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Preliminary communication

SURFACE DEGRADATION MONITORING CAUSED BY CAVITATION EROSION AFTER CORROSION IN THE MARINE ENVIRONMENT

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ABSTRACT

Monitoring cavitation erosion in materials is crucial for their performance in environments characterized by severe fluid flow conditions. Materials such as metals, ceramics, and composites, commonly used in these applications, must possess specific mechanical properties to effectively resist cavitation erosion. Additionally, various environmental factors, including different chemical solutions, can significantly alter a material's response to cavitation. In this study, the impact of the marine environment was investigated using a prepared NaCl solution, following the standard procedure of ISO 11130:2017(E), to evaluate its influence on further cavitation erosion exposure of materials. Cavitation erosion tests were performed on steel samples (42CrMo4) after immersing them in NaCl solution for 120 days. An ultrasonic vibratory test, conducted according to the ASTM-32-16 standard, was employed to assess the material's erosion resistance. To evaluate the extent of cavitation damage, various methods were utilized, including monitoring mass loss and calculating the mass loss rate, as well as conducting image analysis to quantify pit dimensions, the number of pits, and overall degradation levels. The results provide valuable insights into the relationship between material properties, environmental exposure, and cavitation erosion, with implications for the design and selection of materials for use in marine and intensive fluid flow applications.

Keywords: corrosion; cavitation; image analysis; degradation level.

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1. INTRODUCTION

The cavitation erosion phenomenon is the result of a complex interaction between flowing fluids and metal surfaces. When bubbles of gas or vapor form in a fluid, they undergo what is known as a "sudden collapse" under the effect of increased pressure, causing an implosion [1-4]. Cavitation erosion also depends on the material properties and the fluid properties. Most of the experimental testing related to cavitation erosion monitoring was conducted using water as a fluid. The choice is important where the influence of the fluid and its specific properties are minimized. However, the cavitation erosion of materials, particularly various steel alloys, is influenced by a range of environmental

conditions and the nature of the surrounding fluids. One of the interesting fluids, with specific characteristics, is seawater. A wide range of materials, especially diverse types of steel alloys, are utilized in different applications, including those involving seawater environments [5]. Considering that seawater is a complex fluid with distinct chemical and biological properties that vary depending on factors such as geographical location, temperature, and other parameters, it is obvious that such a complex fluid should be substituted with a simpler alternative. This approach has been employed in numerous studies, where the influence of seawater was simulated by using a NaCl solution prepared according to a standard procedure [6].

The 42CrMo4 steel is a low-alloy carbon steel known for its high toughness, excellent hardness, good ductility, and superior tensile and fatigue strength, which makes it extensively used in the production of various mechanical components. These include parts for marine equipment such as shafts, crankshafts, connecting rods, drilling joints, pump components, steam turbines, and salvage equipment. Beyond its application in marine engineering, 42CrMo4 is also employed in the manufacture of high-strength, wear-resistant components for compressors, turbines, and ship propellers [7-9]. Due to its widespread use in demanding environments, it is essential to assess the resistance of this steel grade to cavitation erosion.

The objective of this study is to investigate the effects of cavitation erosion on steel materials (42CrMo4) in a simulated marine environment, using a NaCl solution prepared according to ISO 11130:2017 (E). The study aims to evaluate the material's cavitation erosion resistance by subjecting the samples to prolonged exposure to the NaCl solution for 120 days and conducting ultrasonic vibratory tests following the ASTM G-32-16 standard [10]. According to the ASTM G-32-16 standard, degradation of the material is described by the cavitation curve, which is divided into four stages: initialization (I), acceleration (A), deceleration (D), and steady state (S). This research aims to improve the understanding of how environmental factors influence cavitation erosion by monitoring mass loss, calculating the mass loss rate, and conducting image analysis to quantify pit dimensions, as well as the number and severity of pits. The findings will also be helpful in material selection for applications exposed to marine environments and/or intense fluid flow conditions.

2. MATERIALS

The material tested in this study is low-alloy steel 42CrMo4, processed through conventional casting techniques (as-cast). The chemical composition of the material is provided in Table 1.

