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The Cavitation Erosion Behavior of UNS A96061 Alloy in Seawater

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ABSTRACT

An ultrasonically induced cavitation facility was used to study the cavitation erosion behavior of UNS A96061 alloy in seawater. The work included measurements of free corrosion potentials, and mass loss in the presence and absence of cavitation. The cavitation tests were made at a frequency of 20 KHz and at temperatures of 25^0C. Cavitation conditions caused a noble shift in the free corrosion potential for UNS A96061 alloy. Cavitation also increased the rate of mass loss of this alloy by several orders of magnitude with respect to stagnant conditions. Another set of cavitation experiments was also carried out for this alloy in distilled water to distinguish between the mechanical and electrochemical factors that contribute to metal loss. Results indicated that the mechanical factor has an overriding role in metal loss of this alloy. Cavitation made the surface of this alloy very rough, exhibiting large cavity pits in the middle region of the attacked area as revealed by the scanning electron microscope (SEM). Cavitation attack was mainly observed at grain boundaries and matrix/precipitates interfaces. Mechanical factors are believed to be the leading cause of metal loss.

Keywords: Mass loss, distilled water, mechanical factors, free corrosion-potential.

INTRODUCTION

The cavitation erosion behavior of UNS A96061 alloy was investigated in seawater. This work stemmed from a previous failure investigation that was carried out on nodular cast iron globe valves of different sizes 3 in (7.62 cm), 4 in (10.16 cm), and 8 in (20.32 cm).[1] The valves were used in the return lines of seawater heat exchangers of refineries and petrochemical plants in Kuwait.[2-5] Several of these valves failed within six months of service. The small size valves 3 in (7.62 cm) suffered from cavitation corrosion and erosion cracks, while the larger size valves failed due to intensified localized attack under voluminous scale and galvanic corrosion with the seat rings. Therefore, it became of interest to study the cavitation-corrosion behavior of UNS A96061 alloy which may be used in the manufacturing of seawater regulating equipment for the Kuwaiti refining and petrochemical industries.

Cavitation damage is a form of a localized attack found on many types of materials exposed to turbulent flow rates of liquids. Although mainly mechanical in nature, this type of damage is more severe in mediums where the cavitation mechanism acts synergistically with corrosion.[6-8] The mechanical action of cavitation usually attacks protective surfaces, exposing unprotected surfaces to corrosion. Cavitation is often defined as the growth and collapse of vapor bubbles because of local pressure fluctuations in a liquid. If the pressure suddenly falls below the vapor pressure, these bubbles then collapse violently when they are submitted to a higher pressure. This collapse is accompanied by the sudden flow of liquid, which imposes stress pulses capable of causing plastic deformation on solid surfaces.[9] UNS A96061 is an aluminum-magnesium-silicon alloy and is usually formulated to make use of the solubility of Mg-Si and thereby utilize precipitation hardening.

Selection of corrosion resistant materials depends on a better understanding of a material's response to corrosive liquids and cavitation stresses. Therefore, continuous reappraisal of proposed construction materials is necessary to confirm that the least expensive material, which will still fully satisfy the requirements of the service, has been selected.

EXPERIMENTAL PROCEDURE

Apparatus

The vibratory apparatus used for this test method works at a frequency of 20 kHz and a peak-to-peak amplitude of 25 μm. This test method produces axial oscillations of a test specimen inserted to a specified depth in the test liquid. The vibrations are generated by a magnetostrictive or piezoelectric transducer, driven by a suitable electronic oscillator and power amplifier. Figure 1 shows a schematic view of such an apparatus.

Material

Specimens were cut from a 15 mm diameter rod of UNS A96061 alloy. Each specimen had a diameter of 1.59 cm and a thickness of about 0.27 cm. The % chemical composition of the UNS A96061 alloy includes 0.43 Si, 0.70 Fe, 0.24 Cu, 0.15 Mn, 0.05 Ni C, 0.006 Zn, 0.02 Ti, 0.802 Mg and Al balance. Before experimental testing, specimens were mechanically polished with silicon carbide papers up to 1200 grit. For morphological examination, some specimens were etched before testing to reveal their microstructure. For etching, the specimens were chemically etched with 0.5% hydrofluoric acid etchant.

