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Iridescent rings around cavitation erosion pits on surface of mild carbon steel

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ABSTRACT

Special rings with iridescent color were found around erosion pits on mild carbon steel surface in rotate disk cavitation erosion experiments. The EDS and XPS examinations proved that the ring was an oxidation film mainly composed of Fe_2O_3. The mean diameter of iridescent rings was 200–300 μm, and the thickness was 200–500 nm. The rings have four main kinds of the shapes, named as O-shaped, U-shaped, pies and comet rings. Their special shapes and chemical compositions indicate that the iridescent rings are products of a kind of local oxidizations related to the collapsing bubbles above them. Based on numerical and experimental results, it is explained that the hot gas in a collapsing bubble is possible to contact the metal surface to cause the high temperature oxidization, and the shape of the bubble at its final stage of collapsing is responsible for the special shape of the ring.

1. Introduction

Recently, separated colorful dapples were found around the erosion pits on steel surfaces in rotate disk cavitation erosion experiments [1,2]. Such pits were also found later by Chen et al. [3] in vibration cavitation erosion experiments. In the center of the dapple, there was a deep pit with some black ablation marks, and iridescent rings were around the pit. Sometimes, the iridescent rings were not round, but had tails that were called "comet pits" by Hodgkiess et al. [4].

The reason for the formation of the rings is not clear yet. It used to be assumed that the rings were results of thermal effect caused by the hot gas in collapsing bubbles. In experiment, Nowotny [5] and Gavranek et al. [6] observed a high temperature in the bubble at the end stage of its collapse, and the temperature was so high that the metal strength was reduced and the metal surface even melted. Recently, surface analyses on the rings proved that the surface experienced a tempering process with the temperature higher than 300 °C [3]. Numerical results provided by Wu and Robert [7] and Ying and An [8] showed that the temperature in the bubble can reach 10,000 °C at the moment of collapsing. Such hot gas was thought to be a possible reason for the formation of the rings. However, there were viewpoints object to such explanations. As Knapp et al. [9] 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 film separating the hot bubble and the solid wall. Another important reason was that the metal surfaces cannot reach high temperature because of their good heat conductivities. It was insisted that the rings were the oxidization film, and the formation reason was just a chemical corrosion. However, it is difficult to explain why corrosion happens within a local area with such a special shape.

Our undergoing study is to find a proper reason for the formation of the iridescent rings. Mild carbon steel with polished surface was installed in a rotating disk cavitation erosion system to record the rings. After the experiment, the surface profiles and chemical composition of the rings were measured. According to the measured results, the possible reasons for the ring's formation are analyzed, and a proper explanation is provided.

2. Experimental

2.1. Schematics and apparatus

Fig. 1 is the schematics of a rotate disk cavitation erosion apparatus. The diameter of the rotating-disk was 300 mm and four equispaced samples were installed on the rotating disk. To induce the cavitation, a hole with 10 mm diameter was made on the rotating-disk in front of each sample. The rotating speed of the rotating disk was 2100 round/min driven by the motor, and the velocity of the samples was near 22 m/s. The fluid used in the experiment was tap water, and the temperature of the water in the experiments was kept at the room temperature using the low temperature water circulation system.

In this experiment, the samples were made of a kind of mild carbon steel (0.45% carbon) without heat treatment, yield stress σ_s was 355 MPa, the ultimate stress σ_b was 650 MPa. Its chemical composition was shown in Table 1 and its size was 40 mm × 30 mm × 6 mm.

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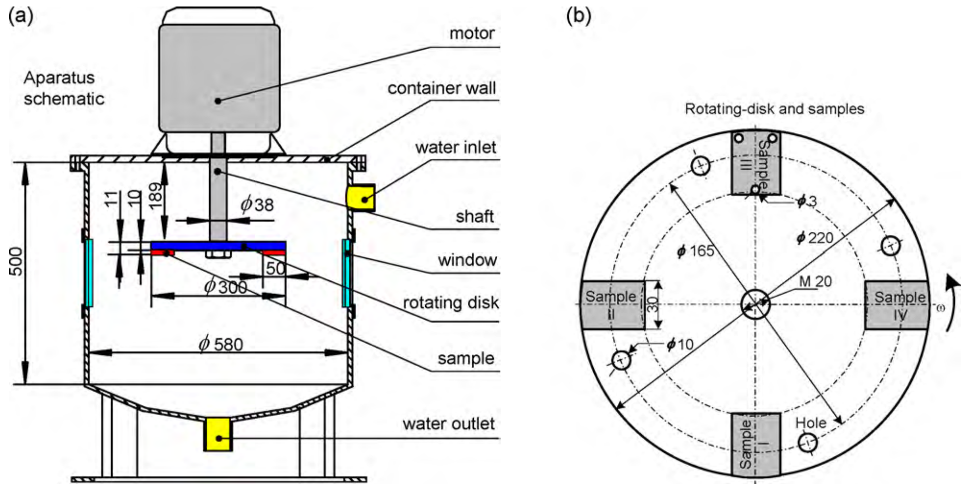

