

Galvanic effects on cavitation damage for 1Cr13 stainless steel

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Abstract: Based on the electric-spark principle, a new kind of cavitation damage testing apparatus was designed, which could produce the bubble. Bubbles collapsed and acted on a small surface area of the alloy surface, so an intensive electrochemical inhomogeneous state would be induced and lead to the existence of surface galvanic effect on the alloy. The galvanic effect of 1Cr13 SS during cavitation damage has been quantitatively investigated in NaCl solution. The results show that intensive galvanic effect of 1Cr13 SS during cavitation damage appears the potential of the damaged area shifting negatively with the bubble collapse and simultaneously the galvanic current generates. The mass loss of alloy due to cavitation increases with the bubble quantity, and increases with the increasing of Cl^- content. And both the total mass loss and the mass loss due to galvanic corrosion increase linearly with the area ratio of cavitation damaged to undamaged area. Such surface galvanic effects speed up the dissolution rate of the alloy, which, in turn, accelerates the mechanical damage, and aggravates the mass loss of the alloy. It has been further confirmed that the mass loss due to the surface galvanic effect can be decreased by cathodic protection.

Key words: cavitation damage; galvanic effect; area ratio; mass loss

1 Introduction

The destruction of metals and alloys due to cavitation is not a pure mechanical process. Cavitation damage is accompanied by corrosion [1, 2]. As noted [3], electrochemical effect can contribute to the damage, especially in corrosive electrolyte.

Due to complicate processes involved in the cavitation damage, there have been kinds of approaches to alleviate it, such as insert gas injection [4-6] and cathodic protection [7]. However, these methods can not be applied effectively or made full use because the mechanism of cavitation has not been revealed clearly and comprehensively. Cavitation damage is still a serious problem to fluid machinery, especially when the velocity is high. According to the past research, cavitation process mainly involves two aspects, mechanical force and corrosion. There has been much study on the former and theories on it tend to be perfect [8]. Some studies on the latter were carried out [9, 10]. However, quantitative study on it was less.

1Cr13 alloy is the material widely used for the rotary parts of fluid machinery. As passive metal, electrochemical effect induced by mechanical force would be significant. It was found [11] that mechanical force and electrochemical effect coexist and co-accelerate in cavitation damage of 1Cr13 stainless steel (SS). During cavitation damage the mechanical force produces when bubbles collapse induce elastic or plastic deformation on the local surface area of the alloy and even

break the passive film. Thus, different surface state is formed on the surface of 1Cr13 SS. The bubble-acted surface, with lower potential, can be called anode. In contrast, the unacted surface is cathode with higher potential. Thus surface galvanic cell comes into being between the cathodic area and anodic area on the surface of the same alloy. Such surface effect will speed up the alloy mass loss in electrolyte during cavitation damage, especially when the cathodic area is large.

So, the quantitative study of the electrochemical behaviors of 1Cr13 SS in the cavitation damage has both theoretical and practical importance. In this article, the spark-generating bubbles apparatus was used to generate bubbles, and the electrochemical measuring system and spectrometer were used to confirm the mass loss caused by galvanic corrosion and the total mass loss caused by galvanic corrosion and mechanical damage.

2 Experimental

Figure 1 is the schematic sketch of the experimental equipment. Bubbles were generated and collapsed every other a second. The impact strength generated by bubble collapse was adjusted by setting values of four parameters, *i.e.* discharge voltage (U), distance between discharge electrodes (d), distance between discharge electrodes and working sample (L) and the quantity of bubbles generated continuously (n) every other a second.