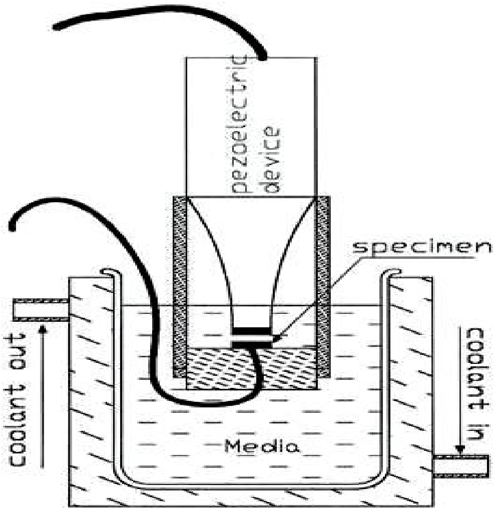


Figure 1: Schematic of Vibratory Cavitation Test Apparatus.

Two specimens of the alloy were tested. The test specimens were fixed on a special holder which was placed at a distance of 0.125 cm from the apparatus horn. At the end of each cavitation test, detailed morphological examinations were carried out on the specimens. Optical microscopy and scanning electron microscopy (SEM) were used to identify the initiation and mode of damage in addition to the role played by the constituent phases of the alloy.

Test Solution

The chemical composition of the natural seawater from the Arabian (Persian) Gulf used in this study is shown in Table 1. The seawater was contained in an open 600 mL glass beaker surrounded by a copper coil in a water bath maintained at 25±1°C. Mass loss tests were done on the basis of 2 hours for each test for a total duration of 40 hours. The weight of the specimen was taken before and after each test. Potential-time measurements were done using a Potentiostat and calomel reference electrode for duration of three hours for the test on the basis of one hour before cavitation, one hour during cavitation and one hour after cavitation.

Table 1
Chemical Composition of Arabian Gulf Seawater (Doha Plant)

Parameter	Concentration (ppm ± SD)	Parameter	Concentration (ppm ± SD)
Sodium	12,300 ± 20	Bicarbonate	185 ± 18
Magnesium	1700 ± 150	Carbonate	14 ± 8
Potassium	470 ± 20	Total Hydrocarbon	0.204
Calcium	570 ± 45	TDS	47,000 ± 2000
Chloride	24,000 ± 700	pH	8.2 ± 0.1
Sulfate	3400 ± 300		

RESULTS AND DISCUSSION

Mass Loss of UNS A96061 Alloy

Figure 2 (a and b) shows the cumulative mass loss and rate of mass loss of UNS A96061 versus exposure time for this alloy in seawater under cavitation and stagnant conditions at 25°C.

(a)

(b)

Figure 2: Typical (a) cumulative mass loss and (b) rates of mass loss of UNS A96061 alloy specimen exposed to seawater water at 25°C.

A gradual increase in mass loss rate with time was observed for this specimen with a very small incubation period of less than 0.05 h in seawater at the testing temperature under cavitation conditions as shown in Figure 2b, and a negligible mass loss with time was observed in seawater under stagnant conditions with an incubation period of about 30 h as shown in the same Figure. However, the mass loss of this alloy under cavitation conditions in distilled water was also gradual with an incubation period of about 0.15 h with a value less than that in seawater. The rate of mass loss for this specimen in seawater exhibited a sharp increase up to 2.50 h at a value of 7.5x10^{-2} g/h then a semi steady state rate of mass loss was observed between the values of 1.45 x10^{-2} g/h after 30 h and up to 40 h as shown in Figure 2b. The semi steady state mass loss rate of this alloy in seawater under stagnant conditions remained very negligible while the steady state mass loss rate value under cavitation conditions in distilled water was averaged at about 1.5 x10^{-2} g/h as shown in Figure 2b.

General Observation on the Rate of Mass Loss

In order to determine the effect of the mechanical and electrochemical factors on the rate of mass loss of the UNS A96061 alloy in seawater at 25˚C, many investigators recommend comparing rate of mass loss in the steady state period of the curves.[6,11-15] Initial rate of mass loss is affected by many factors such as the type of alloy, aging temperature, surface in-homogeneities, alloy microstructure and the surface of the sample. Therefore, the steady state or semi-steady state period of the rate of mass loss will be considered as a measure of the cavitation-corrosion performance of this alloy in seawater. The observed averaged semi-steady state rate of mass loss values in seawater under cavitation conditions are about 1.45 x10^{-2} g/h and that under stagnant conditions are about 0.00 g/h as shown in Figures 2b.

