



Erosion and heating of polyurea under cavitating jets

Pauline Marlin¹, Georges L. Chahine^{*,1}

Dynaflow, inc., 10621-J Iron Bridge Road, Jessup, MD, USA

ARTICLE INFO

Keywords:

Cavitation
Jets
Erosion
Temperature
Polyurea

ABSTRACT

Earlier observation of cavitation erosion of polyurea coatings has shown that failure is due to synergetic effects between the locally imparted impulsive loads and heating of the material. Both result from the interaction between large amplitude cavitation bubble dynamic and material response and deformation. In order to investigate this interaction and quantify damage and heat generation in the material subjected to cavitation, cavitating jet tests were conducted on polyurea coated samples while measuring both the erosion of the polyurea and the temperature evolution. The effects of polyurea composition, cavitation field intensity, material of the substrate, and thickness of the polyurea coating on the erosion and temperature were deduced from the tests.

1. Introduction

Cavitation in a liquid occurs when the local pressure drops below the liquid vapor pressure (e.g. due to high local velocities) leading microscopic bubble nuclei to grow and then collapse violently [1,2]. The successive violent collapse of a multitude of bubbles in a cavitating field generates repeated impulsive loads on the material surface, which could result in material local failure and cavitation erosion. A recent comprehensive description of the state-of-art experimental and numerical techniques to investigate the physics of cavitation erosion can be found in [2–4]. Cavitation damage is a problem in turbomachinery such as pumps, propellers and impellers, and protection of the material surface by polymeric coating can be an approach to delay substrate deterioration and avoid to have to replace parts. The general wear characteristics of these coating have been studied [5,6], and reported cavitation erosion studies include erosion of polymers [7], non-metallic coatings [8], epoxy resins and coating layers [9,10], ultra-high molecular weight polyethylene [11], various coating materials used in ships [12], and polyurea coatings on hydraulic concrete structures [13]. Coatings are also been applied more often on ship hulls and propellers as anti-fouling, drag reducing, and/or energy saving aids [14–17], and it is now important to further understand their resistance to cavitation. Cavitation erosion tests in [18] demonstrated that the temperature rise of plastic specimens subjected to cavitating flows was an order of magnitude higher than for metals, such as aluminum and stainless steel. Substantial work in this field is still required to provide a better understanding of the cavitation erosion mechanism of polymeric materials and to guide the development of more erosion resistant coating

materials.

Amongst many polymeric materials, polyurea is of particular interest due to its reported good performance as a reinforcement of metal structures against shocks from blast and impact loads [19]. In addition, polymers with urea bonding involve faster reaction time than those associated with polyurethane and this fast reaction time enables the desirable spray process of polyurea coating applications. Experiments characterizing the material properties of polyurea have been conducted under a range of different strains and strain rates [20–23]. The experiments indicate that polyurea is sensitive to strain rate, i.e. there is a rubbery-to-glassy transition in the material response as the strain rate is increased. It is also known that the rheological and yield properties of polymers are highly sensitive to temperature.

We have already reported cavitation erosion experiments on polyurea and the effects of polyurea coating thickness, composition, and temperature on the cavitation erosion in [24]. This study showed that the damage was in the form of a crater with a strong evidence of plastic flow. Some data suggested that thinner coating resisted cavitation better than a thicker coating. The studies also showed that the material resistance to cavitation erosion increased significantly at low temperatures and numerical simulations explained this behavior by the heat generation in the viscoelastic material when it is exposed to repeated microscopic bubble collapse loading [25]. As the temperature increases, the material shear modulus drops dramatically, followed by material plastic flow and large crater shape deformation.

Examples of cavitation damage produced by a cavitating jet translating over a 1 mm thick polyurea coating on an aluminum substrate is shown in Fig. 1. As we discuss in further details in the paper, the jet was

* Corresponding author.

E-mail address: glchahine@dynaflow-inc.com (G.L. Chahine).

¹ www.dynaflow-inc.com.

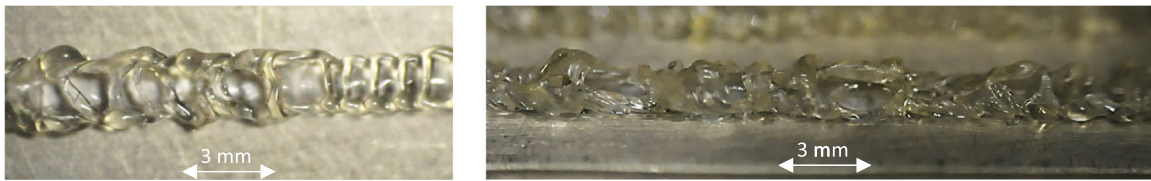


Fig. 1. Photographs of the eroded polyurea following a translating cavitating jet test. 1 mm thick PU-650 on aluminum substrate. Jet translation speed 0.01 in/s (0.25 mm/s). Jet pressure \sim 1000 psi (\sim 7 MPa).