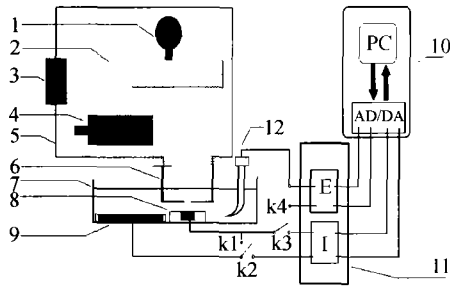


Figure 1 Schematic of cavitation damage apparatus, 1—Micrometer; 2—Support frame; 3—Bubble generating apparatus; 4—Micrometer; 5—Wire; 6—Discharge electrode; 7—Electrolyte; 8—Working electrode (sample A); 9—Galvanic electrode (sample C); 10—Data processing system; 11—Electrochemical measuring system.

The experimental solution was NaCl aqueous solution. According to the testing results of the spark-generating equipment, the radius of the bubble generated by the experimental apparatus was about 4 mm [12]. So, sample A, as a part of the bubble-acted area, was mechanically processed into cylinder with the radius of 4 mm. Sample C, not damaged by bubbles, was processed into rectangular with changeable surface area. The untested surfaces of sample A and C were sealed by epoxy resin. Samples were rinsed with distilled, deionized water. The area of the bubble-acted surface, namely anodic area is defined as S_A , while the area of the coupled passive surface is called S_C , the cathodic area.

Electrochemical measuring system and spectrometer were used respectively for quantitative measurement of the mass loss caused by galvanic corrosion and the total mass loss. The galvanic potential between sample A and C during cavitation damage process is defined as E_g and the galvanic current is called I_g . The electrochemical measuring system composed mainly of two kinds of sensors was used to monitor the variation of E_g and the value of I_g . The data were collected by the AD/DA interface and corresponding electrochemical measuring software. According to Faraday Law (see equation (1)), the mass loss due to galvanic corrosion can be calculated (see equation (2)).

$$\Delta g = \frac{Q}{F} \cdot N = \frac{I \cdot t}{F} \cdot N \quad (1)$$

where Δg is the dissolved quantity of the anode, I the electric current, t the time, F the Faraday constant and N the quotient of atomic mass and atomic valence.

$$M_g = \frac{\int I_d^A dt}{F} \cdot N \approx \frac{\int I_g dt}{F} \cdot N \quad (2)$$

where M_g is the mass loss caused by galvanic corrosion, I_d^A the dissolution current occurred on sample A.

In order to identify the intensity of galvanic effects on cavitation damage, the total mass loss M_t was measured under two kinds of experimental conditions: (1) in the case of A-C, namely, sample A and sample C were short-circuited by turning on switch k1; (2) in the case of A, namely, sample A and sample C were separated by turning off switch k1.

3 Results and discussion

3.1 The galvanic effects on cavitation damage

Figures 2(a) and 2(b) show the typical E_g-t and I_g-t curves recorded in the experiment, respectively. It can be seen that there are peaks of potential and current in the I_g-t and E_g-t curves of 1Cr13 SS in 3% (mass fraction) NaCl solution during cavitation damage. Cavitation bubble collapse is a violent process that generates highly localized, large-amplitude shock waves and microjets in the fluid at the point of collapse. The potential of sample A shifts negatively and then increases with time. Galvanic current is thus generated between sample A and sample C and then decreases with the diminishing of impact pressure. These peak values are the typical electrochemical parameters of 1Cr13 SS behavior in the process of cavitation damage.

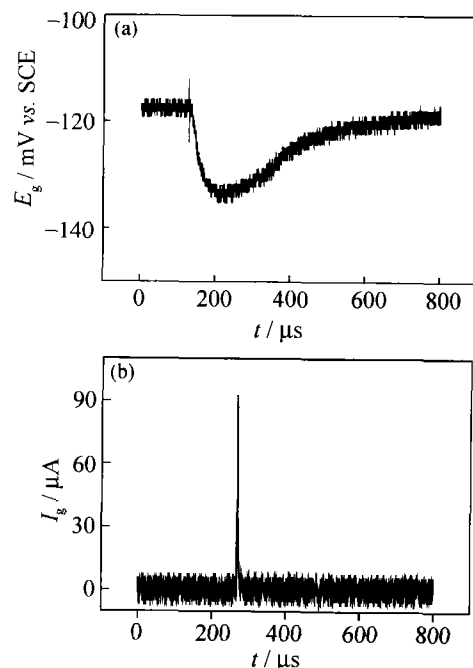


Figure 2 The relationship between the anode potential and time (a) and that between galvanic current and time (b) for 1Cr13 SS in 3% (mass fraction) NaCl solution with $U=940$ V, $d=0.3$ mm, $L=3$ mm, $S_c=9504$ mm².

