Improvement of the cavitation erosion resistance for \( \text{Cr}_3\text{Si} \) film on stainless steel by double cathode glow discharge

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Abstract. In this study, sputter-deposited \( \text{Cr}_3\text{Si} \) film was prepared by double cathode glow discharge (DCGD) technique onto 304 stainless steel. The phase constituents, surface microstructure and chemical compositions of the film were examined by using X-ray diffraction (XRD), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). After the DCGD process, the hardness of \( \text{Cr}_3\text{Si} \) film was 26 GPa, about 10 times of the stainless steel, 2.5 GPa. The cavitation erosion resistance of \( \text{Cr}_3\text{Si} \) film and stainless steel were investigated by using an ultrasonic vibration cavitation erosion system. After 30 hours of cavitation tests, the cumulative mass loss of \( \text{Cr}_3\text{Si} \) film was only 60% of the stainless steel. Compared with the untreated stainless steel, the cavitation erosion resistance of \( \text{Cr}_3\text{Si} \) film was improved. The cavitation mechanism of \( \text{Cr}_3\text{Si} \) film is due to the delamination and spalling of local surface layer derived from its inherent brittleness.

1. Introduction

Austenitic stainless steels are widely applied in many fields, such as fluid machinery, marine, hydraulic machines, machine tool spindle, and as well as in nuclear industries because of their excellent properties containing good mechanical properties, corrosion resistance and weldability, etc. In addition, austenitic stainless steels are also chosen as candidate materials in water lubricated bearings and seals [1-2]. However, the damage of cavitation erosion existed in these environments under the combined action of corrosion and mechanical wear, inevitably, which leads to their premature failure [3-6].

In the past decades, in order to enhance the cavitation erosion behavior of austenitic stainless steels, several surface modification techniques, including thermal spraying, laser surface modification, physical and chemical vapour deposition have been employed [7-10]. However, it is found that several problems still need to be solved though some active effects have been brought through the surface technologies. For example, TiN and CrN coatings are easier to generate microcracks and flake away from the tops of micro folds of the stainless steel matrix although they have good corrosion resistance and wear performance under cavitation erosion damage.

Among the transition metal silicides, \( \text{Cr}_3\text{Si} \) has excellent combination of wear, corrosion and oxidation resistance. In order to improve the cavitation erosion resistance of stainless steel, the \( \text{Cr}_3\text{Si} \) coating was prepared onto 304 stainless steel by DCGD technique. In view of this, the present work aims at evaluating the cavitation erosion resistance of \( \text{Cr}_3\text{Si} \) film, and attempts to reveal the cavitation mechanism of \( \text{Cr}_3\text{Si} \) film.
2. Experiment details

2.1. Test apparatus

Figure 1 (a) shows an ultrasonic vibration system to estimate the cavitation erosion behavior of specimens, Figure 1 (b) and Figure 1 (c) presents the schematic of this ultrasonic vibration system. During cavitation erosion tests, the beaker was filled with tap water, and the ultrasonic vibration cavitation erosion system has the amplitude of 6 μm and was ensured the frequency of 20 kHz with an axial vibration by the vibration horn to generate the cavitation bubbles at the tip surface. In addition, fresh water would replace the used water in the beaker in every half hour, and the temperature of the medium was kept at 20±5 °C.

![Figure 1](image)

(a) (b) (c)

Figure 1. The ultrasound vibration system

2.2. Test samples

Austenitic stainless steel 304 was used as the substrate. The specimens (10×7×5mm) were polished with #5000 emery paper, and the surface roughness Ra < 0.2μm. Then, the Cr₃Si film was prepared onto 304 stainless steel by DCGD technique. Table 1 was the deposition parameters of Cr₃Si film.
employed in this work. Figure 2 shows the cross-sectional micrograph of Cr$_3$Si film with the thickness of 5 μm. Figure 3 shows a distinctive XRD pattern of the films by using a Smartlab (3) X-ray diffractometer (40kv and 30mA, Cu Kα radiation) with a step size 0.02° in the range of 20-80° and Cr$_3$Si phase can be seen from XRD pattern of the Cr$_3$Si film through a series of broad peak. Figure 4 (a) shows the TEM brightfield micrograph of the Cr$_3$Si film. Figure 4 (b) shows HRTEM image of Cr$_3$Si film.