Potential-time Measurements of UNS A96061

Figure 3 shows the potential-time measurements versus calomel reference electrode (CRE) for UNS A96061 in seawater under stagnant and cavitation conditions. The open circuit (OC) potential of this alloy begins with a more active value under stagnant conditions and then immediately shifts towards more noble direction upon the imposition of cavitation conditions. The value of the negative shift in potential under cavitation conditions is approximately 20 mV. The OC-potential returns to more negative values when cavitation conditions were lifted.

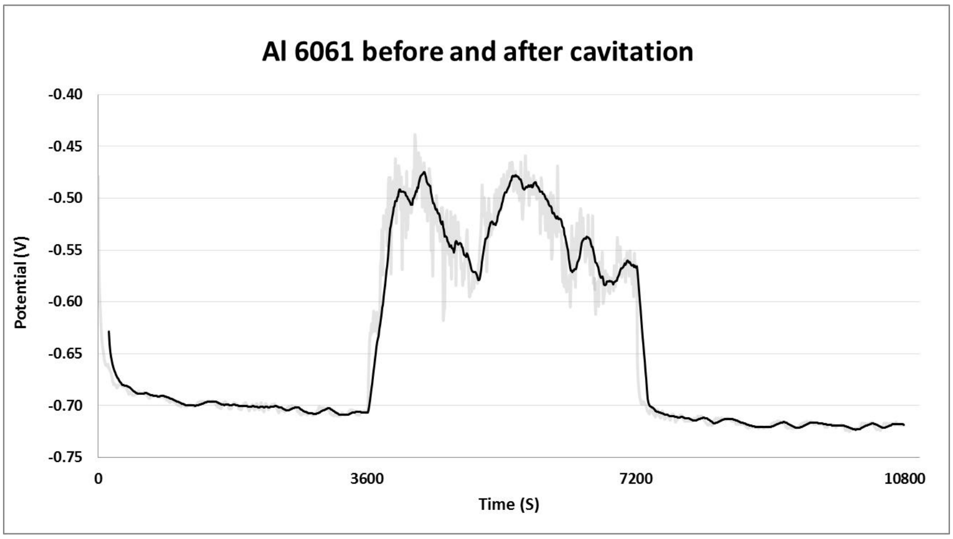
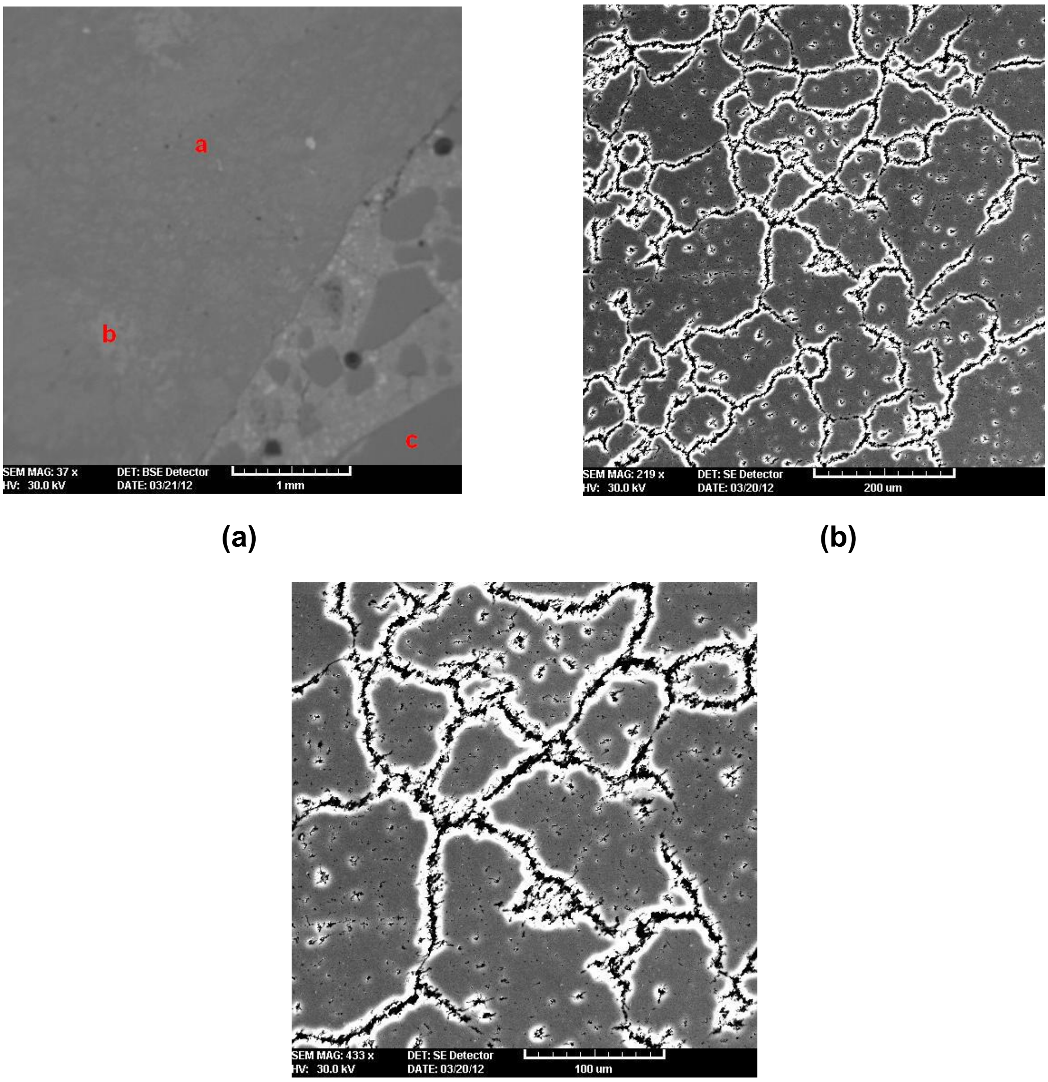


