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Study on cavitation erosion resistance and surface topologies of various coating materials used in shipbuilding industry

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ABSTRACT

Cavitation erosion tests were conducted to evaluate the cavitation erosion resistance of five coating materials: epoxy clear coat, commercial epoxy coating, glass-flake-reinforced epoxy coating, polyurethane coating, and silicone coating. The relationships between cavitation erosion resistance and the mechanical and thermal properties were studied. Eroded surfaces were observed using scanning electron microscopy and 3D confocal microscopy. We found that the cavitation erosion resistance was greater in coating materials with better ductile and tough properties than in coating materials with higher strength or hardness. Thermal stability was also a very important factor that determined cavitation erosion resistance.

Introduction

Cavitation can occur in rudders or propellers of ships, causing vibration or erosion. Cavitation erosion can affect the structural integrity and safety and can lead to the failure of components. In order to prevent the cavitation erosion of ships, Lloyd's Register's Technical Investigation Department (TID) has researched the cavitation in rudders and propellers of ships for a long time [1]. Especially, rudders are easily damaged by cavitation erosion due to the explosion of bubbles generated by the rotation of propellers and propagates the cavitation erosion and corrosion. Cavitation erosion is more significant in high-speed ships such as container ships, passenger ships, and warships. Cavitation erosion causes expensive repair or replace of damaged parts as well as potential problems for the structural integrity and safety. Several researchers have studied the application of organic coatings, composite materials, and ceramic coating to prevent the corrosion of inner turbines against slurry erosion and reported good results [2–5]. On the other hand, successful results for coatings applied to prevent the wear or erosion under cavitation conditions have been rare; this is mainly because of adhesion problems between the coating and substrate as well as the initiation of cavitation erosion spots due to the micro defects of coatings. Nevertheless, research and development of polymeric coating materials for cavitation erosion has been conducted because of their numerous advantages such as easy application, convenient maintenance, and relatively lower cost. Hammitt et al. [6] conducted vibratory cavitation erosion tests using a stationary specimen method for various polymeric coating materials such as natural rubber, neoprene, epoxy, and Plexiglas. The test yielded a rough correlation between hardness and cavitation erosion resistance. Barletta and Ball [7] conducted cavitation erosion tests using twenty-six polymeric coating materials and classified them into three according to their cumulative volume loss. Yamaguchi et al. [8] conducted cavitation erosion tests for various plastics and metals and reported a comparison of the cavitation erosion resistances of plastics and metals. In addition, Hojo and Tsuda [9] reported the cavitation erosion performance of several thermoplastics, thermosetting plastics, and composite materials. They reported that brittle coatings such as polystyrene showed higher erosion rates than ductile materials such as polyethylene.

Hattori and Itoh examined the inside temperature of plastics during a vibratory cavitation erosion test (ASTM G32-10 standard) and reported that the inside temperature of plastics increased to the range of 40–60 °C, depending on the plastic, because of the low thermal conductivity [10].

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In this study, vibratory cavitation erosion tests were conducted using 5 coating materials used in shipbuilding industry. The mechanism of the cavitation erosion is discussed in terms of temperature and thermal properties by measuring the mean erosion depth and mechanical strength as well as by observing the eroded surface.

Experimental

Materials

Five coating materials were considered in present study. DGEBA-based epoxy clear resin (EC) was supplied by Kukdo chemical in South Korea, and commercial epoxy coating (EP), glass-flake-reinforced epoxy coating (EGP), and silicone coating (SP) used in shipbuilding industries were supplied by international paint in the UK. MDI-based urethane coating (UP) was supplied by Noroo paint in South Korea.

Cavitation erosion test

The cavitation erosion tests were conducted using a vibratory device (supplied by DU-U2020, Dong-A Sonic, South Korea), with modified ASTM G32-10 method. The vibrating horn was composed of titanium of 16-mm diameter, and the applied frequency and amplitude were 20 ± 0.5 kHz and 50 μm ± 0.5%, respectively. The coated carbon steel specimens were placed into an ultrasonic vibratory bath with distilled water at 23 ± 2 °C, and the distance between the titanium horn and the coated surface was maintained at 0.5 mm, as shown in Fig. 1. Prior to the cavitation test, the coated specimens were washed with distilled water in the ultrasonic treatment for 5 min, dried in a vacuum desiccator for 5 min, and then weighed using a precision balance with an accuracy of 0.01 mg. The weight loss of coated specimens was measured periodically with respect to cavitation erosion time, and the mean erosion depth was calculated by dividing the measured mass loss by the density of the material. In order to analyze the eroded surface of coated specimens, the surface morphology was observed using SEM (Jeol JSM-6610LV, USA) and laser confocal microscopy (Carl Zeiss LSM 700, Germany)