Table 1. Chemical composition 42CrMo4 low alloy steel

	42CrMo4										
Element (wt. %)	C	Cr	Mo	Mn	Si	Ni	Cu	Al	S	P	Fe
	0.40	0.93	0.20	0.65	0.29	0.03	0.04	0.003	0.003	0.009	Bal.

3. METHODS

The corrosion behaviour of structural steel 42CrMo4 was investigated by immersion in a 3.5% NaCl solution according to standard ISO 11130:2017 (E) for 120 days [11]. The cavitation erosion test was conducted using the ultrasonic vibration method (with a stationary sample) according to the ASTM G-32-16 standard procedure [10]. To produce cavitation bubbles, an ultrasonic generator with a 20 ± 0.2 kHz frequency was used. The ultrasonic horn tip diameter was 16 mm, and the working distance between the horn tip and the exposed specimen surface was set to

0.5 mm. Test samples were placed on a holding platform in a beaker filled with distilled water at a temperature of 23 ± 1 °C. The specimen was placed 10 mm under the free liquid level. Cavitation testing was performed in intervals, with a total testing time of 150 minutes. Before and after each interval of the cavitation testing, the mass of the samples was measured using an analytical balance with an accuracy of ± 0.1 mg. Mass losses and corrosion rates are measured and calculated using standard procedures. Pit dimensions resulting from cavitation erosion can be quantified using appropriate tools for image analysis in the Image Pro Plus 6.0 software (IPP) package (Media Cybernetics, 2006, Rockville, MD). The sample surface was scanned at high resolution (1200 dpi) after each specific cavitation erosion period and then processed by IPP.

4. RESULTS AND DISCUSSION

One of the historical attempts for degradation monitoring, including the monitoring of cavitation erosion, is mass loss measurements. The results obtained from steel samples (42CrMo4) after immersion in the NaCl solution for 120 days and subsequent exposure to cavitation erosion are presented in Figure 1.

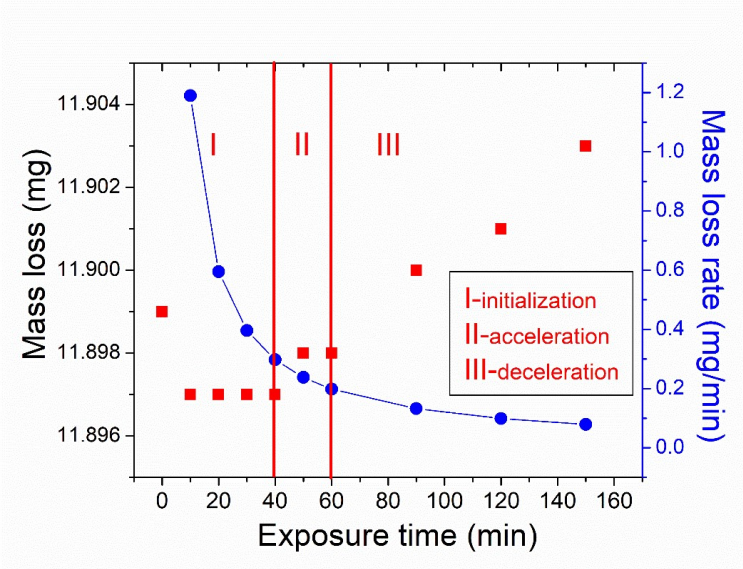

Figure 1. Mass loss and mass loss rate during cavitation testing

It can be seen that three distinct stages are present:

- Initialization (I), observed till 40 minutes of testing,
- Acceleration (A), observed from 40 to 60 minutes of testing, and
- Deceleration (D), observed after 60 minutes of testing.

The final stage, known as the steady-state phase, was not reached within the 150 minutes of testing. It is expected that this stage will be achieved with a longer duration of testing or exposure. Calculated results for the mass loss rate of the steel sample after 120 days of immersion in 3.5% NaCl solution during different exposure times to cavitation are presented in Figure 1. Generally, as the exposure time increases, the mass loss rate of the specimens decreases. A gradual decrease in mass loss rate is observed with extended test periods. Cavitation erosion was monitored by scanning the sample surface at a high resolution (1200 dpi) before and during testing, as shown in Figure 2.