Table 1. Deposition parameters of Cr$_3$Si film.

| Parameters                          | Cr$_3$Si |
|-------------------------------------|----------|
| substrate temperature (°C)          | 800      |
| treatment time (h)                  | 3        |
| target electrode bias voltage (V)   | -900     |
| substrate bias voltage (V)          | -300     |
| working pressure (Pa)               | 35       |
| Ar flow rate (sccm)                 | 60       |
| parallel distance between the source electrode and the substrate (mm) | 15       |

The nanohardness tester was used to measure the elastic modulus and hardness of the stainless steel and Cr$_3$Si film by using the method of Oliver and Pharr. Table 2 was the elastic modulus and nanohardness of stainless steel and Cr$_3$Si film.
Table 2. Properties of Cr$_3$Si film and substrate.

| Properties              | 304 steel | Cr$_3$Si |
|-------------------------|-----------|----------|
| film thickness (μm)     | -         | 5        |
| roughness (μm)          | 0.2       | 0.2      |
| hardness (GPa)          | 2.5       | 26       |
| elastic modulus (GPa)   | 193       | 300      |

2.3. Experiment procedures

Cavitation experiments were carried out with 30 hours in an ultrasonic vibration system. An ultrasonic cleaner (KQ118) was used to clean the cavitation samples with acetone, cavitation samples were weighed every two hours and dried in drying basin. The digital analysis balance was used in the mass changes of the samples at least three times and the precision of balance is 0.01 mg. The erosion test of each specimen is repeated at least three times to verify the result. The optical photographs were shown in Figure 5 for the specimens of 304 steel, Cr$_3$Si film after 30 hours experiment.

![Figure 5. Specimens after 30 hours of cavitation test, (a) 304 steel, (b) Cr$_3$Si film](image)

3. Results and discussions

3.1. Mass loss

Figure 6(a) shows the mass loss of the stainless steel and Cr$_3$Si film specimens with the test time. Figure 6(b) shows the erosion rate of the specimens by curve fitting and derivation method of the mean mass loss. As shown in Figure 6, it is clear that distinct stages with four different erosion rates for the tested samples can be observed. As the erosion process continuing, weight loss of samples increases, accompanied by an increase in the number of erosion pits. The cumulative mass loss of the Cr$_3$Si film sample was 3.26 mg, which is only 60% of the stainless steel sample after 30 h of cavitation erosion experiment.

![Figure 6. The test curves of Cr$_3$Si film and 304 steel. (a) mass loss, and (b) erosion rate](image)
3.2. SEM discussion of the erosion surfaces
Figure 7 shows the SEM images of the stainless steel and Figure 8 presents the Cr$_3$Si film after 30 h of cavitation erosion experiment. After the cavitation erosion experiment, a lot of erosion pits could be seen on the surface of the 304 specimen ranging from several microns to tens of microns in size in Fig.7 (a-c). At the beginning, plastic deformation of the surface occurs, causing to yield hardening, stress and fatigue cracks that result in the fatigue fracture of the stainless steel. Lots of slip band agglomerated and some cracks formed on the surface after their cavitation test as in the Ref. [11, 12]. As shown in Fig.8 (a-c), a few erosion pits with the diameters of tens of microns are found on the damaged area of the Cr$_3$Si film after 30 h test. The result indicates that the Cr$_3$Si film exhibit slight surface damage in the form of material loss and increased particles removal at grain regions of the film compared to the 304 stainless steel because of its higher hardness, wear, corrosion and chemical composition which effectively improves the cavitation erosion resistance. Hence, the resistance of the Cr$_3$Si coating is higher than the stainless steel. The cavitation erosion mechanism of Cr$_3$Si film is due to the silicon compound brittleness and the poor adhesion to the substrate.

![SEM images](image1.jpg)

(a) (b) (c)

**Figure 7.** The SEM images of the specimen of 304 after 30 h test. (a) the damaged area (×1000), (b) the damaged area (×5000), (c) the damaged area (×20000).

4. Conclusions
In this work, the cumulative mass loss of the Cr$_3$Si film sample was only 60% of the stainless steel after 30 h of cavitation erosion experiment and Cr$_3$Si film has higher cavitation erosion resistance. The better adhesion force can improve cavitation erosion resistance of Cr$_3$Si film. The cavitation erosion mechanism of Cr$_3$Si coating could be attributed to not only the silicon compound brittleness but also the surface grain spalling with poor adhesion.
Figure 8. The SEM images of the specimen of Cr₃Si film after 30 h test. (a) the damaged area (×1000), (b) the damaged area (×5000), (c) the damaged area (×20000).

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