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Effect of Solution Temperature on the Cavitation Degradation Properties of Epoxy Coatings for Seawater Piping

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Since epoxy resin coating shows excellent properties in formability, adhesion, and corrosion resistance, they have been extensively used in many industries. However, various types of damages in the epoxy coated tube within a relative short time have been reported due to cavitation erosion, liquid impingement, variation of temperature and pressure. Nevertheless, there has been little research on the effect of temperature on the cavitation degradation of epoxy coatings. Therefore, this work used an ultrasonic cavitation tester to focus on the effect of solution temperature on the cavitation properties of 3 kinds of epoxy coatings in 3.5% NaCl. The cavitation properties were discussed basis on the material properties and environmental aspects. As the solution temperature increased, even though with large fluctuation, the cavitation degradation rates of A and B coatings were reduced rapidly, but the rate of C coating was decreased gradually. In addition to the cushioning effect, the reason that the cavitation degradation rate reduced with solution temperature was partly related to the brittle fracture and water absorptivity of the epoxy coatings, and the water density, but was little related to the shape and composition of the compound in the coatings or the phase transition of the epoxy coating.

Keywords: *Corrosion, Carbon Steel, Epoxy Coating, Cavitation, Temperature*

1. Introduction

Since seawater is used as cooling water, scale due to salt and various factors forms on the surface and various corrosion forms in the heat exchanger's tubing, and thus leakage from the tubes has been occasionally reported [1]. Chloride ions in seawater are well known as a representative aggressive ion, and they facilitate the corrosion of the inside of tube with dissolved oxygen and elevated temperature [2-4]. To solve these kinds of problems, the inside-coated tube has been used [5-7]. Such coatings can afford a barrier layer to protect from contact with seawater, and from corrosion, increase the lifespan of the tube, and reduce the cost of repair. The coating methods can be summarized as; rubber lining [8] and epoxy resin coating [9,10]. Since the rubber lining has advantages in corrosion control, thermal shock, and erosion resistance while the epoxy resin coating shows excellent properties of formability, adhesion, and corrosion resistance, they have been extensively used in many industries [11,12]. However, various damage to the rubber lined tube after long-term usage, and to the epoxy coated tube within a relative short time, have been reported due to cavitation erosion, liquid impingement, variation of temperature and pressure [13-15], and the cavitation corrosion rate of the matrix – carbon steel depends upon the ultrasonic cavitation amplitude [16].

According to a survey of the Korea Hydrographic and Oceanographic Agency [17], the maximum and minimum temperatures of the East Sea were (28.39 and 7.3) ºC, and of the West Sea were (30.6 and 0.94) ºC, of the South Sea (32.1 and 4.85) ºC. The temperature of seawater depends upon the season, and the temperature of cooling water in the facilities may increase due to heat exchange through the seawater system. Particularly, the solution temperature is one of the factors affecting corrosion, which factors include dissolved oxygen, salt concentration, weather, ocean current, and season [18].

Recent work reported that the cavitation of 3 kinds of

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epoxy coatings was evaluated in 3.5 % NaCl at 15 ºC using an indirect ultrasonic cavitation method [19]: The cavitation erosion mechanism includes the initial stage and propagation stage; in the initial stage of cavitation erosion, the compound, matrix, or interface of the matrix and compound, depending upon the components used in each coating, were partly damaged. In the propagation stage, the coating was severely damaged regardless of the matrix and compound. High cavitation resistance coating showed high flexural strength, tensile strength, pull-off strength, and wear resistance, and thus these properties could affect the resistance of the initial and propagation stages in cavitation erosion of the coatings, and small polygonal shaped compounds were also effective for its resistance.

It is to be expected that the variation of pressure and temperature will affect cavitation damage through several mechanisms, which are more or less important in different cases: (1) 'Thermodynamic' effects upon bubble growth and collapse, due to the fact that as the temperature rises, the growth and collapse begin to vary significantly from isothermal behavior; (2) Change in dissolved gas content due to temperature variation; and (3) Change in material properties due to temperature variation [20]. Consequently, the cushioning effects on bubble collapse are reduced, whereas the number of bubbles increases, because there is more dissolved air, resulting in an increase in damage because of increased bubble collapse for this low-temperature range. Reduction in viscosity and surface tension may also be involved. However, for higher temperatures, the amount of damage decreases strongly, because with the rapid increase in vapor pressure, the cushioning effect (now due to the increased vapor content of the bubbles) increases strongly. The reduction in mechanical properties for higher temperatures may also affect the cavitation damage. However, it seems to be less important in the shift in maximum damage temperature with amplitude since the variations in mechanical properties can be expected to cause similar behavior for every amplitude [21].

However, there has been little research on the effect of temperature on the cavitation degradation of epoxy coatings. Therefore, this work uses an ultrasonic cavitation erosion tester to focus on the effect of the solution temperature on the cavitation properties of 3 kinds of epoxy coatings in 3.5% NaCl. The cavitation properties are discussed based on materials properties and environmental aspects.

2. Experimental Methods

2.1 Materials

Three kinds of epoxy coating were used, and each specimen was made by the respective supply company. In this work, 'A coating', 'B coating', 'C coating' are designated, respectively. All specimens for cavitation test have 29mm diameter.