Figure 3: The effect of cavitation conditions on the free-corrosion potential of UNS A96061 in seawater at 25˚C.

Assessment of Surface Damage

Figure 4 shows time lapsed SEM micrographs of UNS A96061 surface at lower and higher magnification exhibiting the microstructure and cavitation attack at the grains region and along the grain boundaries as well the Fe_3SiAl_2 and Mg_2Si rich particles after 0.05 h in seawater at 25^0C. Figure 4a shows un-attacked region of UNS A96061 specimen which was cavitation tested with time to observe the nature of damage to the alloy microstructure. Figures 4b and c show the cavitation attack at and around the Fe_3SiAl_2 and Mg_2Si rich particles leading to the dislodgement of these particles and formation of relatively small cavity pits as well as large ones within the grains of UNS A96061. The presence of cavities and ductile tearing is readily explainable in terms of the known devastating mechanical effects of the cavitation action.



(a) **(b)**

(c)

Figure 4: SEM micrograph of the surface of UNS A96061 alloy after etching in 0.50 % hydrofluoric acid showing the characteristic microstructure (a) Before cavitation and after (b) and (c) 0.05 h of cavitation testing.

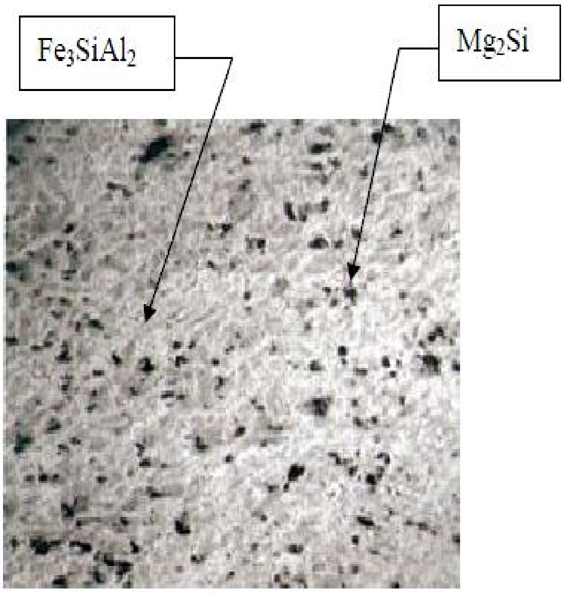


Figure 5 shows an SEM micrographs of UNS A96061 microstructure revealing the iron-silicon and magnesium-silicon particles within the grains. (Courtesy of Kaiser Aluminum & Chemical Corp.)