Fig. 1. (a) Schematics of the cavitation experimental apparatus and (b) the installment of the samples.

Table 1
Chemical composition of mild carbon steel used in experiment (%).

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

The specimen surface is polished, and the mean squared surface roughness (Rq) is 28 nm.

2.2. Profiles of the rings

After 2-h cavitation erosion experiments, colorful dapples appeared on the steel surface as shown in Fig. 2(a). Each dapple has an erosion pit in its center and a kind of ring shaped area with different colors around the pit as shown in Fig. 2(b). The colorful ring area is called iridescent ring here. Some of the rings are round, while others have tails.

Generally, the iridescent rings can be classified into four kinds according to their special shapes, and they are called here O-shaped rings, U-shaped rings, pies and comet rings. Fig. 3(a)–(d) shows such kinds of rings observed by confocal laser scanning microscopes. The surface profile of the ring along the cross section line is shown below each image of the ring. There are some characteristics of the shapes and the surface profiles.

First, the iridescent ring is a kind of film covering on the steel surface. In Fig. 3(b) and (d), some of the steel surfaces within the ring area were not covered by the iridescent film. Seen from the surface profile curves, the exposed steel surface is almost at the same height of the undamaged surface. On the other hand, the film is composed of many tiny particles as shown in Figs.3(c) and (d) and 4(a). Thus, the ring is a kind of new formed film standing on the steel surface, not the deformed steel surface that forms under the impaction from cavitation erosion. Usually, the ring is 200–300 μm in diameter, and the thickness of the rings can reach 500–600 nm. The thickness of the comet ring is lower, usually 200–300 nm. For the O-shaped and U-shaped rings, the film in the center is thinner than that in the iridescent zones, but for pies and comets, the film in the center is much thicker, and the thickness decreases gradually outside.

Second, the ring has a special multilayer structure, and each layer has a different color. Fig. 3(c) shows the steps between adjacent layers clearly, and the height difference between two layers is 100–200 nm. The iridescent color is thought to be caused by the film

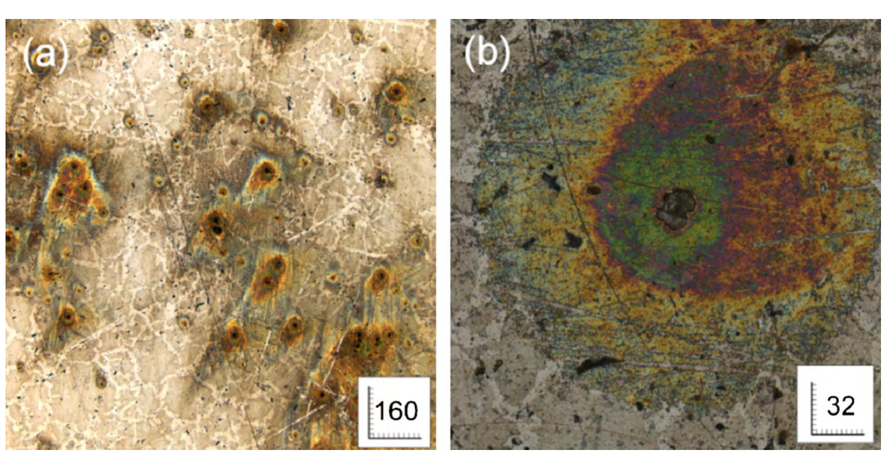

Fig. 2. (a) Cavitation erosion pits with iridescent color rings scatted on the carbon steel surface after 2-h cavitation experiment and (b) an erosion pit surrounded by iridescent rings. The unit of the scale in the figure is μm.