2.2 Cavitation Degradation Test

The cavitation degradation tester (R&B-RB111-CE, Korea) was made by a magnetostrictive driven method and by modifying ASTM G32 standard [22]; Maximum power output of the tester was 1,000 W, and an ultrasonic transducer showing (20 ± 5 KHz) was used (In this work, the peak-to peak amplitude was termed 'ultrasonic amplitude). The horn tip was made by super duplex stainless steel (Fe-25.8Cr-2.3Mo-0.2W-0.5Si-10.7Ni-0.65 Mn-0.03C-0.42N), and its diameter was 16 mm. The distance between the horn tip and specimen was 0.5 mm and a freshly ground (#2,000 SiC) horn tip was used in every test. Fig. 1 shows a schematic of the cavitation degradation tester using an indirect cavitation method.

2.3 Surface Analysis

Surface morphology was observed using a digital camera, 3D Stereographic microscopy (Hirox, KH-7700, Japan), and FE-SEM (Tescan, LYRA 3 XMH, Czech Republic) and EDS (Tescan, VEGA II LMU, Czech Republic). The surface of the specimen for the analysis was coated with osmium.

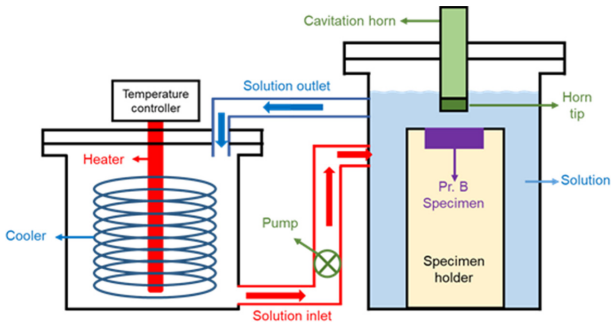

Fig. 1. Schematic of the cavitation erosion test equipment [22]

2.4 Instrumented Indentation Test

Yield strengths of each coating samples were estimated by spherical instrumented indentation with a tip radius of 250 μm. Indentation force-depth curves were measured from AIS 2100 (Frontics Inc., Seoul, Korea) with a depth resolution of 0.1 μm, and a force resolution of 0.055 N. The indenter is partially unloaded 15 times for every 10 μm until reaching maximum penetration depth of 150 μm. The unloading ratio was 50 % of each indentation depth, and testing speed was 0.3 mm/min. More than 5 tests were conducted on surface of each specimen, providing over 3 reproducible data. Prior to testing, specimens were immersed in the solution for 30 minutes. To prevent specimen temperature change, indentations were conducted instantaneously upon removal of specimen from the solution. The testing temperatures indicate the solution temperatures [23].

2.5 Dynamic Mechanical Analysis

Dynamic mechanical analysis (DMA) was used for the measurement of 3 kinds of epoxy coatings using different deformation modes. The instrument used was (DMA Q800, TA Instruments, USA). Measuring temperature was in the range (0-150) ºC, and the heating rate was 10 ºC/min. Frequency of 1 Hz was applied and its amplitude was 20 μm. The glass transition temperature and temperature dependence of the modulus were measured and analyzed.

2.6 Differential Scanning Calorimeter

DSC (Differential Scanning Calorimeter) is widely used to examine polymeric materials to determine their thermal transitions. Important thermal transitions include the glass transition temperature (T_g), crystallization temperature (T_c), and melting temperature (T_m). DSC Q20 instrument (TA Instruments, USA) was used, and the range of measuring temperature was from (0 - 100) ºC and the scan speed was 5 ºC/min under a N_2 gas environment.

3. Results and Discussion

3.1 Effect of solution temperature on the cavitation degradation rate of epoxy coatings

Fig. 2 shows the effect of solution temperature on the surface morphologies of the 3 kinds of epoxy coatings after cavitation for 6 h at the ultrasonic amplitude of 85 μm in 3.5% NaCl. A and B coatings showed similar color, circular areas of severe damaged were formed, the matrix

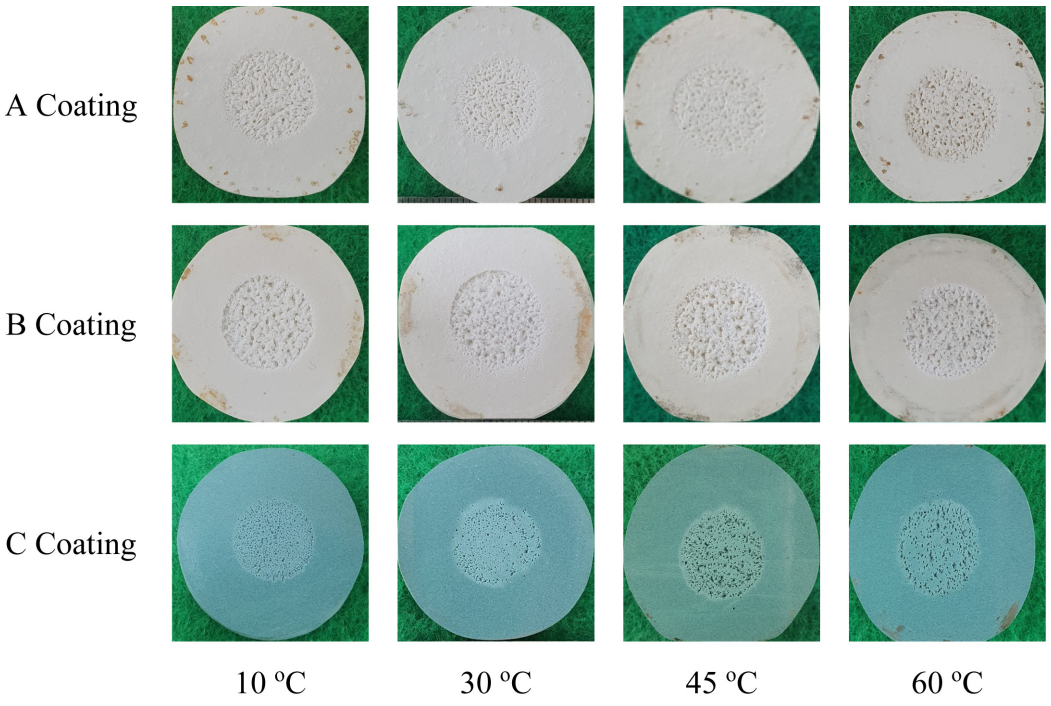

Fig. 2. Effect of the solution temperature on the surface morphologies of the 3 epoxy coatings after cavitation in 3.5% NaCl (ultrasonic amplitude 85 μm, cavitation time 6 h)

