cavitation erosion system. The sample surface is polished, and the root mean square (Rq) value of the surface roughness is 15.5 ± 2.5 nm, which is tested by an Atomic Force Microscope (AFM) CSPM 4000. It should be noted here that there are three measuring regions on the sample surface marked as 1–3 in Fig. 1(b). Each region is the size of $5\,\mu m \times 5\,\mu m$, and the surface roughness is the mean value of the three regions. The composition of the stainless steel specimen is listed in Table 1.

The experiment lasted 1 min. Fig. 2(a) shows the erosion pit on the steel surface observed by an Olympus LEXT OLS3100 confocal laser-scanning microscope. It was found that an area with a distinguished round shape and an iridescent color was formed around each erosion pit. Here, the area is called 'ring area' according to its shape. The surface profile of the erosion pit with an obvious ring area is shown in Fig. 2(b). The continuous line represents the surface profile of the cross section of the sample surface, and it shows both the shapes of the pit and of the ring. The erosion pit is narrow and deep, and it is usually called needle-liked pit [1], which is a characteristic phenomenon appeared at the incipient stage of the

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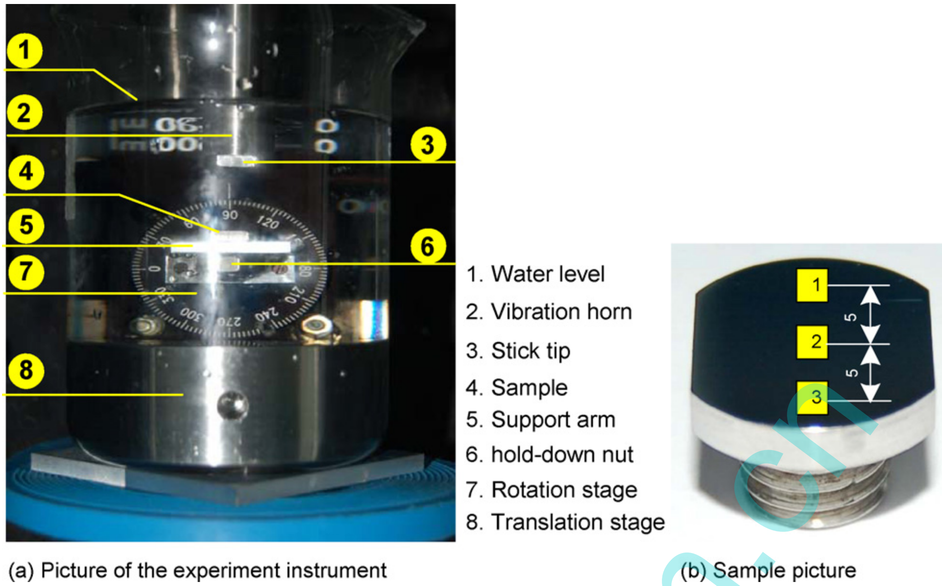

Fig. 1. (a) Vibration cavitation system, and (b) the picture of the sample with testing regions.

cavitation erosion. The ring area is a little bit raised from the base, which is also found on the aluminum surface in the erosion experiment done by Knapp [8]. The ring area is believed to be the result of the plastic deformation of the material following the pit's formation caused by the impaction at the moment of the bubble collapse [9]. So both the formation of the erosion pit and the deformation of the ring area indicate that a mechanical action with high pressures is the main damage mechanism for the cavitation erosion.

The hardness of the damaged surface shown in Fig. 2 was tested by a Nano Tester (MML Co.). 10 indents were made on the sample surface along the radius direction, which are shown in Fig. 3(a). The interval between the indents is 10 μm, and the maximum load was 50 mN. The hardness data of the surface within and outside the ring area is shown in Fig. 3(b). It is found that the mean value of the hardness inside the ring is obviously lower than that outside the ring. Also, obvious plastic deformations were seen around the indents inside the ring, while the edge of the triangle shape of the indent outside of the ring is clear. Moreover, as shown in Fig. 2 and Fig. 3(a), the ring is colorful and the color of the surface within the ring changes from red to blue gradually. The appearance of the iridescent color indicates that the temperature on the steel surface may reach 300 °C according to Wang's experiment [10]. On the other hand, it is known that the hardness of the steel decreases when the steel is tempered under the temperature higher than 300 °C. So, the iridescent color and the decreased surface hardness both indicate that the ring area has experienced a high temperature tempering process.