It is demonstrated in figure 3 that the galvanic corrosion mass loss of 1Cr13 SS in cavitation damage grows with the bubble quantity. The mass loss due to galvanic corrosion increases linearly with the area ratio (see figure 4). According to galvanic kinetics, the corrosive current density on the anodic area (i_{corr}^A) is

equal to the oxygen-electronation rate ($i_{O_2}^L$) when the oxygen transport process is the controlling step.

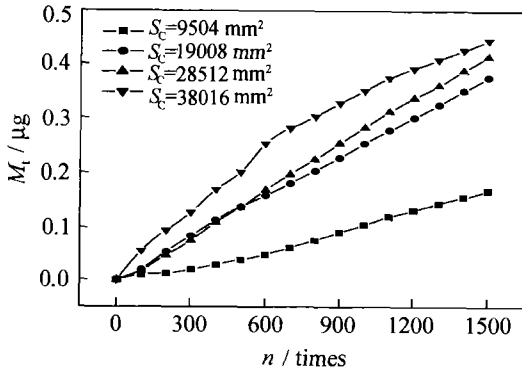


Figure 3 The relationship between the galvanic corrosion mass loss and bubble quantity for 1Cr13 SS with $U=940$ V, $d=0.3$ mm, $L=3$ mm, $w_{NaCl,aq}=3\%$ (mass fraction).

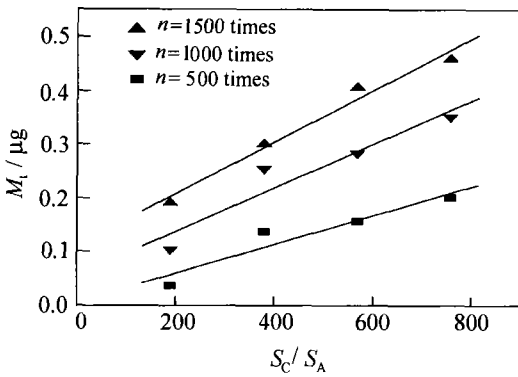


Figure 4 The relationship of galvanic corrosion mass loss and the area ratio (S_c/S_a) in 3% (mass fraction) NaCl solution with $U=940$ V, $d=0.3$ mm, $L=3$ mm for 1Cr13 SS.

According to the electrochemical kinetics equation (see equation (3)), it can be deduced that $i_d^A \approx i_{O_2}^L \cdot \frac{S_c}{S_a}$ when S_c/S_a is substantial. It proves that the galvanic effect becomes stronger when the area ratio (S_c/S_a) increases.

$$i_d^A = i_{O_2}^L \left(1 + \frac{S_c}{S_a}\right) \quad (3)$$

As the anodic dissolving current density (i_d^A) at the galvanic potential can be thought to be equal to the galvanic current density in this experiment (see equation (4)), the galvanic current density is of the direct ratio to the area ratio (see equation (5)). The experimental results accord with the theoretical deduction.

$$i_d^A(E_g) \approx i_g \quad (4)$$

$$i_g \approx i_{O_2}^L \cdot \frac{S_c}{S_a} \quad (5)$$

In order to indicate the difference between case A and case A-C, we define ρ as the accelerating strength of galvanic effect on cavitation damage, which equals to the quotient of 1Cr13 SS mass loss in case A-C and A (see equation (6)).

