Thermal Effect at the Incipient Stage of Cavitation Erosion on a Stainless Steel in Ultrasonic Vibration Cavitation

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An ultrasonic vibration cavitation erosion experiment was performed to study the thermal effect during the erosion process. The ring affected zone was observed on the sample surface around the erosion pit at the incipient stage of the cavitation erosion. The results of the surface testing on roughness, hardness, and chemical composition proved that the zone was caused by thermal effect, and that the zone surface experienced a tempering process with the temperature higher than 300°C. Numerical simulation results show that the high temperature domain in the bubble directly contacting the solid wall is a necessary condition for the occurrence of the tempering process on the zone surface, or the heat in the bubble can hardly be transferred to the solid wall under the effects of the great temperature gradient in the bubble and the quick cooling process in the water.
[DOI: 10.1115/1.3054282]

Keywords: cavitation erosion, bubble dynamics, thermal effect, ultrasonic vibration cavitation

1 Introduction

It has been acknowledged that the collapse of a bubble close to a solid wall is the main reason for the cavitation erosion, and thermal effect may appear during the bubble compress and collapse processes [1]. The experimental phenomenon observed by Nowotny [2] and Gavranek et al. [3] showed that high temperature was reached in the bubble at the end stage of the bubble collapse. In the experiment, the temperature was so high that the metal strength was reduced and the metal surface even melted. On the other hand, numerical results formally reviewed by Knapp et al. [4] and recently provided by Wu and Robert [5] and Ying and An [6] showed that the temperature in the bubble can reach 10,000°C at the moment of collapse. However, in many cavitation erosion experiments, it is difficult to find the evidence of thermal effect on the damaged surface. As Knapp et al. [4] pointed out, although the temperature was very high in the bubble, the heat was hard to be transferred to the surface efficiently with the existence of water separating the hot bubble and the solid wall. Another important reason was that the surface of some materials, such as steel, cannot reach high temperature because it has good heat conductivity.

According to Knapp's explanation, it seems that the sample surface may not be affected by the thermal effect during the cavitation erosion process. However, at least two questions still need to be answered. First, can every bubble be separated by the water and none of them have the chance to contact the solid wall? Second, it is well known that the collapse process is very quick, for example, a bubble with 1 mm radius will collapse in several microseconds. When a bubble collapses near a solid surface, high temperature will be reached in a very short time, which is like the formation of *flash temperature* [7]. It is proved that the flash temperature can damage the local metal surface before it is decreased by the metal heat conductivity. Hence, the thermal effect may have the chance to take part in the erosion process on a metal surface.

Our undergoing study investigates whether the thermal effect takes part in the formation of the pit. To achieve this goal, samples made of stainless steel (1Cr18Ni9Ti) were 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 were tested to look for the evidence of the thermal effect at the incipient stage of the cavitation erosion. Later, numerical analyses are given to explain the experimental results.

2 Vibration Cavitation Experiment

Figure 1 shows an ultrasonic vibration cavitation system. The vibration stick performs an axial vibration with the frequency of 20 kHz and the amplitude of 6 μm. A sample piece was installed on the support arm of a two dimensional table. The testing surface of the sample faced the tip of the vibration stick. The interval between the two surfaces was adjusted by the translation stage, while the pitch angle of the sample surface was adjusted by the rotation stage. The experiment was performed in a beaker filled with de-ionized water, which is provided by a supplier, with the standards of resistivity higher than 10 MΩ/cm, a reactive silica level of generally less than 20 μg/l, and the maximum total dissolved solids less than 10 mg/1. The temperature of the water during the experiment was measured by a mercury thermometer. The original temperature before the experiment was 20°C, while it increased to 23.5°C at the end of a 5 min experiment. The dissolved gas content in the de-ionized water before experiment is 1.78% measured by HI9804 water quality analyzer. Figures 1(*b*) and 1(*c*) show the sample and its surface profile, respectively. The sample was designed according to Chinese standards (GB6383–86) on vibration cavitation erosion system. The sample surface was polished, and the root mean square (Rq) value of the surface roughness was 12.5 nm, which was tested by an atomic force microscope (AFM) CSPM 4000. It should be noted here that there were three measuring regions on the sample surface marked as 1–3 in Fig. 1(*b*). Each region was the size of 5×5 μm^2, and the surface roughness of the sample surface was the mean value of the three regions.