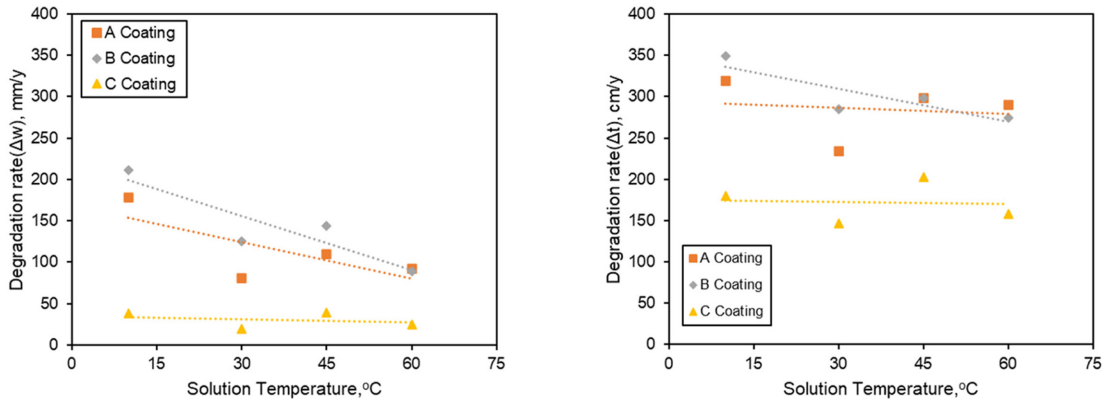

Fig. 3. Effect of the solution temperature on the cavitation degradation rate of the 3 epoxy coatings in 3.5% NaCl at ultrasonic amplitude 85 μm, cavitation time 6 h; (a) degradation rate by Δw, (b) degradation rate by Δt

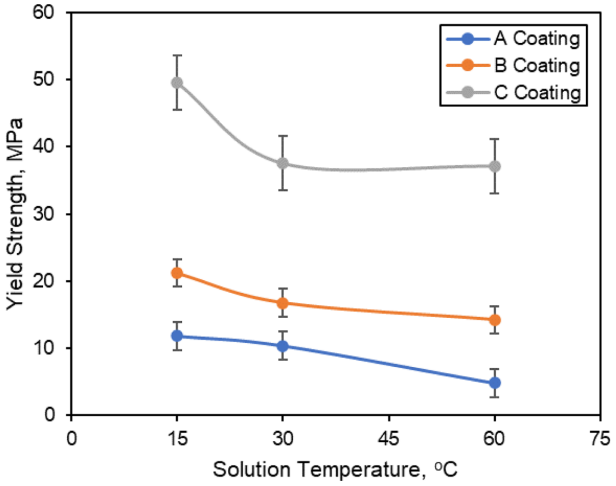

Fig. 4. Variation of the yield strength of the 3 epoxy coatings by solution temperature

was deeply detached, and the damaged trend varied with the solution temperature. C coating showed that the matrix was detached as a plate-like aspherical shape, and circular areas of slight damage were formed.

Fig. 3 summarizes the cavitation degradation rates by (a) weight loss (Δw) and (b) damage depth (Δt) obtained from Fig. 2 (The damage depth was measured using 3D microscope). Regardless of measuring methods, the rates of A and B coatings were larger than that of C coating, and this behavior was discussed elsewhere [19]; the cavitation resistance of the coating was closely related to the flexural strength, tensile strength, wear resistance and pull-off strength of the coating. High cavitation resistance coating showed high flexural strength, tensile strength, pull-off strength, and wear resistance, and thus these properties could affect the resistance of the initial and propagation stages in cavitation erosion of the coatings, and small polygonal compounds were also effective for its resistance.

As the solution temperature increases, even though there was large fluctuation, the rates of A and B coatings reduced rapidly, but the rate of C coating decreased gradually.

Fig. 4 shows the yield strength of 3 kinds of coatings with the solution temperature obtained from the instrumented indentation test. Regardless of solution temperature, the yield strength of C coating was higher than those of A and B coatings, and this implies that the yield strength is one of the factors that affect the cavitation resistance of epoxy coating [19].

Fig. 5 compares the cavitation degradation rates obtained from the weight loss and from the damage depth of the coatings with the solution temperature in 3.5 % NaCl. The rates by damage depth for A, B, and C coatings were (17.9~31.3) times, and (16.5~30.9) times, and (47.8~73.2) times faster than those by weight loss, respectively. This behavior reveals that localized damage can be formed in the epoxy coated pipes, rather than uniform thinning.