DISCUSSION

Cavitation damage is associated with components that are being driven at high velocity through a fluid, for example propellers, impellers, water turbines, valves and pumps. Numerous studies[5-8] have been made on cavitation. Reports[16-24] have been published which show that both mechanical and electrochemical factors are involved. Cavitation may be defined as the growth and collapse of vapor bubbles due to localized pressure changes in a liquid. The bubbles are formed in the liquid in regions of very low pressure, for example, behind the leading edge of a propeller blade. The collapse process takes place extremely rapidly, producing a strong shock wave that damages the material. Because a few millions of bubbles may collapse in a second, damage quickly occurs.

Rate of mass loss results for UNS A96061 in seawater and distilled water are slightly similar indicating that mechanical factors override the electrochemical factors as the main cause of metal loss for this alloy. However, electrochemical dissolution due to structural heterogeneity is indeed contributing to the surface damage during cavitation. It is also believed that synergistic effects of the mechanical and electrochemical actions played a role in enhancing the rate of metal loss from the surface of this alloy.

Results of the corrosion potential versus time tests indicated that cavitation caused a rapid negative shift in the free-corrosion potential for UNS A96061 which increased slightly during the cavitation period. The potential shift for UNS A96061 alloy quickly reversed when cavitation was stopped, suggesting reformation of the protective oxide layer on the surface of this alloy.

The morphological investigation revealed that corrosion initiated locally at grain boundaries and around the Fe_3SiAl_2 and Mg_2Si rich particles in the UNS A96061 alloy. The Fe_3SiAl_2 and Mg_2Si rich particles embedded in the metal matrix are bombarded with vapor bubbles and being cathodic to the aluminum rich matrix are eventually dislodges from the matrix. It is believed that both the mechanical action of the bombarding vapor bubbles and the micro-galvanic activity around these particles lead to their dislodgements from the matrix. In this manner, the underlying surface becomes rough, and locally eroded cavities are formed due to uneven cavitation-corrosion.

CONCLUSIONS

The ultrasonically induced cavitation conditions of UNS A96061 alloy in seawater at 25°C resulted in the following:

1. A slight increase in mass loss and in the rate of mass loss with exposure time for this alloy.

2. A slight shift in the free corrosion potential toward the more noble direction for UNS A96061.

3. The formation of slightly rough surfaces for this alloy with attacks along grain boundaries as well as plastically deformed matrix regions.

4. Corrosion of UNS A96061 alloy also initiated around Fe_3SiAl_2 and Mg_2Si rich particles leading to loosening and removal of these particles from the aluminum matrix.

5. The slight difference between the rate of mass loss of this alloy in seawater and distilled water indicates that the leading cause of mass loss is due mechanical factors.

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REFERENCES

1. V.K. Gouda, H.M. Shalaby, and W.T. Riad, Materials Performance, 28 (1989): p.53.

2. A. Al-Hashem, H. Tarish, A. Akbar, and J. Carew, “Cavitation Corrosion Behavior of Copper- and Nickel Based Alloys in Seawater” Presented at the 11th Middle East Corrosion Conference, Manama, Kingdom of Bahrain, 26th February – 1st March 2006.

3. A. Al-Hashem, H. Tarish and A. Akbar, “Cavitation Corrosion Behavior of Carbon Steel, Al-Bronze and Cobalt-Based Alloys in Seawater”, CORROSION 2007, Paper # 07253, NACE International, Nashville, Tennessee (2007).

4. H.M. Shalaby, S. Attari, W.T. Riad, and V.K. Gouda, “Erosion-Corrosion Behavior of Some Cast Alloys in Seawater”, Corrosion Journal, Vol. 48, No.3 (1992): p.206.