Based on the heat treatment theory [11], the surface hardness reduction during the tempering process is caused by the precipitation of the carbides on the surface. Therefore, the elemental composition of surface materials on the damaged surface was tested by EPMA-1600 electronic probe with a wavelength dispersive spectrometry (WDS). Six elements as ferro, carbon, oxygen, chrome, nickel and titanium were detected within the ring area. The quantitative concentrations of the six elements are shown in Fig. 4

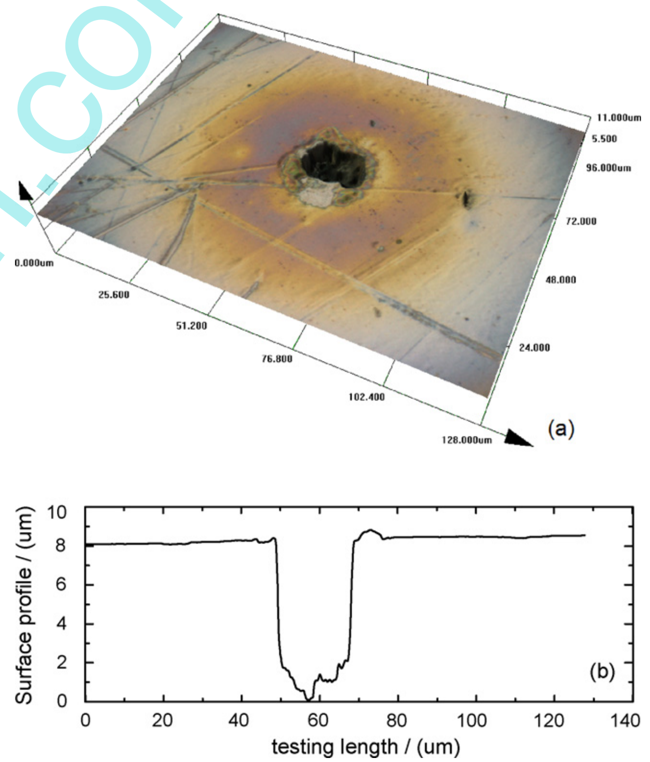

Fig. 2. Surface profile of the erosion pit with ring are tested by confocal laser scanning microscope. (a) Picture of the pits scattered on the surface and (b) surface profile of the cross section of the pit.

using line scan along the horizontal diametric line across the erosion pit. *Y*-axis represents the percentage of each element counts compared with its maximum atom counts except for oxygen whose value is the percentage of counts compared with 100. The numbers

Table 1
The composition of the stainless steel specimen

C (%)	Mn (%)	Al (%)	Cr (%)	Ni (%)	Ti (%)	Si (%)	S (%)	P (%)
≤0.12	≤2.00	≤0.001	17.0–19.0	8.0–11.0	0.3–0.8	≤1.00	≤0.03	≤0.035