3.2 Cavitation mechanism of epoxy coatings with solution temperature

As described above [20,21], the cushioning effects on bubble collapse are reduced, whereas the number of

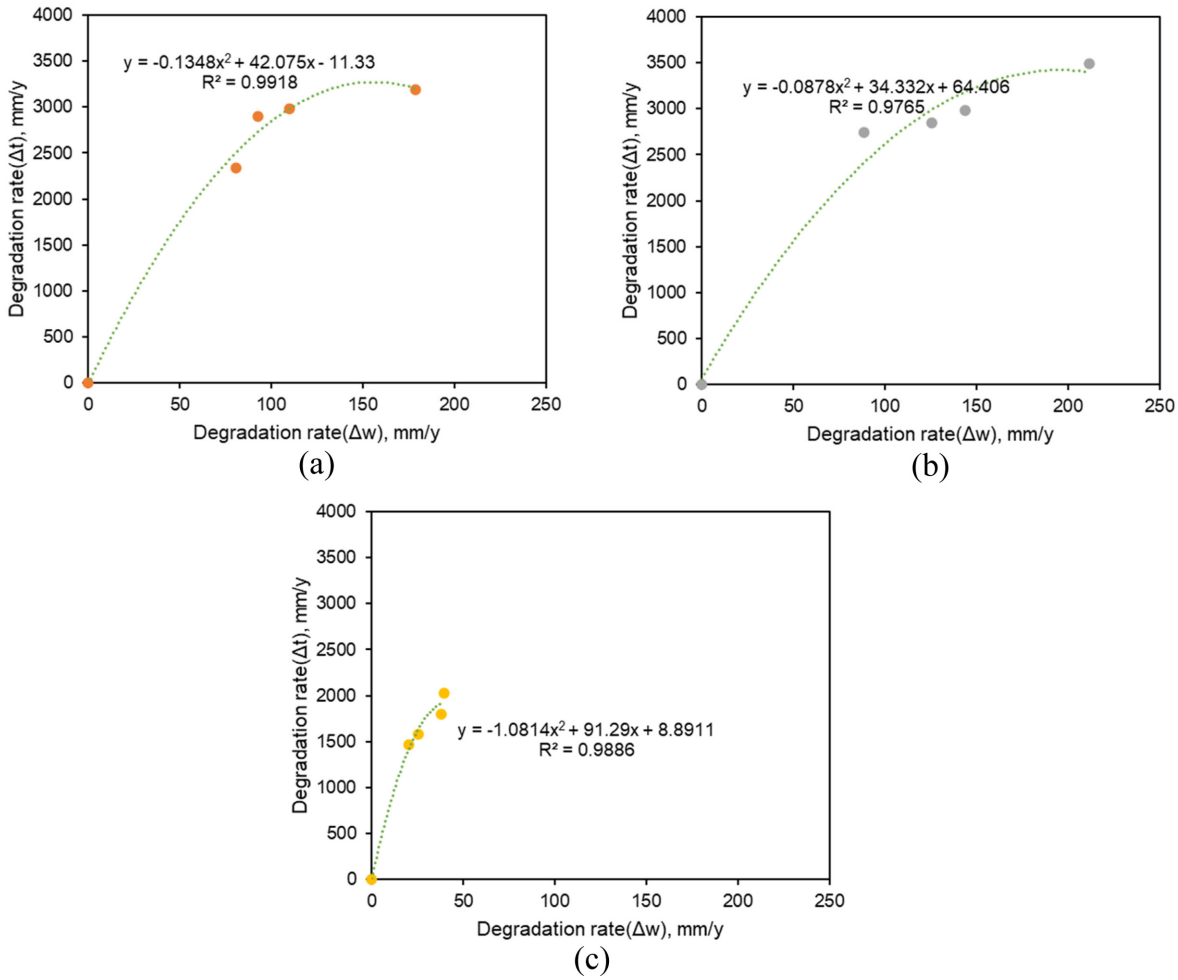

Fig. 5. Comparison of the cavitation degradation rates obtained between the weight loss and damage depth of the coatings with solution temperature in 3.5 % NaCl (ultrasonic amplitude 85 μm, cavitation time 6 h); (a) A Coating, (b) B Coating, (c) C Coating

bubbles increases, because there is more dissolved air, resulting in an increase in damage because of increased bubble collapse for this low-temperature range. Reduction in viscosity and surface tension may also be involved. However, for higher temperatures, the amount of damage decreases strongly because with the rapid increase in vapor pressure, the cushioning effect (now due to the increased vapor content of the bubbles) increases strongly. However, in this work, the other reasons besides the above cushioning effect are discussed.

Fig. 6 shows the SEM-EDS results on the cavitated surface of A coating with solution temperature. The effect of the solution temperature was not observed in the damage morphology and composition, and glass-flake containing silicon etc. was more detached, as can be seen in the left area, than along the dashed line.

Fig. 7 shows the SEM-EDS results on the cavitated surface of B coating with solution temperature. The effect of the solution temperature was not observed in the damage morphology and composition and glass-flake containing silicon etc. was more detached as can be seen in the left area, than along the dashed-line, and this behavior was similar to the result of A coating.

Fig. 8 shows the SEM-EDS results of the cavitated surface of C coating with solution temperature. The effect of the solution temperature was not observed in the damage morphology and composition, but after the cavitation, the spherical silicon compounds still existed and this seems to be one reason to resist the cavitation among the 3kinds of epoxy coatings.

Fig. 9 shows the DMA of the coatings with temperature from (0 to 150) ºC at the heating rate of 10 ºC/min.