5. A. Al-Hashem, H. Tarish, A. Akbar, and N. Tanoli, “The Effect of Ultrasonically Induced Cavitation Conditions on the Behavior of Copper and Cobalt-based Alloys in Seawater”, CORROSION/2008, Paper # 08228, NACE International, New Orleans, LA (2008).

6. V. K. Gouda; A. H. Al-Hashem; A. M. Abdullah and W. T. Riad, "Effect of Ultrasonically Induced Cavitation on the Behavior of Nodular Cast Iron in Seawater" Br. Corros. J., 26, 2, (1991): p. 109.

7. A. Al-Hashem, H. Tarish, and J. Carew, “The Effect of Ultrasonically Induced Cavitation Conditions on the Behavior of Copper and Nickel Based Alloys in Seawater”, CORROSION/06, paper No. 299 (NACE International, Houston, TX, 2006).

8. A. Al-Hashem, H. Tarish, and N. Tanoli, “The Effect of Ultrasonically Induced Cavitation Conditions on the Behavior of Ni-Resist Cast Alloys in Seawater”, CORROSION/10, paper No. 10392 (NACE International, Houston, TX, 2010).

9. A. Al-Hashem, H. Tarish, N. Tanoli, “The Cavitation Corrosion Behavior of UNS N06022 Alloy in Seawater”, CORROSION 2011, Paper # 11415, NACE International, Houston, Texas (2011).

10. A. Al-Hashem, H. Tarish and N. Tanoli,” The Ultrasonically Induced Cavitation Corrosion Behavior of UNS R31233 Alloy in Seawater ”, CORROSION 2012, PAPER # 22751, NACE-International, Salt Lake City, Utah (2012).

11. A. Al-Hashem, H. Tarish and N. Tanoli, “The Cavitation Corrosion Behavior of UNS G10950 Alloy in Seawater“, CORROSION 2013, Paper # 2201, NACE-International, Orlando, Florida (2013).

12. A. Al-Hashem, H. Tarish and N. Tanoli, “The Ultrasonically Induced Cavitation Corrosion of UNS N08825 in Seawater”, CORROSION/2014, Paper # 3803, NACE-International, San Antonio, Texas (2014).

13. H. Tarish, A. Al-Hashem and N. Tanoli, “The Cavitation Erosion Behavior of UNS N04400 Alloy in Seawater ”, CORROSION/2015, Paper # 5582, NACE-International, Dallas, Texas (2015).

14. H. Tarish, A. Al-Hashem and N. Tanoli, “The Effect of Alloy UNS S32550 Microstructure on its Cavitation Erosion Behavior in Seawater ”, CORROSION/2016, Paper # 7377, NACE-International, Vancouver, British Columbia, Canada (2016).

15. J. M. Hobbs, in Erosion by Cavitation or Impingement, STP 408; Philadelphia PA, ASM (1967): p. 159.

16. T. McGuiness and A., Thijuvengadam, in Erosion Wear and Interfaces with Corrosion, STP 567: P. Philadelphia, PA, ASTM. (1974), 30.

17. VC. M. Preece. Cavitation Erosion, in Treatise on Material Science and Technology. Vol. 16, C. M. Preece, ed. New York, NY: Academic Press, (1979), p. 249.

18. R. L. Chance, in Engine Collant Testing, State of Art, (ed. W. H. Ailor), STP 705: Philadelphia, PA, ASTM (1980), p. 270.

19. A. H. Al-Hashem, H. M. Shalaby and V. K. Gouda, Proc. 12th Int. Cong. On Metallic Corrosion, Sept. 19 - 24, Vol. 5B, p. 3600, Houston, Texas, (1993).

20. J. G. Auret, O.F.R. Damm, G. J. Wright and F.P.A. Robinson, Corrosion 49, 11: p. 910, (1993).

21. C. McCaul, "An Advanced Cavitation Resistant Austenitic Stainless Steel for Pumps" CORROSION/96, paper No. 415 (NACE International, Houston, Tx, 1996).

22. T. Okada, Y. Iwai, A. Yamamoto, Wear 84 (1983): p. 167.

23. H.M. Tawancy, V.R. Ishwar, B.E. Lewis, J. Materials Science Lett 5, (1986), pp. 337-341.

24. H. Farhangi, R.W. Armstromg, W.F. Regnault, Materials Science and Engineering, 114, (1989), pp.25-28.