$$\rho = \frac{M_{t(A-C)}}{M_{t(A)}} \quad (6)$$

Figure 5(a) illustrates that in the range of experimental bubble quantity, the total mass loss in case A-C is more than that in case A. Figure 5(b) shows that ρ decreases with the bubble quantity growing when $n < 1000$ times, and increases when $n > 1000$ times. The results can be explained from the relationship of mechanical force and metal surface electrochemical state. With the bubble quantity (n) growing local metal surface would change from elastic deformation to plastic deformation or even suffer its film being peeled off. Therefore, the variation of galvanic potential (ΔE_g), the electromotive force, would increase. Galvanic effect is thus intensified and thus speed up the dissolution rate of the anode (sample A), which, in turn, accelerates the mechanical damage and aggravates the mass loss of the anode.

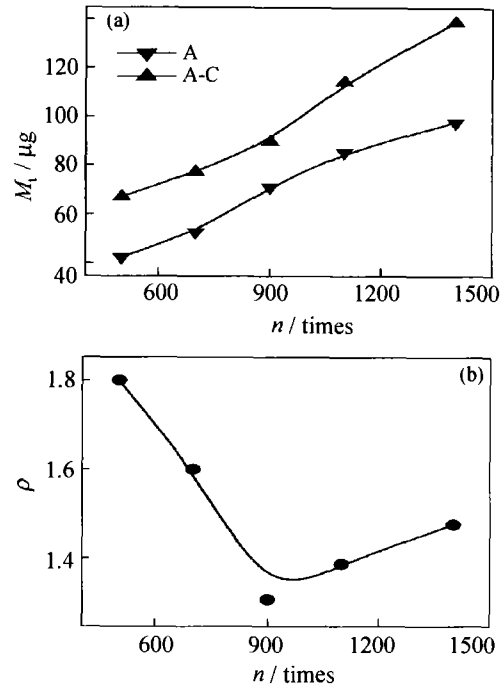


Figure 5 The relationship between the mass loss and bubble quantity (a) and that between ρ and bubble quantity (b) for 1Cr13 SS with $U=940$ V, $L=3$ mm, $d=0.3$ mm, $w_{NaCl,aq}=3\%$ (mass fraction), $S_c=9504$ mm².

The relationship of the total mass loss and the area ratio is shown in figure 6. The mass loss increases linearly with the area ratio. And, the larger the bubble quantity is, the more quickly the total mass loss increases.

In order to study percent of the galvanic effect to the cavitation damage, we define R as the percent of the galvanic corrosive mass loss to the total mass loss (see equation 7).

$$R = \frac{M_g}{M_t} \cdot 100\% \quad (7)$$

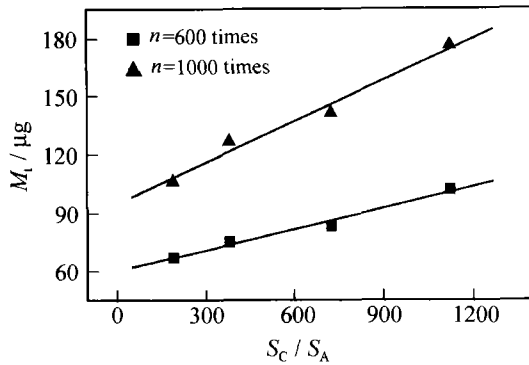


Figure 6 The relationship of the total mass loss and the area ratio in 3% NaCl with $U=940$ V, $d=0.3$ mm, $L=3$ mm for 1Cr13 SS.

Figure 7 shows that the proportion of galvanic corrosion in the cavitation damage is not more than 0.4% under the experimental condition. However, it increases exponentially with the area ratio. From the difference between $M_{t(A-C)}$ and $M_{t(A)}$, we can draw a conclusion that though the percent of galvanic corrosion in cavitation damage is small, its accelerating effect on the mass loss is considerable.