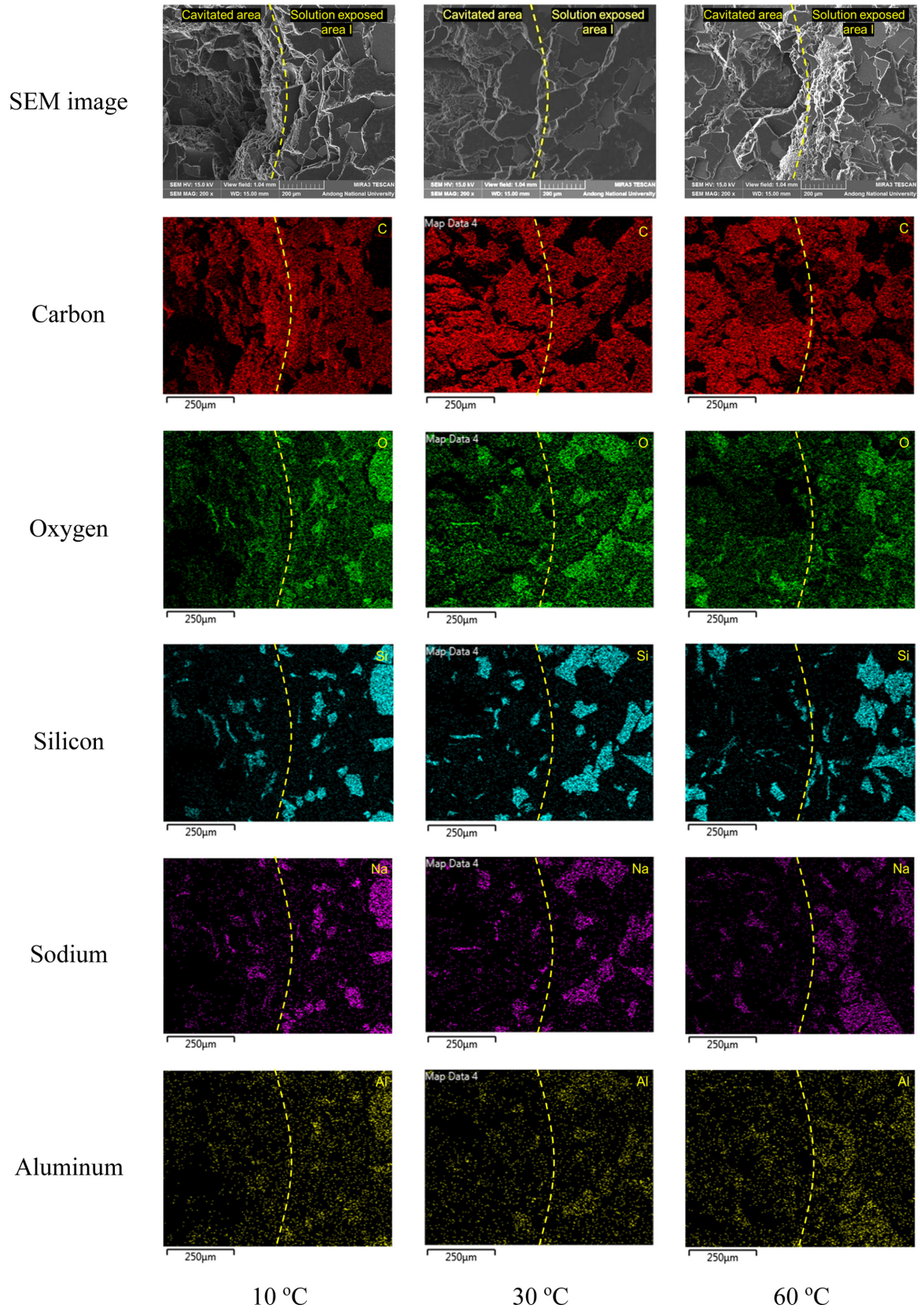

Fig. 6. SEM image and elemental analysis of the cavitated area and the solution exposed area of A Coating in 3.5 % NaCl (ultrasonic amplitude 85 μm, cavitation time 6 h, ×200)