The experiment lasted 5 min. The cavitation phenomena captured by a digital camera was shown in Fig. 1(*d*). A clear cavitation domain was found near the vibration stick's tip, and some bubbles were seen rushing toward the sample surface. Figure 2(*a*) shows the erosion pits on the steel surface observed by an Olympus LEXT OLS3100 confocal laser scanning microscope. It was found that a distinguished ring zone with an iridescent color was formed around some erosion pits. An erosion pit with an obvious ring zone was tested and its surface profile was shown in Fig. 2(*b*). The continuous curve represents the surface profile of the sample surface at the position where the dashed line stands. The erosion pit is narrow and deep, and it is usually called needlelike

Contributed by the Fluids Engineering Division of ASME for publication in the JOURNAL OF FLUIDS ENGINEERING. Manuscript received June 12, 2007; final manuscript received May 3, 2008; published online January 9, 2009. Assoc. Editor: Steven Ceccio.

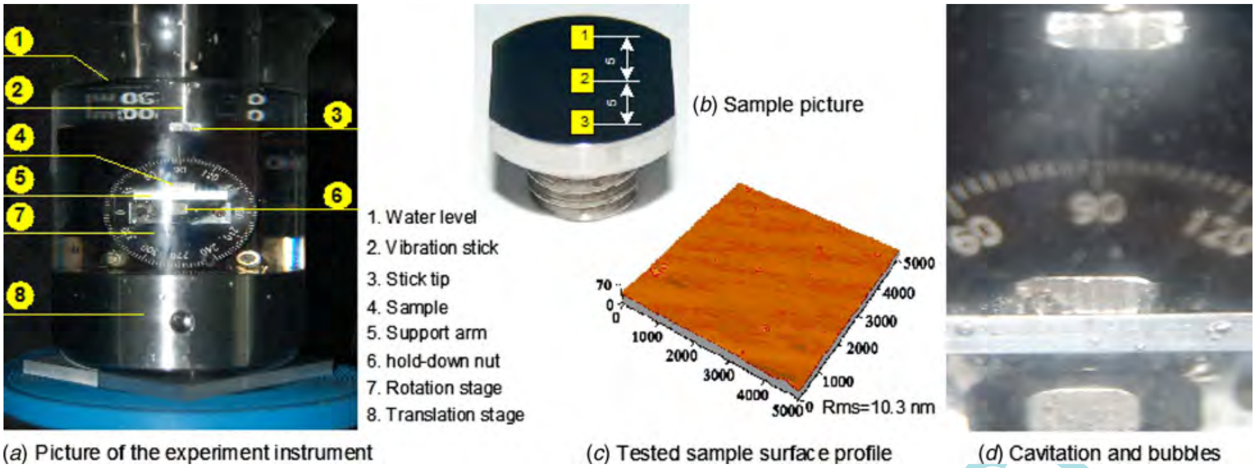

Fig. 1 (***a***) **Vibration cavitation system, (*b*) the picture of the sample, (*c*) surface profile of the sample surface, and (*d*) experimental phenomenon**

pit [1], which is a characteristic phenomenon that appeared at the incipient stage of cavitation erosion. The ring zone was raised from the base, which copes with the experimental results done by Knapp [8] on the aluminum surface. The ring zone is believed to be the result of the plastic deformation of the material under the effect of the microjet formed at the moment of the bubble collapse [9]. This result proves that the cavitation erosion occurs, and a kind of ring zone appears at the incipient stage of the cavitation erosion.