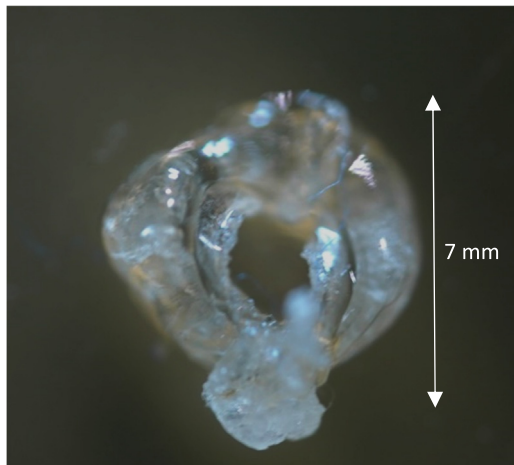


Fig. 2. Failed polyurea sample after 2.5 min under a fixed cavitating jet discharging at 700 psi (4.8 MPa). 9 mm thick PU-650 on aluminum substrate.

translated in order to reduce the heat accumulation obtained with stationary jet experiments. In absence of translation and at sufficiently intense cavitation (large jet speeds or nozzle pressure), the material fails as shown in Fig. 2. Both figures show evidence of plastic flow of the material caused by the softening of the polyurea. The failed polyurea can be seen initially to not be removed from the sample but to instead come out of the path of the cavitation and to be extruded on the edges of the region where the loads were applied. This is due, as we will see below, to poor conductivity of the viscoelastic material and measurable temperature rise.

In an effort to understand this heat generation and its relation to the intensity of the cavitation field, this paper presents systematic experiments where both the level of cavitation and temperature were measured. Relations between the temperature rise, the cavitating jet pressure, the measurement radial location away from the jet axis, the thickness and composition of the polyurea coating, and the material substrate were investigated. Correspondence of the cavitation intensities used in the present study to those encountered in hydrodynamics applications is illustrated in Fig. 3. Extensive studies conducted in [2] and recently summarized in [4] have shown that all cavitation fields (e.g. in hydrodynamic fields, cavitating jets, ultrasonic devices) can be universally characterized by a normalized distribution of cavitation impulsive pressures, $n_{impulse}(P_{impulse})$, where $n_{impulse}$ is the number of impulsive pressures of amplitude $P_{impulse}$. Each field has a characteristic, N^* and P^* , which renders the normalized plot of $n_{impulse}(P_{impulse})$ unique. Fig. 3 shows how N^* and P^* vary with the cavitation intensity. It is seen that cavitating jet pressures less than 10 MPa correspond to laboratory tests of cavitation in a hydrodynamic channel setup.

2. Polyurea samples for temperature measurements

Two types of Polyurea samples were used in this study: circular samples molded in a Plexiglas substrate and rectangular samples formed on top of an aluminum block substrate. The circular sample

were made of a 6 mm thick Plexiglas with a circular cavity measuring 25.4 mm in diameter and 2 mm deep which held the polyurea. The polyurea was prepared by the University of Massachusetts at Lowell by using various mixtures of Isonate 2143 L and Versalink [19]. Underneath the polyurea, a PVDF sensor was embedded on the Plexiglas substrate and was used for pressure measurements. These are not specifically discussed in this paper but were addressed in previous work [24,25].

To measure the temperature distribution at various radial distances from the cavitating jet axis, four K-type thermocouples (Omega[®] Model No. 5SC-KK-K-30-36) were implanted at 2.5 mm intervals along a straight line (Fig. 4a), with the first thermocouple positioned directly under the axis of the jet. The thermocouples were installed from the bottom of the sample through holes made in the substrate (Fig. 4b). After inserting the thermocouples, the holes were sealed with silicon adhesive E6800 to prevent contact of the sensitive parts of the thermocouple with the surrounding water. The temperature was obtained using a Thermocouple-to-Analog Converter (Omega[®] SMC-J). The effective measurement range for this unit is from -148°F to $+2282^{\circ}\text{F}$ with an accuracy of $\pm 4^{\circ}\text{F}$. Additionally, measurements were also taken at different depths to observe the distribution of the temperature through the thickness of the material.

The rectangular polyurea samples had various thicknesses and had 12.5 mm thick aluminum or Plexiglas substrates. Three types of Polyurea were tested: P-1000, P-650 and a Blend of the two. All three formulations are combination of Isonate 143 L and an Amine: PU-1000 uses VP1000 for the amine, PU-650 uses VP650, and the blend uses a 76:24 wt ratio of a mixture of VP1000 and VP650. The length of each sample was 102 mm (4 in.) and the width was 51 mm (2 in.). Table 1 lists the samples that were used in the tests reported in this paper.

3. Experimental setup and procedures

3.1. Stationary jet tests

The cavitating jet erosion test facility used in this work is a flow loop, which is composed of a CAVIJET[®] nozzle, a sample holder, a test tank, a water reservoir, and a pump capable of generating 1200 psi (8.3 MPa) at a flow rate of 5 gpm (19 l/min). Fig. 4 shows a photograph of the flow loop. The cavitation erosion tests were conducted utilizing cavitating jet nozzle with the orifice diameter of 0.086 in. (2.2 mm) (Fig. 5). The CAVIJET[®] nozzle induces cavitation in the submerged jet shear layer initiated from a sharp corner at the orifice exit to produce extremely high, localized stresses on a surface due to cavitation bubble collapse near the jet stagnation region on the sample. The cavitation generated by a cavitating jet provides realistic cavitation bubble clouds with distribution of various size micro bubbles, which then collapse on the test material surface.

Fig. 6 shows the 2-mm thick circular polyurea P-650 sample poured into a recess in a 2 in. by 2 in. (5.08 cm x 5.08 cm) square Plexiglas block positioned in the sample holder inside the test chamber. The sample holder ensures that the sample is maintained in place during the test and can be returned to the same position between successive measurements and observations. The sample was placed at a standoff distance of 1 in. (2.54 cm) from the nozzle exit, and the cavitating jet from the nozzle impinged perpendicularly on the sample surface. All

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