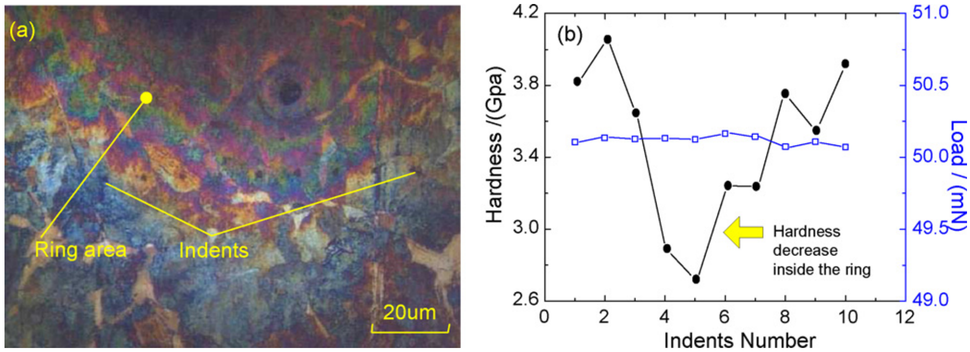

Fig. 3. Surface hardness testing, (a) is the pit with indents, (b) is the hardness in and outside the ring.

marked in the figure are the true maximum and minimum atom counts for each element. In Fig. 4, it is found that the carbon also forms a ring in the ring area, which is called ‘carbon ring’ here. The carbon concentration increased in the ring while the concentrations of the other five elements did not change much. It proves that the carbon and carbides precipitate on the surface, and the ring area has experienced a tempering process. The concentration variation of the oxygen on the surface indicates that the ring area is not a chemical oxygenized result under a lower temperature. The special distribution of the carbon in the ring area is considered here to be related to the bubble profile at the final stage of the collapse near the surface. The numerical results acquired by Best [12] and Zhang et al. [13] show that a bubble will change its shape from spherical to toroidal after the first collapse, and the temperature in the toroidal bubble is still high. Because the ring area is raised after the first impaction caused by the micro-jet, its surface becomes closer to the toroidal bubble or even contact it, then the surface is tempered with higher temperature at the place where the ring forms.

The characteristics of the pits at the incipient stage of the cavitation erosion are investigated after 1 min cavitation erosion experiment, and some of the conclusions are drawn as follows:

(1) The surface profile of the erosion pit shows that a raised ring area is formed around each pit. The narrow and deep profile of the pit and the plastic deformation of the ring area indicate that the mechanical impaction is the main reason for the cavitation erosion at the incipient stage.
(2) The iridescent color, the surface hardness reduction and the appearance of the precipitated carbon rings on the surface all indicate that the ring area has experienced a tempering process