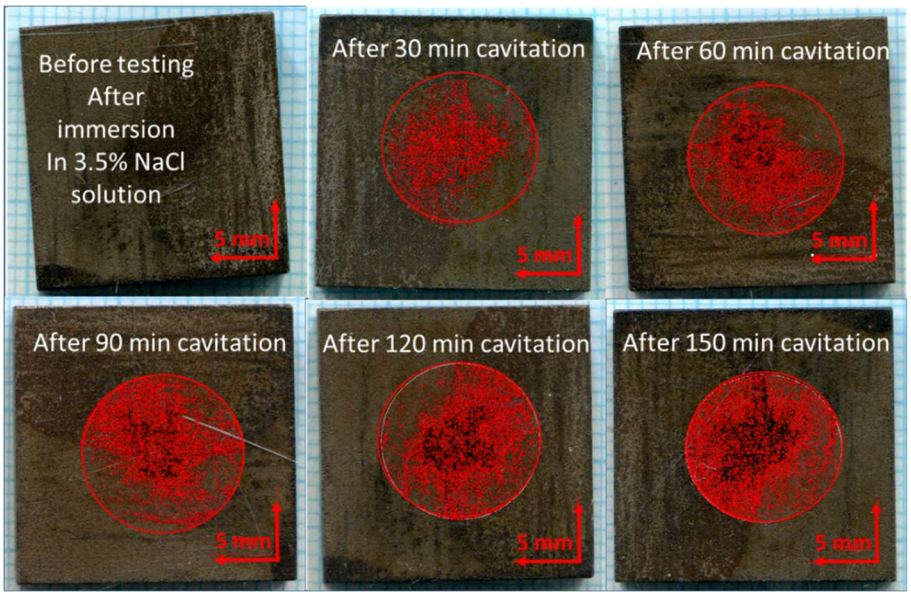

Figure 2. Sample images before and during testing.

Image analysis (Image Pro Plus 6.0 software (IPP) package) was used for visual quantification of pits formed during testing. Selected morphological parameters for monitoring were: number of pits, average diameter of the pits, and total area of the formed pits (Figure 3).

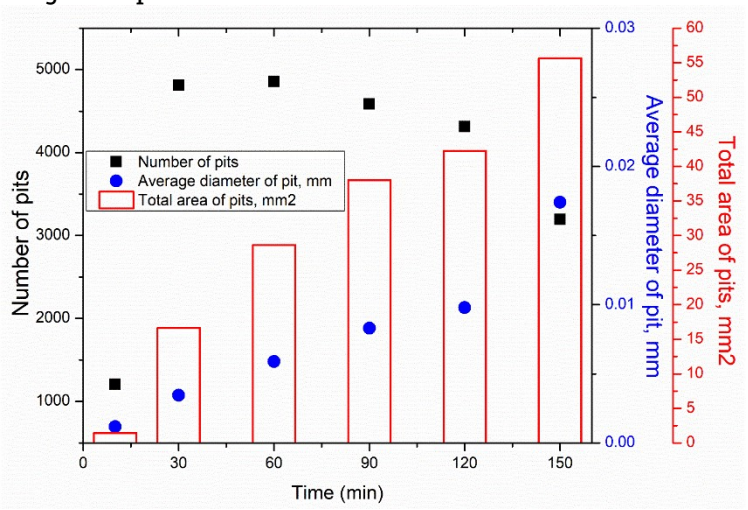

Figure 3. Morphological parameters: number of pits, average diameter of formed pits, and total area of formed pits

The results presented in Fig. 3 indicate that the number of pits formed increases up to 60 minutes, after which the number begins to decrease between 60 and 150 minutes. This suggests that, during the first 60 minutes, the dominant mechanism is pit formation, while after 60 minutes, the merging of pits becomes significant. This phenomenon occurs as the damaged surface area stabilizes, leaving less area available for the formation of new pits. Throughout the testing, both the average and total area of the formed pits increase. Based on these results, the level of degradation can be calculated by the equation:

$$\text{Level of degradation} = \left(\frac{P_i}{P_o}\right) \cdot 100 \qquad (1)$$

where:

P_i is the total area of the formed pits after, i is a number of cycles, and P_o is the original area equal to the surface of the probe (200.96 mm^2).