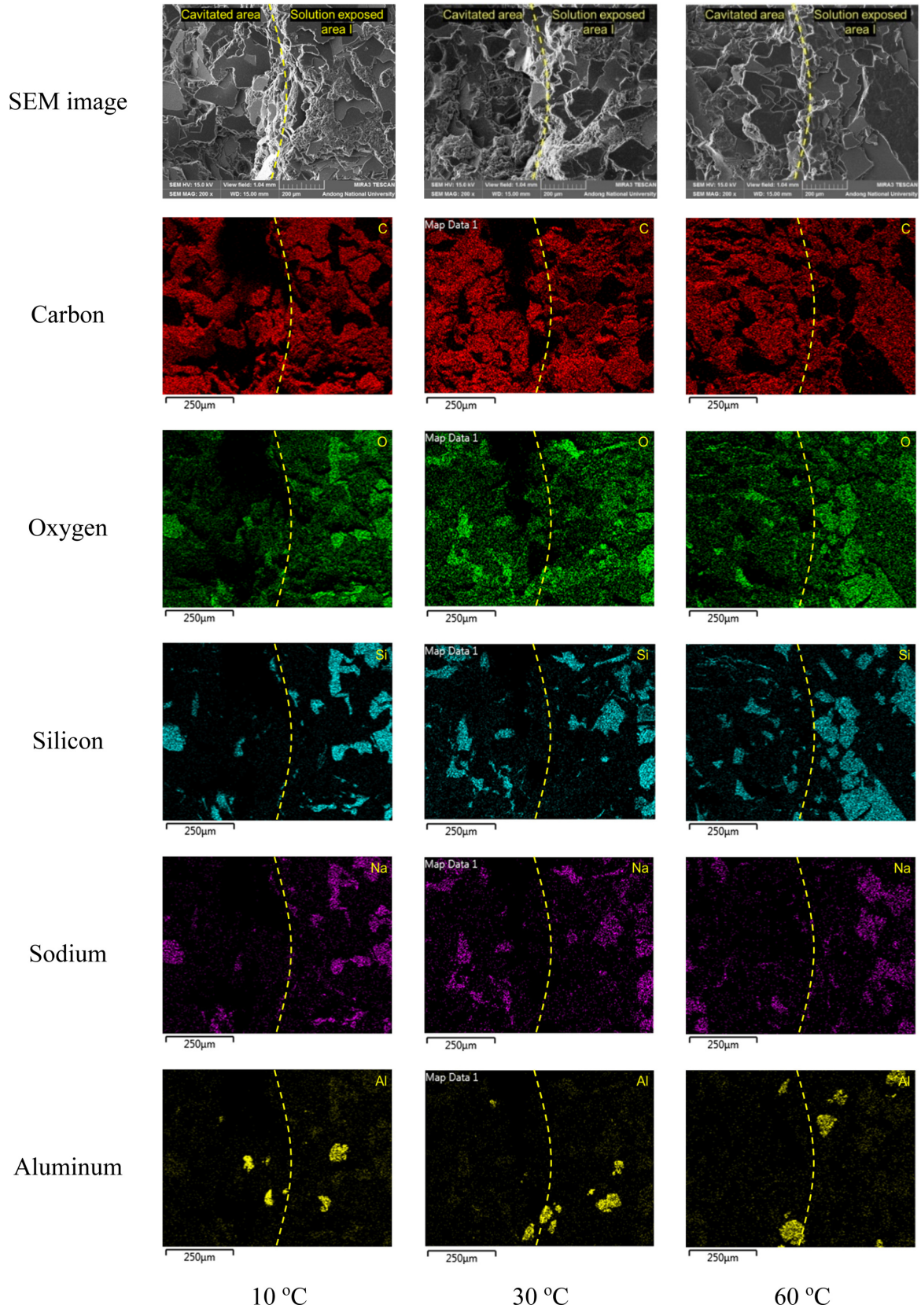

Fig. 7. SEM image and elemental analysis of the cavitated area and the solution exposed area of B Coating in 3.5 % NaCl (ultrasonic amplitude 85 μm, cavitation time 6 h, ×200)

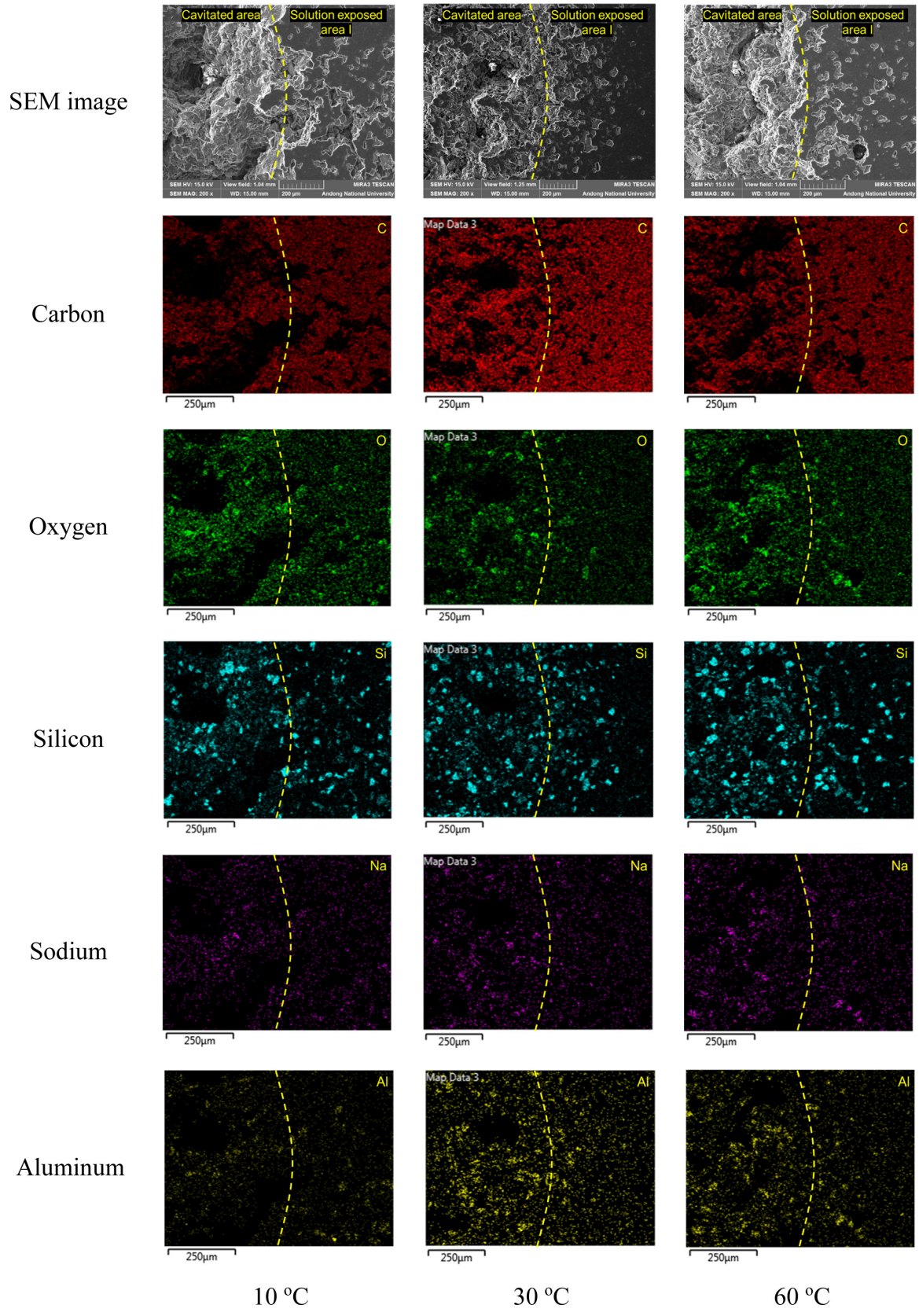

Fig. 8. SEM image and elemental analysis of the cavitated area and the solution exposed area of C Coating in 3.5 % NaCl (ultrasonic amplitude 85 μm, cavitation time 6 h, ×200)