The hardness of the damaged surface was tested by a Nano Tester (Micro Materials Ltd.). Twelve indents were made on the sample surface shown in Fig. 3(*a*). The interval between the indents was 15 μm, and the maximum load was 50 mN. The hardness 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 triangle shape of the indent outside of the ring is clear. Moreover, as shown in Figs. 2 and 3(*a*), the ring is colorful. The appearance of the iridescent color indicates that the temperature on the steel surface may reach 300°C according to the experiment of Wang et al. [10]. On the other hand, it is known that the hardness of the steel decreases when the steel is tempered with the temperature higher than 300°C. Hence, the iridescent color and the decreased surface hardness both indicate that the surface within the ring 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 the damaged surface was tested by EPMA-1600 electronic probe with a wavelength dispersive spectrometry (WDS). Six elements, namely, ferro, carbon, oxygen, chrome, nickel, and titanium were detected within the ring. In Fig. 4(*a*), the distribution of the carbon on the damaged surface was tested using an area scan method, where the concentration was represented by the color. It is found that the carbon distribution also has a ring shape. The quantitative concentrations of the six elements are shown in Figs. 4(*b*) and 4(*c*) using line scan along the horizontal diametric line, as shown in Fig. 4(*a*). The *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 marked in the figure are the tested maximum and minimum atom counts for each element. Each curve is the mean result of three scanned results at the same position, the uncertainty of each curve is calculated according to the standard error calculation method. The uncertainties of concentrations with respect to different elements are $\pm 3.5\%$

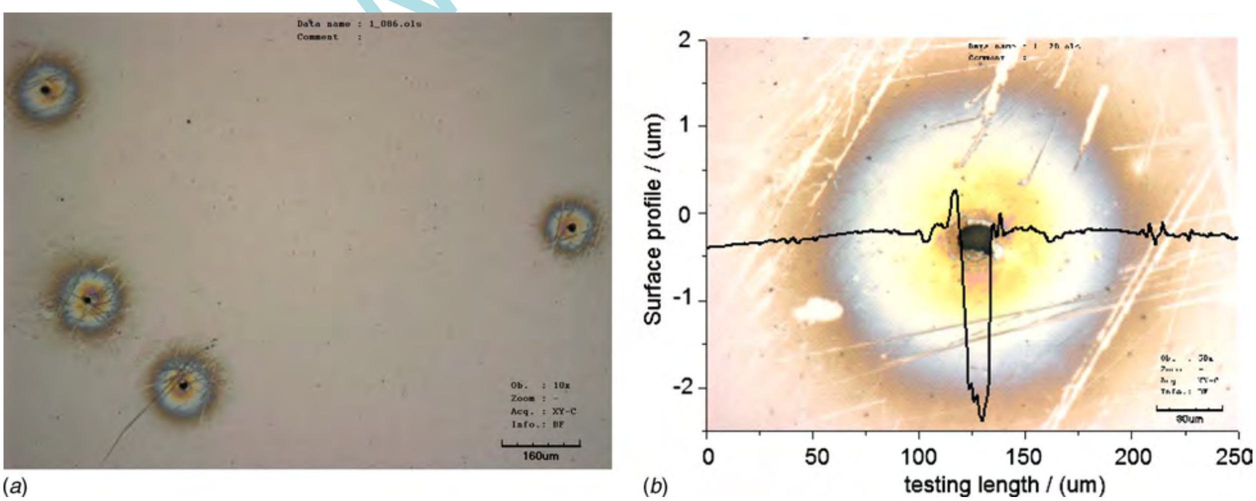

Fig. 2 (***a***) **Pits scattered on the surface and (*b*) surface profile of the erosion pit tested by confocal laser scanning microscope; the uncertainty of the measured data is 0.01 μm according to the precision of the microscope**