Calculated results using the image analysis approach are given in Figure 3, and the calculated level of degradation in Figure 4.

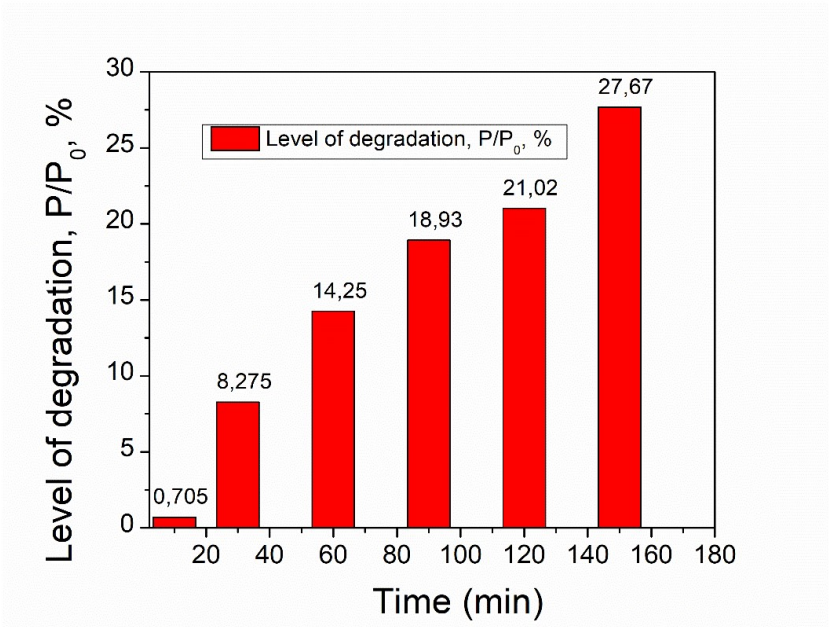

Figure 4. Level of surface degradation during the cavitation exposure.

The diagram in Figure 4 shows the calculated values of the surface degradation level during testing. This method provides a reliable and objective assessment of the extent of degradation caused by cavitation exposure. According to the scanned images shown in Fig. 2, it can be observed that the 42CrMo4 steel samples' surface area is covered with small pits and that the number of pits increases as the testing progresses. The results obtained, as shown in Fig. 4, refer to the surface degradation level, exhibiting a trend that corresponds to the previously provided cavitation curve of mass loss throughout the entire testing period. As expected, the level of degradation gradually increases throughout the testing period.

5. CONCLUSION

This study assesses the cavitation erosion behavior of 42CrMo4 steel in a simulated marine environment using a NaCl solution. The results highlight the significant impact of environmental exposure on material degradation, identifying key stages of erosion: Initialization (up to 40 minutes), Acceleration (40-60 minutes), and Deceleration (after 60 minutes). The steady-state phase was not reached during the 150 minutes of testing, suggesting that longer exposure is needed for complete stabilization. Image analysis revealed that the number of pits increased up to 60 minutes, after which it decreased due to the merging of pits. The total pit area consistently increased, indicating continuous surface degradation, and the calculated degradation level showed a steady rise over time, aligning with the cavitation erosion curve. These findings emphasize the importance of considering environmental factors like seawater or simulated marine fluids when evaluating material performance in harsh fluid flow conditions. The study offers valuable insights into the relationship between material properties, fluid characteristics, and cavitation erosion, aiding in better material selection and design for marine and fluid flow applications. The employed methods, including mass loss and image analysis, provide reliable tools for future research and the development of more resilient materials.

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Conflicts of Interest
The authors declare no conflict of interest.

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