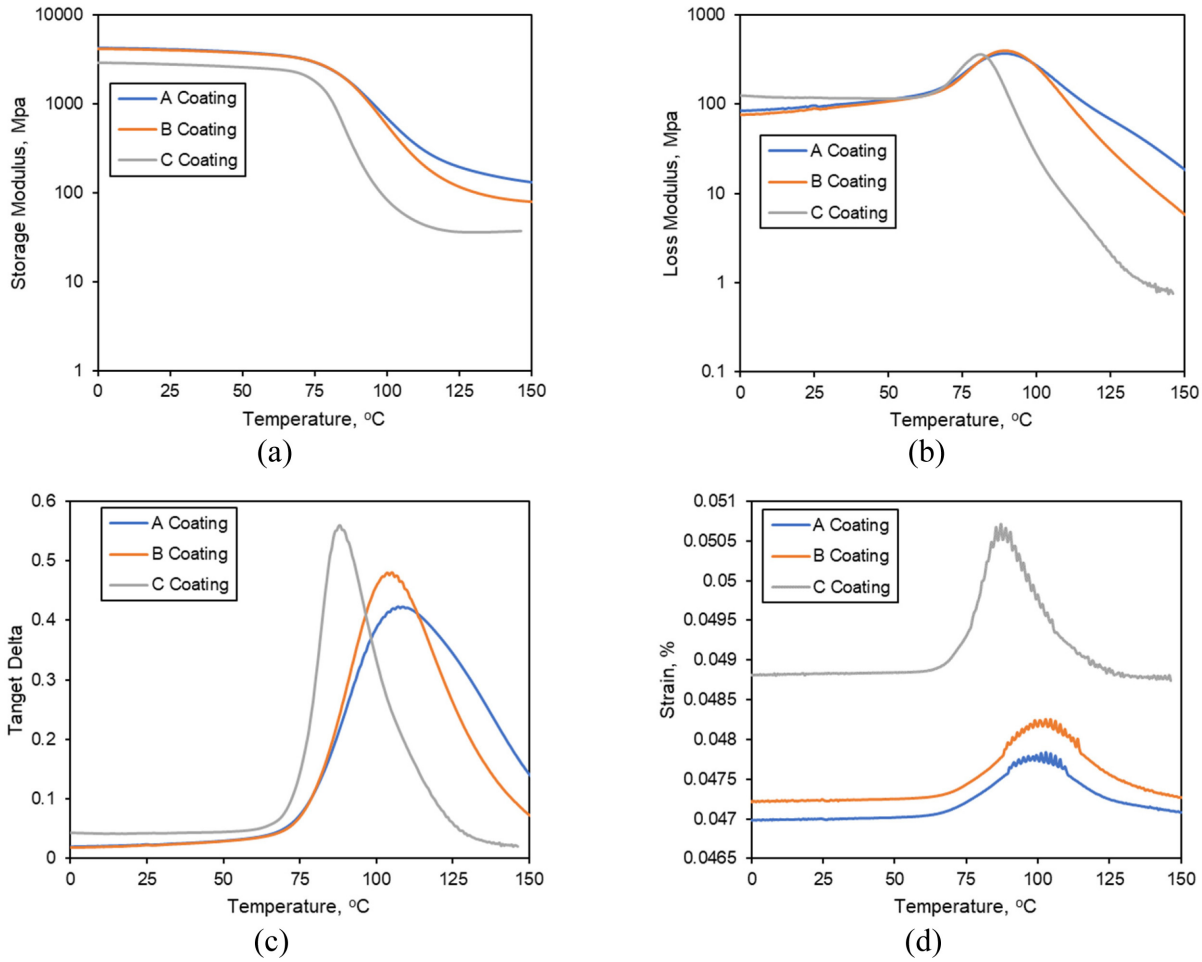

Fig. 9. DMA analysis of the coatings; (a) Storage Modulus, (b) Loss Modulus, (c) Tangent Delta, and (d) Strain

Fig. 9a shows the storage modulus (E') which is a measure of the elastic response of a material but not the same as Young's modulus. The storage modulus of 3 kinds of the coatings was very slightly reduced with temperature. Fig. 9b shows the loss modulus (E") which is a measure of the viscous response of the coatings. The loss modulus of 3 kinds of coatings was very slightly increased with temperature. Fig. 9c shows the tangent delta (Tan δ) which is the ratio of E"/E'. Since peak temperature of tangent delta defines the glass temperature (Tg), it was calculated that Tg of A coating was 107.3 ºC, 103.8 ºC for B coating, and 88.3 ºC for C coating. Fig. 9d shows the strain of the coatings with temperature, and 3 kinds of the coatings reveal the very low strain and thus they will show the brittle fracture within solution temperature.

Fig. 10 shows the DSC thermogram of the coatings. With Heat-flux DSC, the changes in heat flow are calculated by integrating the ΔT_{ref} curve. For this kind of experiment, a sample and a reference crucible are placed on a sample holder with integrated temperature sensors for temperature measurement of the crucibles. Heating and cooling were performed from (0 to 100) ºC at the scan rate of 5 ºC/min under the N_2 environment. None of the coatings, revealed the phase transition within the test temperature.