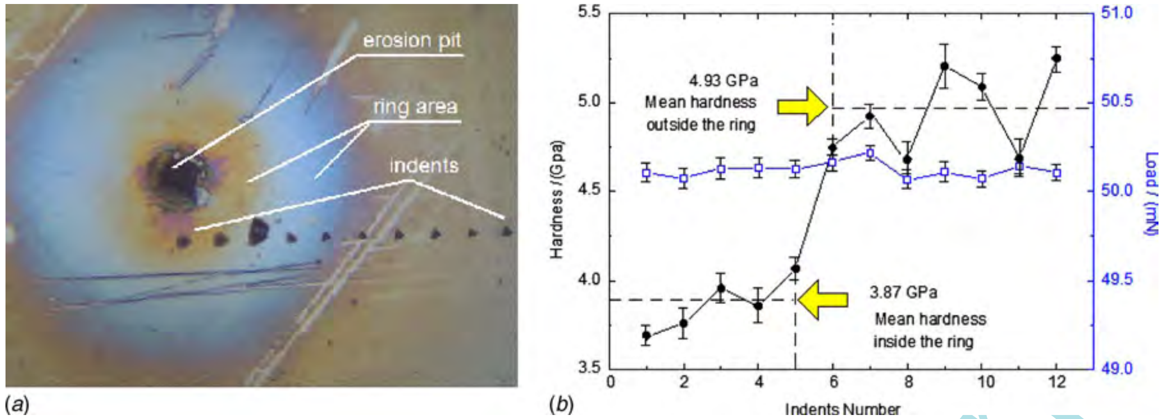

Fig. 3 Surface hardness testing; (*a*) is the pit with indents, and (*b*) is the hardness in and outside the ring affected zone

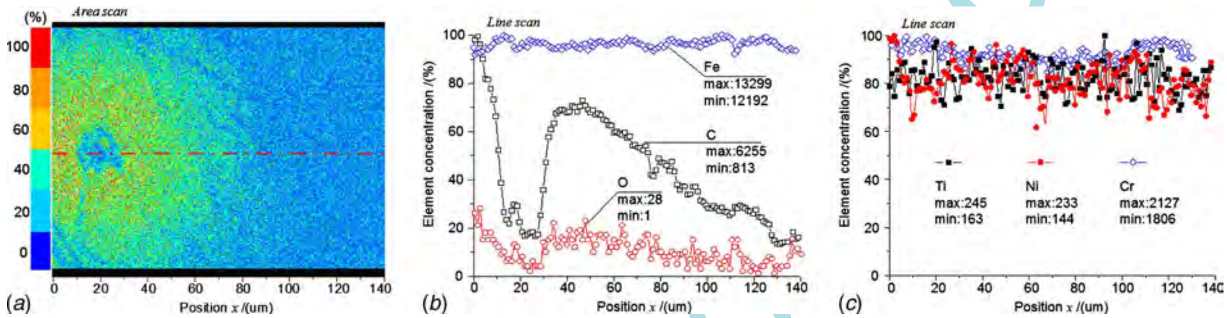

Fig. 4 The elemental composition of surface materials tested by EPMA-1600 electronic probe: (*a*) is the area scan result of carbon; (*b*) is the line scan results of Fe, C, and O; and (*c*) is the line scan results of Cr, Ti, and Ni

(Fe), ±7.5% (C), ±7.0% (O), ±9.5% (Ti), ±12.5% (Ni), and 6.5% (Cr). The carbon concentration increased in the ring while the concentrations of the other five elements did not change much. It proves that the carbon precipitated on the surface, and the ring has experienced a tempering process. The lack of oxygen on the surface indicates that the ring area is not a chemical oxygenized result under a lower temperature.

3 Conclusions

A kind of ring heat-affected zone is observed around the erosion pit on a steel surface in an ultrasonic vibration cavitation erosion system. Surface analyses on roughness, hardness, and chemical composition proves that the zone is caused by the thermal effect, and that the zone surface is considered to experience a tempering process with temperature higher than 300°C.

Acknowledgment

Project (No. 50505020) supported by the NSFC and project (No. 2007CB707702) supported by the National Basic Research Program of China are thanked.

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