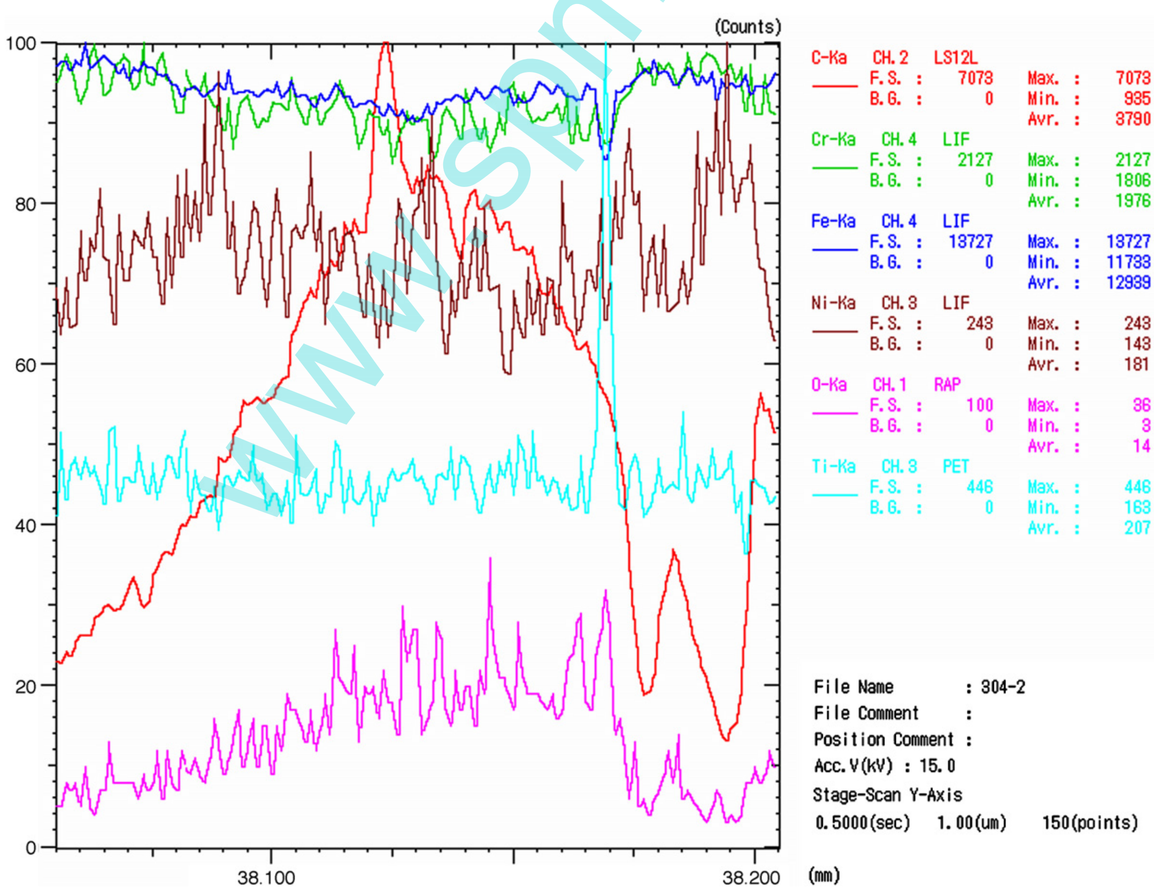

Fig. 4. The line scan results of the elemental composition of surface materials tested by EPMA-1600 electronic probe.

with a temperature higher than 300 °C. The lack of oxygen in the ring area also proves that it is not a chemical oxygenized action under a lower temperature. The carbon ring is considered to be heated by the toroidal bubble on the ring area at the final stage of the bubble collapse.

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References

[1] F.G. Hammitt, Cavitation and Multiphase Flow Phenomena, McGraw-Hill Inc., USA, 1980, 241 pp.
[2] M.S. Plesset, Bubble dynamics, in: R. Davis (Ed.), Cavitation in Real Fluids, Elsevier Pub. Co., Amsterdam, 1964.
[3] H. Nowotny, Destruction of Materials by Cavitation, VDI-Verlag, Berlin, 1942.
[4] V.V. Gavranek, D.N. Bol'shutkin, V.I. Zel'dovich, Thermal and mechanical action of a cavitation zone on the surface of a metal, Fiz. Metal I Metalloved. 10 (1960) 262–268.
[5] C.C. Wu, P.H. Robert, Shock-wave propagation in a sonoluminescence gas bubble, Phys. Rev. Lett. 70 (22) (1993) 3424–3427.
[6] C.F. Ying, L. An, High temperature and high pressure distribution in gas bubbles generated by sound cavitation, Sci. China, Series A 32 (4) (2002) 305–313.
[7] R.T. Knapp, J.W. Daily, F.G. Hammit, Cavitation, McGraw-Hill, New York, 1970.
[8] R.T. Knapp, Recent investigations of cavitation and cavitation damage, Trans. ASME 77 (1955) 1045–1054.
[9] M.S. Plesset, A.T. Ellis, On mechanism of cavitation damage, ASME Trans. 77 (1955) 1055–1064.
[10] Z.C. Wang, Y. Zhang, X.Q. Zhang, Thermal effect of cavitation erosion, Chin. J. Mater. Res. 15 (6) (2001) 287–290.
[11] E. Gregory, N. Simons, The Heat-Treatment of Steel, Pitman & Sons, Ltd., London, 1958.
[12] J.P. Best, The formation of toroidal bubbles upon the collapse of transient cavities, J. Fluid. Mech. 251 (1993) 79–107.
[13] S. Zhang, J.H. Duncan, G.L. Chahine, The final stage of the collapse of a cavitation bubble near a rigid wall, J. Fluid. Mech. 257 (1993) 147–181.