Fig. 11 shows the water absorptivity of the 3 kinds of the coatings in 3.5 % NaCl with solution temperature. Every weight gain was measured after drying for 48 h in 'dry keeper'. Regardless of the coatings, as the solution temperature increased, the weight gain increased. This water absorptivity of the coating may be one of the reasons for the underestimation of the cavitation degradation rate with solution temperature.

Fig. 12 shows the variation of the density of water with

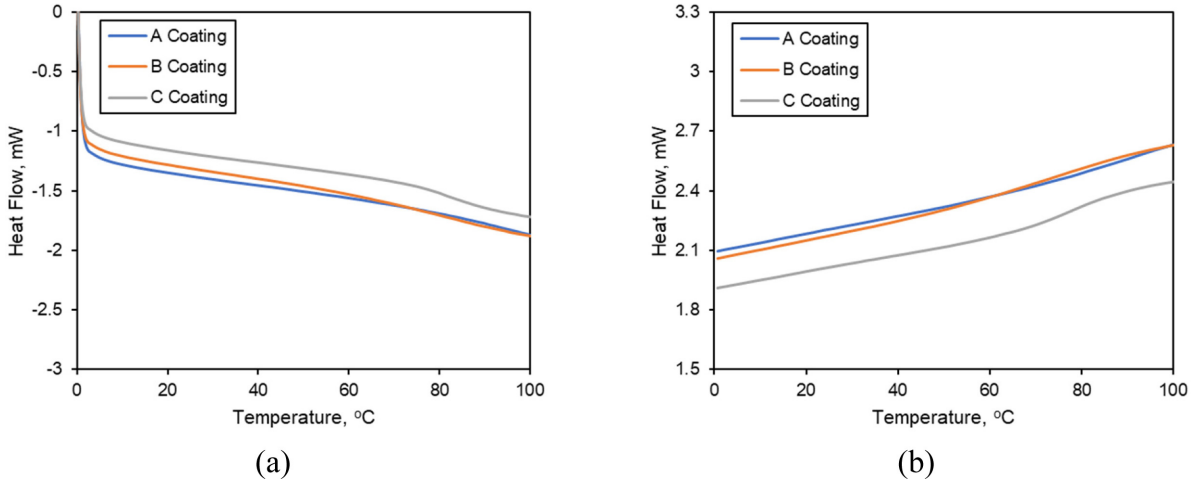

Fig. 10. DSC thermogram of the 3 epoxy coatings; (a) heating, and (b) cooling

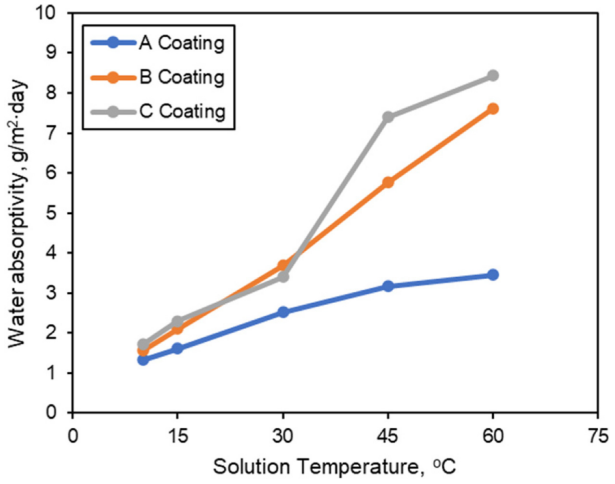

Fig. 11. Water absorptivity of the 3 epoxy coatings in 3.5 % NaCl with solution temperature (after drying for 48 h in 'dry keeper')

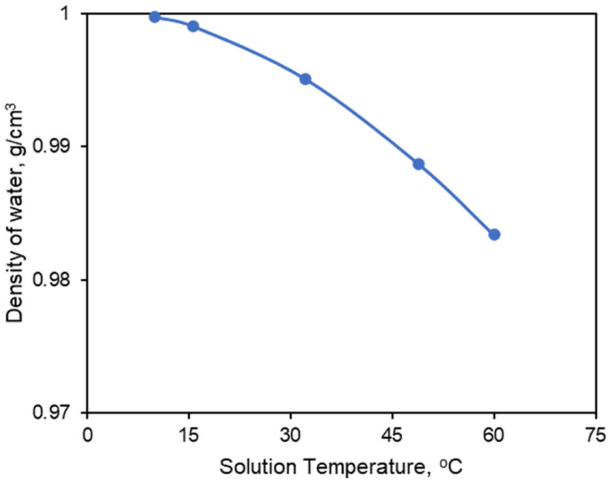

Fig. 12. Variation of the density of water with solution temperature [24,25]

solution temperature [24,25]. As the solution temperature increases, the water density reduces, and this may be one of the reasons for underestimation of the cavitation degradation rate with solution temperature.

4. Conclusions

In this work, the 3 kinds of epoxy coatings were used, and an indirect ultrasonic cavitation method was used to evaluate the cavitation resistance of the coatings in 3.5% NaCl with temperature. The following conclusions were derived:

As the solution temperature increased, even though with large fluctuation, the cavitation degradation rates of A and B coatings reduced rapidly, but the rate of C coating decreased gradually.

In addition to the cushioning effect, the reason that the cavitation degradation rate reduced with solution temperature was partly related to the brittle fracture and water absorptivity of the epoxy coatings, and the water density, but was little related to the shape and composition of the compound in the coatings, or the phase transition of the epoxy coating.

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