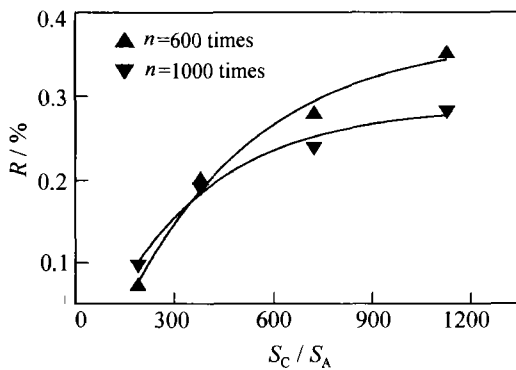


Figure 7 The relationship of the percent of galvanic corrosion mass loss to the total mass loss and the area ratio in 3% NaCl with $U=940$ V, $d=0.3$ mm, $L=3$ mm for 1Cr13 SS.

3.2 The influence of electrolyte content

Figures 8(a) and 8(b) show the influence of Cl^- content on 1Cr13 SS behavior in cavitation damage and the relationship between ρ and NaCl content, respectively. It can be seen from figure 8(a) that the mass loss increases with the Cl^- content increasing, though there is a small minimum around $w_{\text{aq,NaCl}} = 7\% - 8\%$ (mass fraction). Figure 8(b) shows that ρ grows with NaCl content increasing in the range of 1%-7% (mass fraction) and then decreases with it.

In the process of cavitation damage galvanic effect is mainly controlled by oxygen-electronation reaction on the cathode. The effects of NaCl solution mainly lie in the following two aspects.

(1) The process of cathode and anode polarization. On one hand, Cl^- helps to eliminate anode polarization.

On the other hand, in diluted solutions, oxygen solubility increases relatively with the electrolyte concentration while decreases in concentrated solutions.

(2) The electric conductivity of electrolyte. The increase of electrolyte concentration can improve the solution conductivity and thus accelerate ion transportation, which will speed up the electrochemical process.

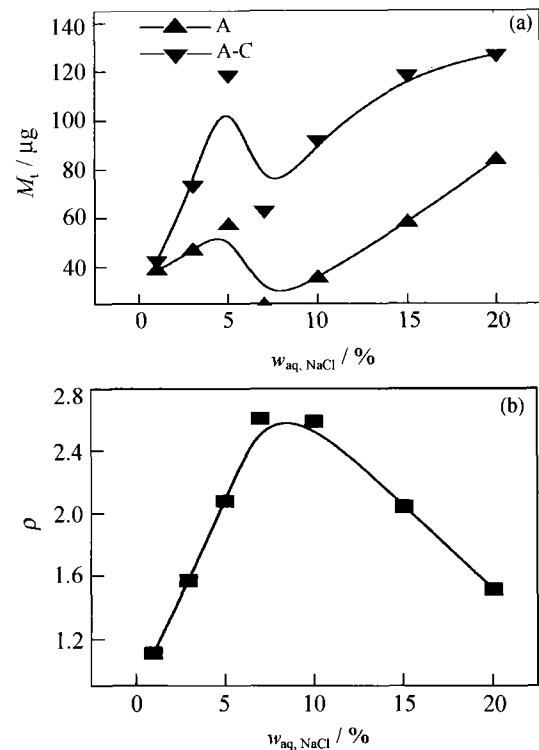


Figure 8 The relationship between the total mass loss and the NaCl content (a) and that between ρ and NaCl content (b) for 1Cr13 SS with $U=940$ V, $L=3$ mm, $d=0.3$ mm, $S_c=9504$ mm², $n=600$ times.

Such dual effects will lead to a peak value of accelerating strength of galvanic effect in cavitation damage at certain electrolyte concentration. The interfacial concentrations partly depend on the ionic transport in the electrolyte. In certain range of electrolyte concentration, the increase of concentration results in the increase of electron transfer velocity, which leads to the increase of mass transport rate and thus of the mass loss rate.