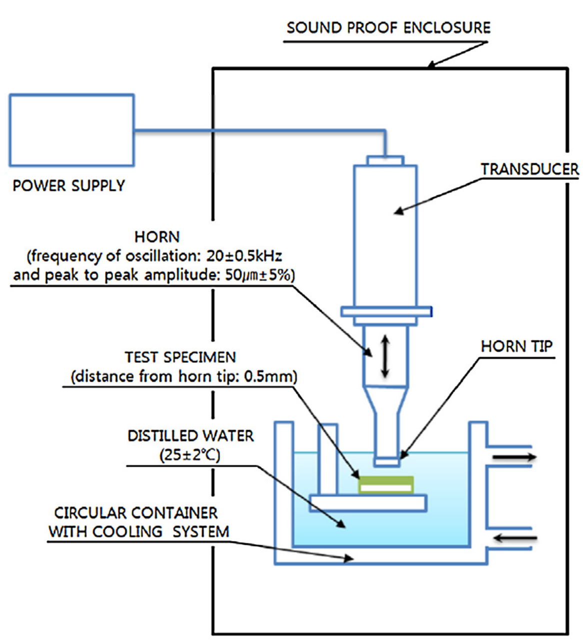

Fig. 1. Vibratory equipment for cavitation erosion test in distilled water.

Mechanical test

In order to investigate the relation between mechanical properties (tensile strength, Young's modulus and elongation) and cavitation erosion resistance of the coating, tensile tests were carried out using a universal testing machine (Instron 3367, UK). A video extensometer (Instron 2663-822, UK) was used to measure the elongation. The coating specimens were prepared using a casting mould with the dimensions shown in Fig. 2. When the organic coating materials are exposed to repeated bubble collapse pressures, increased of temperature occurs and the mechanical properties of organic coating materials are affected by the test temperature [9]. Therefore, the tensile strength, Young's modulus, and elongation were measured at various temperatures, including 25, 50, 75, and 100 °C. The tensile test was performed with a crosshead speed of 3 mm/min.

Thermal property test

In order to examine the relation between the thermal properties and cavitation erosion resistance of coatings, differential scanning calorimeter (DSC, Q10, USA) analysis was performed. Approximately 10 mg of coating samples were placed into aluminum pans and closed with aluminum covers. Subsequently, the aluminum pans were placed in the DSC instrument, which was continuously purged using pure dry nitrogen gas. The heating rate was 10 °C/min. The epoxy-based coating samples were heated from 25 °C to 200 °C, whereas polyurethane and silicone coatings were heated from −40 °C to 200 °C and −80 °C to 200 °C, respectively, because of its low glass transition temperature (T_g).

Results and discussion

Results of mechanical test

The mechanical properties of the five free-film samples were investigated using tensile tests. The tensile strength, Young's modulus, and elongation of the coatings were measured at different temperatures, as shown in Figs. 3–5, respectively. The tensile strengths of the epoxy-based coatings (EC, EP, and EGP) were in the range of 17–25 MPa at 25 °C, and they dramatically decreased to 1.6–3.7 MPa on increasing the temperature to 100 °C. The tensile strengths of UP and SP coatings were 3.2 MPa and 1.5 MPa at 25 °C, respectively, which was relatively much lower than those of epoxy-based coatings. The tensile strength of UP coating slightly decreased to about 2.1 MPa on increasing the temperature to 100 °C, and the tensile strength of SP coating did not change on increasing the temperature to 100 °C. These results clearly indicate that the tensile strengths of SP and UP coatings are much more stable with respect to temperature than those of EC, EP, and EGP coatings, even though the tensile strength values of SP and UP coatings were much lower than those of epoxy-based coatings.

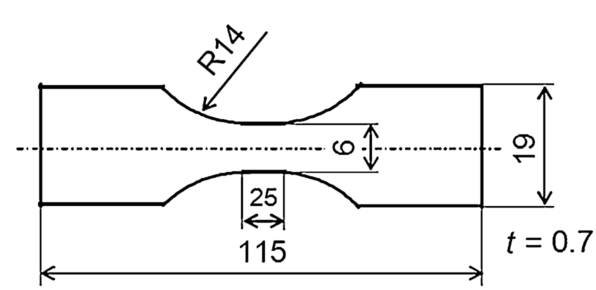

Fig. 2. Shape and dimensions of specimen in tensile test (mm).