3.3 SEM analysis

The SEM micrographs of 1Cr13 SS after cavitation damage are shown in figures 9(a) and 9(b). It is apparent that there are some differences between (a) and (b). The edges of pits in (a) are sharp while in (b) are relatively smooth and the damaged area is larger in (a) than that in (b).

In case A, mechanical force was the main reason for mass loss. Therefore, the edges of the pits due to mechanical cuttings are sharp. In case A-C, galvanic

effect should be considered and the mass loss is due to the collaboration of mechanical force and galvanic effect induced by mechanical force. According to dissolution kinetics, the corners and edges are the favorite places for anodic dissolution of the metal. So metal at such places dissolves fast. That may be why the edges of pits in figure 8(b) are smooth.

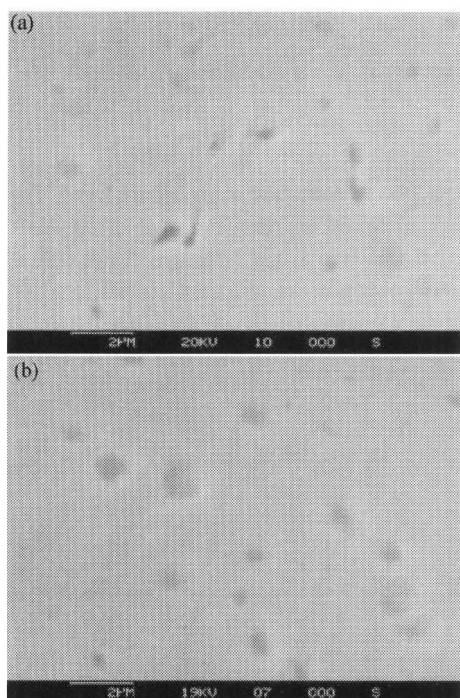


Figure 9 SEM photographs of the surface of 1Cr13 SS in 3% NaCl after cavitation damage with $U=940$ V, $d=0.3$ mm, $L=1$ mm, $n=50$ times, (a) in case A; (b) in case A-C.

3.4 The effect of cathodic protection during cavitation damage

Based on the assumption that the galvanic effect exists during the cavitation damage, the cathodic protection is tentatively applied in the experiment. The result shows that the cathodic protection can reduce the total mass loss due to cavitation damage under certain impressed potential (see **figure 10**).

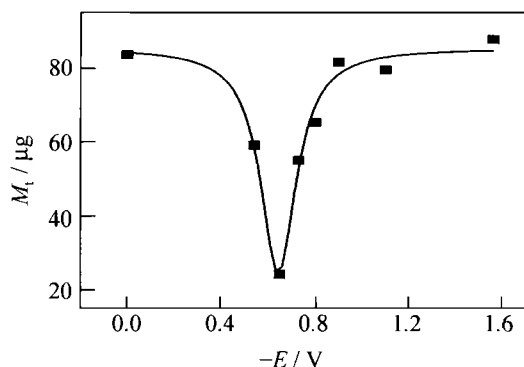


Figure 10 The relationship of the total mass loss and the impressed potential for 1Cr13 SS with $U=940$ V, $d=0.3$ mm, $L=1$ mm, $n=8000$ times.

3 Conclusions

(1) Surface galvanic effect can speed up the mass loss of 1Cr13 SS in cavitation damage.

(2) The total mass loss due to cavitation damage for 1Cr13 SS increases with the increasing of Cl^- content, except that there is a small minimum around $w_{aq,NaCl} = 7\%-8\%$ (mass fraction).

(3) The total mass loss and the mass loss of 1Cr13 SS due to galvanic corrosion increase linearly with the area ratio of cavitation damaged area to undamaged area.

(4) The damage degree with galvanic effect is larger than that without galvanic effect for 1Cr13 SS.

(5) The cathodic protection can reduce the total mass loss during cavitation damage for 1Cr13 SS at certain impressed potential.

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